MASTER THESIS

Performance Development of Off-Pump Coronary Artery Bypass Surgeons

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Abstract

Introduction: Off-pump coronary artery bypass grafting (OPCAB) is a highly complex cardiac surgery procedure and requires considerable skill of the surgeon. It has been debated in the literature whether OPCAB is an improvement on the 'gold standard', which uses the heart-lung machine. To adequately evaluate performance (improvement) and create trainings, various outcome variables, their predictors and learning of OPCAB were investigated.

Method: This project is a single-institutional retrospective analysis of all surgeon, patient and procedural data of OPCAB cases between May 2015 and December 2019. Various outcome variables were visually and theoretically explored in their usefulness, three of which were chosen to represent accuracy and efficiency of the surgeon, and patient outcomes. The three chosen outcome variables were used to build Bayesian generalized linear mixed effects models, testing a total of 50 possible predictors. The development of performance over time was visually inspected, including CUSUM curves, and compared to the development of patient risk factors.

Results: Lowest systolic blood pressure (LSBP) was chosen as accuracy measure, operation duration for efficiency and a complication score built from all recorded complications for patient outcomes. Variance in LSBP could be explained for more than 70% by the built model, 9% of operation duration could be predicted by the final model, and no predictors could be found for the complication score. Surgeon specialisation, patient characteristics and the number of venous grafts and anastomoses were the factors influencing LSBP and operation duration the most.

Discussion: All outcome variables should be evaluated in the context of the surgical team and patient characteristics. The surgeon is never solely responsible for the outcomes. Hypotension is a useful measure for surgeon accuracy, as many covariates are commonly registered prediction was good. Operation duration appeared almost independent of most predictors and should be used with care. An unweighted score for patient complications should be avoided as in this case none of the 50 available predictors were able to predict its variance. OPCAB training should preferably take place in a safe environment for both patients and surgeons and should include as many differences in patients and scenarios as possible to adequately prepare the trainee for real cases. Venous grafts should be avoided due to intraoperative hypotension, longer operation duration and worse outcomes. Surgeons who decide to learn OPCAB should focus on that and perform most CABGs off-pump.

Acknowledgements

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Contents

Cardiovascular diseases are the leading cause of death worldwide (World Health Organisation (WHO), 2017). The WHO states that most cardiovascular diseases could be prevented and that access to health care for detection and treatment play a role in survival (World Health Organisation (WHO), 2017). In the Netherlands, deaths due to cardiovascular diseases are decreasing, possibly partly due to high availability of quality healthcare and continuous efforts to improve quality of care (Siregar et al., 2013). Surgical interventions can drastically improve patients' quality of life (Kulik, 2017). For coronary artery disease, coronary artery bypass grafting (CABG) is the so-called 'gold standard'. CABG is an open heart operation, where a blood vessel from elsewhere in the body (usually chest, arm or leg) is used to bypass the occluded vessel(s) and ensure blood flow to all parts of the heart. CABG is an internationally often used procedure, which is well researched and safe for patients. Mortality, morbidity and need for reintervention are low (Sellke et al., 2005).

The debate about using the heart-lung machine

A typical CABG can be executed in two ways: with or without the heart-lung machine, also called cardio-pulmonary bypass (CPB). Due to the nature of the machine the two methods are also called on-pump (ONCAB, with CPB) and off-pump (OPCAB, without CPB), these terms are used synonymously throughout this thesis. For decades, researchers and practitioners have been debating the benefits and shortcomings of both methods (Gaudino et al., 2018), an overview of the benefits and limitations can be found in table 9 in supplement 1. After a period of decrease, the use of the heart-lung machine increased in recent years (Mack & Taggart, 2019), which might suggest that practitioners are leaning towards ONCAB. While the benefits of OPCAB relate more to the outcomes for the patients, the benefits of ONCAB are more related to the ease of the procedure (Sellke et al., 2005). In particular, CPB is associated with various complications, including increased blood loss. Especially patients who already have a high risk for complications seem to benefit from avoiding CPB (Ji, Mei, Wang, & Ding, 2014; Ueki et al., 2018). Further, ONCAB patients tend to stay longer in the intensive care unit (ICU) and hospital, leading to higher initial costs (Atluri, Kozin, Hiesinger, & Woo, 2011; Chassot, van der Linden, Zaugg, Mueller, & Spahn, 2004).

On the other hand, OPCAB has been found to have more often incomplete revascularization, meaning that the planned operation was not fully executed (Chikwe, Lee, Itagaki, Adams, & Egorova, 2018; Gaudino et al., 2018; Hlavička, Vaněk, Jarkovský, & Benešová, 2018). Irrespective of use of CPB, incomplete revascularisation has negative

consequences for the patient, e.g. less alleviation of symptoms which might lead to a need for reintervention (Diegeler et al., 2019). Instead, the rate of incomplete revascularisation might depend highly on the individual surgeon and hospital (Farina, Gaudino, & Angelini, 2019), or on the patient characteristics instead of the treatment method and characteristics (Diegeler et al., 2019). The connection between OPCAB and lower rates of complete revascularisation rests on the fact that OPCAB is generally considered to be more technically demanding (Bonchek, 2002; Chassot et al., 2004; Farina et al., 2019; Lazar, 2013; Sellke et al., 2005). The difficulty of OPCAB lies in the fact that without the help of CPB, the heart has to continue to beat. With CPB, the heart can be stopped and the surgeon can operate on a non-moving target, which is easier (Arom et al., 2000).

Similarly to incomplete revascularization, inferior rates of morbidity and mortality for OPCAB have been found in some studies but not in others (Sellke et al., 2005; Wijeysundera et al., 2005). A possible explanation for the differences in results might be surgeon experience (Yadava & Taggart, 2020). With thoughtful training including careful patient selection, the disadvantages of OPCAB have been called “misperceptions and misconceptions” (S.G. Raja & Benedetto, 2014). To achieve the highest quality of care, most patients should be operated on off-pump by a well-trained surgeon (as first surgeon or supervisor), while those patients who benefit from use of CPB should be operated on on-pump (Diegeler et al., 2019; S.G. Raja & Benedetto, 2014; Yadava & Taggart, 2020).

OPCAB performance and learning

Surgeons who cannot demonstrate OPCAB outcomes that are at least similar to ONCAB have been called to abandon the procedure (Lazar, 2013). In order to achieve the necessary skill level for OPCAB, surgeons need to be trained well. To evaluate the quality and efficiency of a training, knowledge about how to measure success and difficulty, and understanding how trainees learn is required (Myles, 2014; Ramsay et al., 2001). Success in surgical interventions can be measured in various ways, each with their own advantages and disadvantages. From a training perspective, measures that are directly influenced by the surgeon are most relevant, measuring the accuracy and efficiency of the surgeon. With high accuracy, the surgeon lays a foundation for the best possible outcomes, while efficiency relates to the resources needed for a given procedure. From a statistical perspective, good outcome measures should be informative, e.g. very rare dichotomous outcomes are difficult to predict and the discrimination between performance levels is low (Ramsay et al., 2001). The patient perspective is the most relevant, because the goal of the procedure is to improve the patient’s quality of life. Therefore,

symptom relief, freedom of complications and quick recovery are highly important (Myles, 2014). These three perspectives are intertwined, as good patient outcomes should not be compromised in a training, and statistics are needed to do analysis of any of the other perspectives. Thus, for evaluation of OPCAB training and performance, all three perspectives should be considered. Thus, the first research question relates to the selection of outcome variables.

Research Question 1:

What are suitable outcome variables for OPCAB procedures?

OPCAB training mostly takes place on the patient. While some work has been done to create OPCAB simulators, usability and feasibility are not satisfactory enough for widespread use (de Vries, 2018; Halkos & Puskas, 2009; Ito, Shimamoto, Sakaguchi, & Komiya, 2013). Residents start with assisting an experienced surgeon and gradually take over more tasks. The senior surgeon has to estimate the skill level of the resident, then select a patient and the tasks that the resident is allowed to execute. The outcome of OPCAB is mostly influenced by case mix (i.e. patient and disease characteristics), therefore the careful selection of a patient is crucial (O. Papachristofi et al., 2017). Patient risk is often estimated with risk scores. Risk scores are often based on a large dataset and have clear definitions of their variables. In a comparison of multiple scores, the EuroSCORE was found to best predict 30 day mortality (Geissler et al., 2000). The EuroSCORE is a commonly used score, e.g. by hospitals connected to the Dutch Heart Registry, leading to standardized data collection and reliable comparisons (Nederlandse Hart Registratie, 2018). The EuroSCORE was created for cardiac surgery in general. Its components were partly chosen on practicality and availability in hospitals (Nashef et al., 1999, 2012). The selection and weighting of risk factors might be different for other scores. Therefore, other factors, if available, should be investigated as well (Bode & Kelm, 2009).

Additional to the surgeon and patient, various studies indicate that procedural variables influence the outcome of a case as well. The surgeon has to choose between possible blood vessels from elsewhere in the body to use as a bypass. The most common options include the internal mammary arteries (chest), saphenous vein (leg) and radial artery (lower arm; Kayatta & Halkos, 2018). While saphenous vein grafts are very common and supposed to be easier, research indicates that arterial grafts have better patency and do not increase complexity by

much (Anyanwu et al., 2001). OPCAB is continually developed as professionals strive to improve patient outcomes. Thus, procedures performed early on might have higher risks than recent ones (Murzi, Caputo, Aresu, Duggan, & Angelini, 2012). Furthermore, the surgeon does not operate alone, cooperation and coordination other team members is essential for the success of the procedure (Olympia Papachristofi, Klein, & Sharples, 2016). While surgeon, patient and procedural factors play a role in the outcomes of OPCAB, it is not clear how these factors influence the various outcome variables. To evaluate performance and training, and to improve OPCAB further, it is essential to know which factors play a role and how they influence the various outcomes.

Statistical methodology needs to fit the research question and be suitable for the data. Frequentist or classic statistical tests have been used to find differences between groups of patients, surgeons, or procedures (Novick et al., 2002, 2001). With these classical tests, researchers can investigate their previously formulated hypotheses under strict assumptions about the data. However, this is an exploratory research and thus no hypotheses are formulated or tested. For this open, exploratory approach Bayesian statistics are more suitable because the philosophy of Bayesian statistics is to update ones beliefs based on new data instead of testing fixed expectations. Furthermore, Bayesian statistics offer an estimation about how certain the results are, for example in a linear model all coefficients are given with credibility intervals (Schmettow, 2021). Knowing about the uncertainty of the coefficients can help the researcher to be more certain about the results. Bayesian generalized linear mixed models are flexible in that they can include various distributions (e.g. to account for strictly non-negative variables like time) and include both random and fixed effects. Including random factors enables one to account for individual differences without knowing which aspects exactly make the difference. Thus, the model is estimated for all cases, and additional for e.g. each surgeon, meaning that every surgeon gets an estimation for every coefficient. This is useful because differences between surgeons are expected. Some surgeons might have more difficulty dealing with certain aspects of OPCAB than others and every surgeon might learn in a different way. This type of models was used to investigate factors influencing OPCAB outcomes because it is very well suited to find and compare factors contributing to an outcome.

Research Question 2:

How are surgeon experience, and patient and procedural characteristics of OPCAB related to the performance (improvement) of surgeons?

With measures of performance and difficulty, the surgeons' performance and improvement thereof can be investigated. According to Bougioukakis, "[t]he importance of understanding and managing the learning curve cannot be overemphasized" (Bougioukakis et al., 2014). Learning curves depict the improvement of performance and are expected to have a period of fast increase, which slows down and approaches an asymptote (Pusic, Boutis, Hatala, & Cook, 2015; Ramsay et al., 2001). The parameters of learning curves can be used as input for training (Gao, Kruger, Intes, Schwaitzberg, & De, 2020; Ramsay et al., 2001). Learning of OPCAB is not restricted to the period of residency (surgeon training), a surgeon can decide to learn OPCAB at a later career stage.

The learning period of OPCAB has been described in the literature with varying methodology. Ramsay et al. describe a hierarchy of methods to investigate learning (Ramsay et al., 2001). Some studies use exclusively descriptive methods (Chen & Wan, 2007; H. K. Song, Petersen, Sharoni, Guyton, & Puskas, 2003). The cumulative sum (CUSUM) plot is a commonly used descriptive technique because it is simple to create and understand (Bougioukakis et al., 2014; Murphy, Rogers, Caputo, & Angelini, 2005). CUSUM plots show trends in performance, often compared to a baseline (e.g. ONCAB or patient risk). While they are suitable for quality control, CUSUM plots cannot provide a description of a learning curve (Ramsay et al., 2001). Visual inspections are a first step in learning curve research. Graphs can provide information about the existence of learning curves, whether they are monotonous, and the general shape of the learning curve.

If learning curves are detected, statistical models can be estimated to confirm the shape of the learning curve and predict future developments. In general, a learning curve often has a steep initial slope. The beginner has everything yet to learn and often improvement is fast. With more experience, the speed of learning decreases and the slope of the learning curve becomes flatter. Learning cannot continue forever because at a certain performance level no improvement is possible due to natural restrictions. If performance is measured in time, for

example, the body needs a certain minimal time to execute or respond a task, this time can never be zero or negative. Thus, the learning curve ends in an approach towards an asymptote (Ramsay et al., 2001). The so-called power-law of practice states that learning curves can best be modelled with power-curves (Newell & Rosenbloom, 1981). However, this was based on between-participant averaged data and for individual learners, exponential curves fit better (Heathcote, Brown, & Mewhort, 2000). Averaging between participants, or in this case surgeons, cannot be desirable as curve shapes can be distorted and individual differences in performance and learning process are neglected (Brown & Heathcote, 2003).

Research Question 3:

Can OPCAB performance improvement be modelled with exponential learning curve models?

For the interested reader, more detailed medical information and background on OPCAB training can be found in supplementary material I.

Method

Data gathering

Data source

To answer all three research questions, data about CABG patients and their cases were retrospectively analysed. The data were provided by the Thoraxcentrum Twente (TCT) of the Medisch Spectrum Twente (MST), a hospital in Enschede, the Netherlands. Data is available since the establishment of the centre in 2004, however in 2015 the quality of the data was drastically improved and therefore only the data since May 2015 until December 2019 was used unless otherwise mentioned. While the data was collected in real time, the analyses performed are retrospective. Originally the data of all surgical patients were collected for a medical research database and are adhering to the standards and definitions of the database (Dutch Heart Register). All variables that were expected to possibly relate to learning or outcomes of CABG were obtained, the choice is described in supplementary material II: Variable selection. Using data from designated research data bases supposedly reduces bias (Heathcote & Brown, 2004). The data is limited to one hospital, thus the organizational procedures are highly similar (e.g. guidelines on when a patient is released). The descriptions and definitions of variables are publicly accessible at https://nederlandsehartregistratie.nl/handboeken/ (Dutch). Variables used in the current project are also named and translated in section Variable names and translations.

Data conduct

Data used in this project are sensitive for patients (health data), surgeons (performance data) and the hospital and therefore responsible conduct is essential. According to the general data protection regulation (GDPR, European legislation on data privacy and security) a valid reason is needed to collect human data. In this case, this project's aim is a goal of general interest: To investigate learning and performance of surgeons throughout their career, and improve training. This could contribute to improvements in performance in a common surgical procedure, which is beneficial for the general population. In the data received for this project patient and surgeon numbers were pseudonymised. This means, that with additional data both surgeons and patients could still be identified, for example by an employee of the hospital. To prevent recognition of an individual, all intermediate reports, figures, tables and discussions of the data were based on anonymized data. The data were stored and analysed on a safe encrypted server of the University of Twente, certified with ISO/IEC 27001 and NEN 7510 standards. A detailed description of the data conduct can be found in the data management plan in appendix A.

Data request and ethical testing

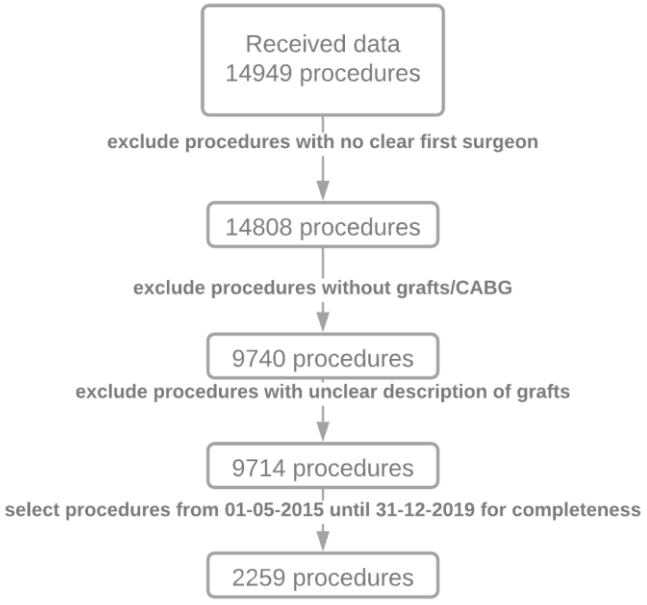
Before the data could be obtained, the research proposal had to be approved by multiple authorities. A data management plan was created and discussed with the privacy contact person of the Techmed centre of the University of Twente (see appendix B). The ethical committee of the faculty of Behavioural, Management and Social Sciences of the University of Twente confirmed that the proposed research followed ethical guidelines (Request no. 200114; for complete request see appendix A). Approval was obtained from the boards of both the TCT and the MST, for the latter see appendix B. Finally, the medical ethical testing committee declared the project legally as not medical scientific research and thus no official testing is required (identifier: K20-29; for complete approval see appendix B). The study was conducted according to the guidelines of the Declaration of Helsinki, and approved by the Institutional Review Board and Ethics Committee of Medisch Spectrum Twente (protocol code K20-29, approved 22-09-2020).

Data cleaning

The original dataset contained 14949 cases, through selection of relevant high quality data, 2259 procedures were left, see figure 1. In consultation with hospital staff, outliers, defined as highly unrealistic values (e.g. patient height >1000cm), were coded as missing values, meaning that the value was deleted but the case remained in the data. After discussion with hospital staff, for a few patients length and weight values were swapped under the assumption that the values were entered incorrectly into the system. The exact steps of the data cleaning can be found in the "setup" section of the R script (Supplementary material III).

Figure 1

Data selection procedure



Variable operationalisation

The variables were operationalised based on the available data. Experience has been calculated in three ways, which were compared during the model building process. First, all

CABG procedures since 2004 received a count per surgeon. Second, only operations since May 2015 were counted. Third, the data since 2015 was split and counted for OPCAB and ONCAB separately. From mortality status and date, mortality after 30 days, 60 days, 120 days and 1 year were calculated. A score for all possible complications was calculated by taking the proportion of all possible complications including one year mortality (1 meaning all complications were present in a patient, 0 meaning no complication). Major adverse cardiovascular or cerebrovascular event (MACCE) was calculated similar to (Halbersma et al., 2009). As opposed to the original calculation, the available follow-up times for the current project were shorter than the stated 1 year, namely cerebrovascular accident: during hospital stay, myocardial infarct: perioperatively, revascularization: within 30 days. The 'textbook outcome' described by Hasper and Gourie (Hasper & Gourie, n.d.) was calculated. However, for the variable myocardial infarct (MI) no follow-up was available and therefore the perioperative occurrence of MI was used with the same weighting. BMI was calculated from length and weight.

Statistical analysis

For all analyses, the programme RStudio version 1.3.1093 with R version 4.0.3 was used with the following packages: tidyverse (Wickham et al., 2019), brms (Bürkner, 2017), bayr (Schmettow, 2020b), scales (Wickham & Seidel, 2020), gridExtra (Auguie, 2017), readxl (Wickham & Bryan, 2019), reshape2 (Wickham, 2007), and asymptote (Schmettow, 2020a). For transparency and reproducibility, the complete code creating analyses and graphs in this report can found in supplementary material III.

Outcomes of CABG

To answer the first research question about the choice of outcome variables, ten outcome variables were initially investigated: lowest systolic blood pressure (LSBP; Roshanov et al., 2019; Weyland & Grüne, 2013), operation duration (Burt et al., 2015; Maruthappu, Duclos, Lipsitz, Orgill, & Carty, 2015), a complication score calculated as percentage of all recorded complications, length of stay (Almashrafi, Alsabti, Mukaddirov, Balan, & Aylin, 2016; Krell, Girotti, & Dimick, 2014; O. Papachristofi et al., 2017), MACCE (Halbersma et al., 2009; Neumann et al., 2019), similarity to a textbook outcome (Hasper & Gourie, n.d.), and mortality with the follow up periods of 30 days (Tsugawa et al., 2018), 60 days (Siregar et al., 2013), 120 days (Siregar et al., 2013), and 1 year (Siregar et al., 2013). These outcomes were selected based on the literature (see Supplementary Material III Variable Selection) and availability. The complication score was expected to contain more information than other patient outcomes because MACCE, or mortality contain dichotomous events that occur very rarely. Furthermore,

freedom of complication is a valuable outcome for patients (Ramsay et al., 2001), thus all recorded complications were included. Each outcome was inspected visually through histograms and plots showing the development of the outcomes over time for each surgeon. These plots were used to determine which outcome variables have the most variance and carry the highest informational value. Variables with more variance and a larger range contain more informational value, which increases predictive accuracy. One variable was chosen for each of the following categories: accuracy, efficiency and patient outcomes.

Generalized linear models (GLMs) predicting OPCAB performance

The second research question was about which and how procedural, patient and surgeon factors influence the outcome variables. Bayesian generalized linear mixed models have been used to investigate these for the chosen variables from research question 1. Generalized linear models allow for error distributions other than the normal (Gaussian) distribution and can thus be used for various types of outcome variables. In linear models the error is assumed to follow a Gaussian shape, while GLMs allow for other shapes which increases model fit. Selecting a distribution that fits the data better (than the normal distribution) leads to better estimations of parameters and better predictions (Pusic et al., 2015; Ramsay et al., 2001). It is often advised to test out various distributions to find the most appropriate for a given variable (Pusic et al., 2015; Ramsay et al., 2001). However, if a variable has many predictors influencing the outcome, the distribution of the variable does not necessarily be the same as the error distribution. Therefore, the error distributions are chosen based on availability in the brms engine and theoretical considerations, i.e. boundaries and type of variable. This choice was made for all ten outcome variables.

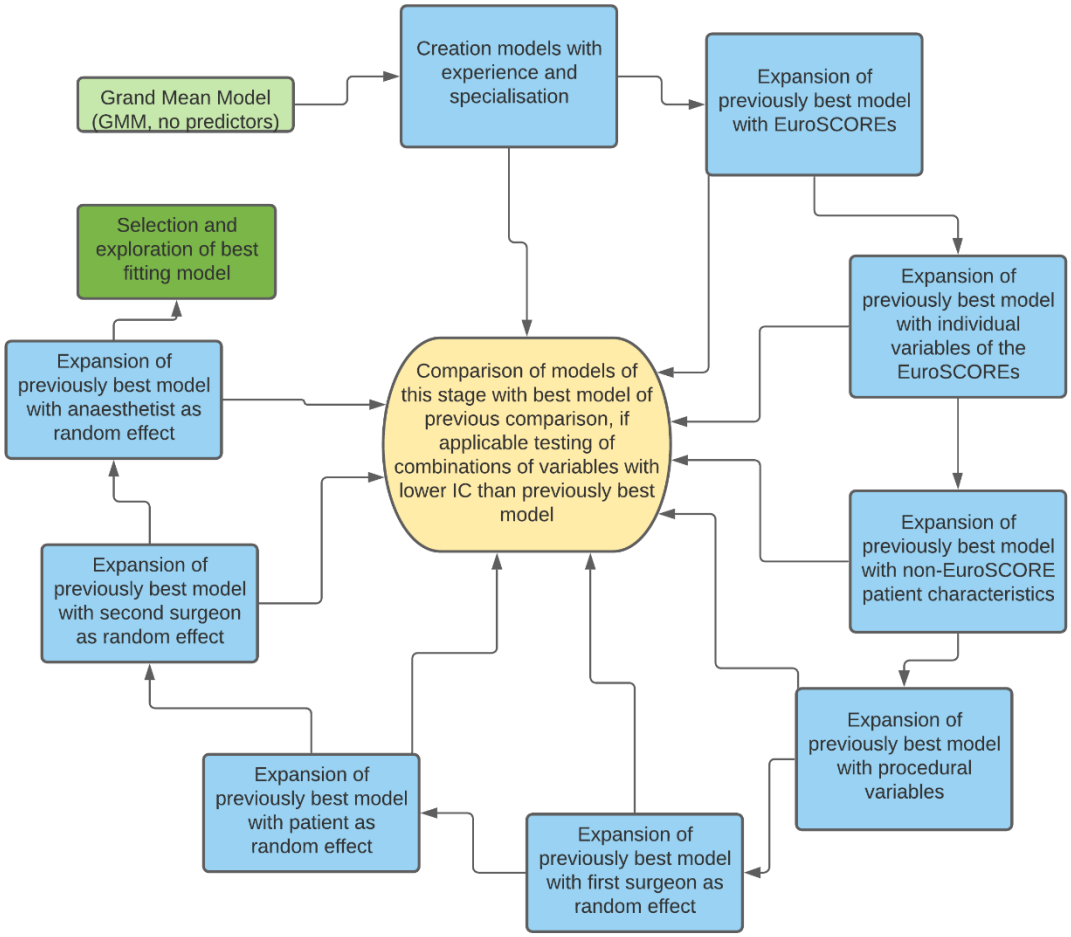
Finding the best model for each of the three chosen outcome variables for accuracy, efficiency and patient outcomes has been done through a series of iterative steps. For each of the chosen outcome variables a Bayesian generalized linear mixed model has been built. Figure 2 gives an overview of the general model building process that has been used for the three chosen outcome variables. All variables are named and translated in section Variable names and translations, a more detailed description can be found in supplementary material II Variable Selection. In each stage (blue boxes), multiple models were created, each with one of the described variables (e.g. three operationalisations of experience and one for specialisation result in four models for stage 1). Then, those models were compared with the previously best model. If multiple individual variables improved model fit compared to the previously best model, combinations of these variables were explored and compared to the then previously best model

without the combinations. These steps of adding individual variables and testing their combinations was repeated for several groups of variables, described in the blue boxes of figure 2.

For model comparisons the leave-one-out information criterion has been used (loo-IC; Vehtari, Gelman, & Gabry, 2017). Other information criteria, like the widely applicable information criterion (WAIC) or deviance information criterion (DIC), are less suitable for Bayesian models. Leave-one-out cross validation would be more accurate, but requires refitting of the model as often as there are observations. Running models for hundreds or thousands of times would result unfeasible highly run times and could therefore not be used for comparison of multiple models. The loo-IC uses the estimates produced with the initial model estimation to approximate a leave-one-out validation. The estimated loo-IC value is efficient to calculate and is highly suitable for comparison (Vehtari et al., 2017). However, the absolute loo-IC values are difficult to interpret. Due to this difficulty and the large number of models estimated, only the ranking of the models in each step are described and not the individual values.

Figure 2

Visualisation of the model building process. IC = information criterium



Learning curves

This section describes the investigation of research question three about learning curves. The first step of learning curve analyses is to inspect the curves visually (Pusic et al., 2015; Ramsay et al., 2001). For each surgeon and outcome variable, a plot was made of the development throughout the surgeons experience between 2015 and 2019. Since outcomes can be influenced by case mix by up to 95% (O. Papachristofi et al., 2017), an additional plot series for the development of the EuroSCORE II has been added for each surgeon.

CUSUM (cumulative sum) plots are tools for visual quality control. They are commonly used for exploration of learning curves in health sciences (Bougioukakis et al., 2014; Chen & Wan, 2007; Murphy et al., 2005; Novick et al., 2003, 2002, 2001; Novick & Stitt, 1985; M. H. Song, Tajima, Watanabe, & Ito, 2005). However, CUSUM plots are mostly useful for investigating "a system going out of control, whereas learning curve data represent a system coming under control" (Ramsay et al., 2001). A CUSUM plot has the number of operations (experience) on the x-axis and the cumulative sum of the EuroSCOREs minus 30-day mortality (1 for dead, 0 for survivor) on the y-axis. Therefore, for each patient who dies within 30 days after the surgery, a 'penalty' is given. The EuroSCORE's have been used to account for the risk of each individual patient (Novick, Fox, Stitt, Forbes, & Steiner, 2006). A CUSUM plot indicates an increase or decrease in quality through a change in the slope. Additional CUSUM plots have been created for those procedures where the second surgeon was an surgical assistant, thus procedures used for teaching have been excluded. Surgeries performed with a surgical assistant reflect surgeon skill more clearly because there is less variance in task distribution than when teaching.

When analysing learning curves, after the visual inspection a model estimation is being made. The model provides estimations for the amount of learning (amplitude), the speed of learning (rate), and the maximum performance (asymptote). Together with the initial performance, these parameters completely describe an exponential learning curve (Heathcote et al., 2000). An attempt has been made to estimate learning curves with the R package asymptote, which provides tools to estimate learning curves with various refinement options (Schmettow, 2020a).

Results

Surgeon, patient and case descriptives

The analyses were based on the dataset of all OPCABs between May 2015 and December 2019, unless otherwise stated. During this period, 14 individual surgeons performed CABG, 13 of them performed both ONCAB and OPCAB while one performed ONCAB only. The surgeons performed between 13 and 381 (median 76) CABGs, and between one and 377 (median 78) OPCABs between May 2015 and December 2019. The four surgeons with the most CABGs performed 66% of all CABG procedures, the two surgeons with the most OPCABs performed 67% off all OPCAB procedures. Two thousand and fifty-six individual patients were included in the sample, their characteristics are described in table 1. Two of the patients underwent CABG twice, both once with and once without heart-lung machine. Table 1 shows patient characteristics including EuroSCOREs and their components. OPCAB and ONCAB patients are highly similar on average, with a slight tendency to higher risk in OPCAB patients. It can be noted that aorta clamping has been done for neither technique as aortic manipulation is associated with inferior patient outcomes and considered an outdated technique (J. D. Puskas, Yanagawa, & Taggart, 2016). Patients with multiple diseased vessels were slightly more represented in the ONCAB group.

Table 1

Patient Characteristics; Values are expressed as n(%) or mean ± standard deviation, missing values (NAs) are only included if applicable

Variable	OPCAB (n = 1002)	ONCAB (n = 1058)
Sex (male)	800 (80%)	868 (82%)
Age, years	67 ± 9.4	67 ± 9.1
BMI, kg/m²	28 ± 4.3	28 ± 4.0
Height of patient, cm	175 ± 8.9	175 ± 9.0
Weight of patient, kg	86 ± 15.2	86 ± 14.5
EuroSCORE I, additive	4.08 ± 2.7	3.97 ± 2.6
EuroSCORE I, logistic	3.72 ± 6.1	3.60 ± 6.0
EuroSCORE II	1.76 ± 2.2	1.68 ± 2.1
Chronic lung disease	114 (11%)	124 (12%)
Extracardiac arteriopathy	182 (18%), NAs: 2	167 (16%) NAs:
Neurological disfunction	27 (3%), NAs: 2	25 (2%), NAs: 1
Previous cardiac surgery	23 (2%), NAs: 2	20 (2%), NAs: 1
Creatinine level, µmol/l	94 ± 43	93 ± 56
Endocarditis	0 (0%), NAs: 2	0 (0%), NAs: 1

Variable	OPCAB (n = 1002)	ONCAB (n = 1058)
Critical preoperative condition	23 (2%), NAs: 2	17 (2%)
Non-stable angina pectoris	53 (5%), NAs: 2	50 (5%)
Left ventricle ejection fraction, percentage	51 ± 8.3	50 ± 8.9
Recent myocardial infarct	261 (26%)	269 (25%)
Pressure in pulmonary artery, mmHg	25 ± 3.2	25 ± 2.8
Surgery on aorta	0 (0%), NAs: 2	0 (0%), NAs: 1
Operation is due to a defect at the intraventricular septum caused by rupture due to a myocardial infarct	0 (0%), NAs: 2	0 (0%), NAs: 1
New York Heart Association functional classification for heart failure class IV	12 (1%), NAs: 27	7 (1%), NAs: 27
Canadian Cardiovascular Classification System class IV	59 (6%)	57 (5%)
Diabetes mellitus	295 (29%)	300 (28%)
Poor mobility	16 (2%)	11 (1%)
Kidney failure	1 (0%)	1 (0%)
Dialysis	2 (0%)	7 (1%)
Current smoker	116 (12%), NAs: 3	133 (13%), NAs: 1
Smoker	391 (39%), NAs:	347 (33%), NAs: 1
Previous cardio vascular accident	50 (5%)	44 (4%)
Multiple diseased vessels	910 (91%)	1025 (97%)
Atrium fibrillation	102 (10%), NAs: 2	109 (10%), NAs: 1
Additional cardiac surgery	2 (0%)	2 (0%)
Urgency		
Elective	482 (48%)	494 (47%)
Urgent	482 (48%)	531 (50%)
Emergency	19 (2%)	16 (2%)
Salvage	0 (0%)	1 (0%)
NAs	19	16

Table 2 gives an overview of the various outcomes, including all components of the scores. Again, most outcomes are highly similar for OPCAB and ONCAB. The duration of the operation is more than one standard deviation lower than for ONCAB, indicating cost savings. Similarly, lowest systolic blood pressure is more than one standard deviation higher for OPCAB patients. However, most complications including mortality are somewhat more common in OPCAB patients, which coincides with the slightly higher risk seen in table 1. Only arm and leg wound infections are more common in ONCAB patients.

Table 2

Descriptives of outcome variables; Values are expressed as n(%) or mean ± standard deviation, missing values (NAs) are only included if applicable

Variable	OPCAB (n = 1002)	ONCAB (n = 1058)
Length of stay, nights	7.7 ± 8.0	7.6 ± 7.5
Operation duration, minutes	174 ± 45	226 ± 49
30 day mortality	11 (1%)	7 (1%)
60 day mortality	15 (1%)	9 (1%)
120 day mortality	21 (2%)	13 (1%)
1 year mortality	36 (4%)	26 (2%)
Lowest systolic blood pressure	67 ± 15.9	44 ± 12.0
All complications	0.03 ± 0.05	0.03 ± 0.04
Textbook outcome, 0 completely resembles textbook outcome, 1 does not resemble textbook outcome at all	0.02 ± 0.08	0.01 ± 0.06
MACCE within 30 days	68 (7%)	47 (4%)
New intervention during stay	7 (1%)	1 (0%)
Perioperative myocardial infarction	31 (3%), NAs: 2	21 (2%), NAs: 3
Deep sternum wound infection within 30 days	9 (1%), NAs: 26	5 (0%), NAs: 31
Refixation within 30 days	3 (0%)	1 (0%)
Rethoracotomy within 30 days	18 (2%)	17 (2%)
Heart rhythm problem	246 (25%)	257 (24%)
Vascular complication during stay	0 (0%)	1 (0%)
Gastrointestinal complication during stay	6 (1%)	2 (0%)
Cardiovascular accident	7 (1%)	5 (0%)
Readmission intensive care	25 (2%)	17 (2%)
Respiration	16 (2%)	15 (1%)
Respiratory insufficiency	11 (1%)	10 (1%)
Lung infection	47 (5%)	43 (4%)
Arm or leg wound infection	1 (0%)	11 (1%)

Procedural characteristics are shown in table 3. The number of ONCABs peaked in 2017, while OPCABs fluctuated more with a recent increase in procedures. Most conversions seem to be registered as ONCAB, which could lead to a worse impression of ONCAB outcomes. No statements about conversion can be made due to the high number of conversions. For both techniques, the number of performed grafts is lower than the number of proposed grafts, both numbers slightly lower for OPCAB which might be due to the smaller number of patients with multiple diseased vessels.

Table 3

Procedural characteristics; Values are expressed as n(%) or mean ± standard deviation, missing values (NAs) are only included if applicable

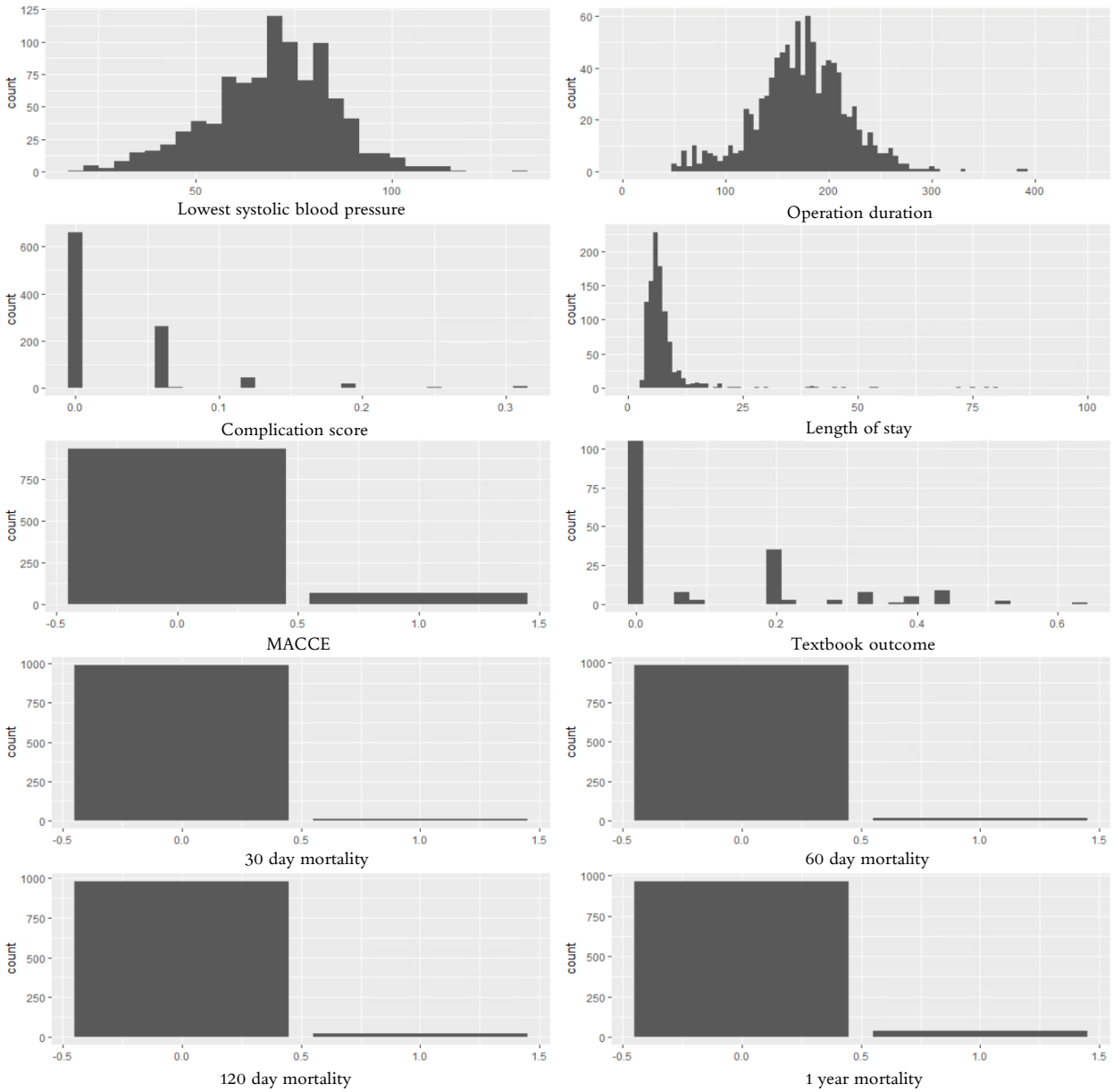
Variable	OPCAB	ONCAB
Number		
2015	156 (16%)	134 (13%)
2016	256 (26%)	194 (18%)
2017	177 (18%)	276 (26%)
2018	180 (18%)	248 (23%)
2019	233 (23%)	206 (19%)
Conversion	1 (0%), NAs: 166	14 (1%), NAs: 590
Total grafts	3.3 ± 1.05	3.4 ± 0.94
Number of proposed grafts	3.6 ± 1.25	3.8 ± 1.09

Exploration of OPCAB outcomes

An outcome suitable for predictive models has to have variance so different values can be predicted. Further, the more different values a variable can have, the more precise a prediction can be. Histograms and bar charts for the ten available outcome variables are shown in figure 3. Mortality and MACCE are dichotomous and therefore contain very little information (Figure 3e, g-j). Mortality is a rare outcome and MACCE is based on similarly rare outcome, thus little information can be obtained from the number of deaths. Textbook outcome seems to have two peaks in its distribution, modelling of which goes beyond this project. Length of stay has a highly concentrated distribution with a large positive skew. Furthermore, length of stay does not naturally fall into one of the three predetermined categories of accuracy, efficiency, and patient outcome. For further analyses, lowest systolic blood pressure is chosen as an accuracy outcome, operation duration is chosen for efficiency, and all complications as patient outcome.

Figure 3

Histograms of the outcome variables



GLMs predicting performance of surgeons

Error distribution per outcome

For each possible outcome, an error distribution has been chosen based on characteristics of the variable and availability of the distribution family in the brms engine. Each variable was categorized as continuous or categorical, boundaries were determined, whether most values are very close to the boundary and the general appearance of the histograms (Figure 3) were viewed. Based on this, a decision was made for an error distribution.

The textbook outcome seems to have two peaks, one at 0 and one around 0.2. The available distribution families do not incorporate multiple peaks, thus the exponential Gaussian distribution is only applicable if the true error distribution has one peak as opposed to the variable distribution.

Table 4

Characteristics and error distribution per outcome variable

Variable	Continuous/ categorical	Boundaries	Close to boundaries?	Histogram shape	Choice of distribution
Lowest systolic blood pressure	Continuous	Natural lower boundary (zero)	No	Skewed normal	Skew-normal
Operation duration	Continuous	Natural lower bound, high upper bound	No	Close to normal	Exgaussian
All complications	Semi-continuous	0 and 1	Yes, lower boundary		Exgaussian
Length of stay	Continuous	Natural lower boundary	Yes, lower boundary	Normal with skew and kurtosis	Skew-normal
MACCE	Categorical (dichotomous)	-	-	Rare event	Zero-inflated binomial
Textbook outcome	Semi-continuous	0 and 1	Yes, lower	2 peaks!	Exgaussian
Mortality (30/60/120 days, 1 year)	Categorical (dichotomous)	-	-	Rare event	Zero-inflated binomial

Model building for accuracy, efficiency and patient outcome

Lowest systolic blood pressure (accuracy). For the lowest systolic blood pressure (LSBP), a total of 77 models were estimated. The final model had the following formula:

Equation 1 Regression formula for final lowest systolic blood pressure model

```
lowest_bp_syst ~ 1 +
        CABGexp04 + specialisation + eurolog + cardiochir_prev + sex + age + neuro_disfunction +
        postinfarct_VSR + thorac_aortachir + BMI + height + multiv + CVA_prev + ven_anast +
        ven_graft + art_graft + conversion +
    (1 | eersteOperateur) +
    (1 + CABGexp04 + specialisation + eurolog + cardiochir_prev + sex + age + neuro_disfunction +
        postinfarct_VSR + thorac_aortachir + BMI + height + multiv + CVA_prev + ven_anast +
        ven_graft + art_graft + conversion | XXXpat) +
    (1 + CABGexp04 + specialisation + eurolog + cardiochir_prev + sex + age + neuro_disfunction +
        postinfarct_VSR + thorac_aortachir + BMI + height + multiv + CVA_prev + ven_anast +
        ven_graft + art_graft + conversion | anaesthetist)
```

LSBP was best predicted by a combination of 17 fixed and 3 random predictors. 11 out of the 17 fixed effects are patient characteristics, 4 describe the procedure and 2 are surgeon characteristics. The coefficient estimates of both the final model and the GMM including 95% credibility interval and random effects standard deviations are shown in table 5. Random effects can be applied to the intercept and/or other coefficients. For the LSBP, the predictive accuracy of the model was higher if the random effect of the surgeon was only applied to the intercept. This means that the intercept value is conditional on the surgeon, but the fixed effects are not. The fixed effects were, however, conditional on random effects of both anaesthetist and patient. Standard deviations (SD) for the random effects of anaesthetist and patient were highly similar, while the intercept SD for first surgeon was higher. Random effects include individual differences, thus the SD gives an estimation of how much individuals of a certain group deviate from the given value of the fixed coefficient.

Table 5

Coefficient estimates including 95% credibility intervals and standard deviations (SD) per random effect for lowest systolic blood pressure model. The last line displays the estimation for the grand mean model (GMM) for comparison. Prev. card. = previous cardiac, VSR = ventricular septal rupture, BMI = body mass index, Prev. CVA = previous cardio-vascular accident

Coefficient	Centre	Lower 95% CI	Upper 95% CI	SD anaesthetist	SD first surgeon	SD patient
Intercept	21.1	-66.0	110.7	4.71	5.64	4.60
Experience since 2004	0.02	0.001	0.03	0.003		0.002
Specialisation	-23.7	-48.5	0.61	3.59		3.91
Logistic EuroSCORE	-0.002	-0.53	0.58	0.28		0.21
Prev. card. Surgery	-9.46	-32.8	15.8	7.05		7.27
Female	-0.72	-10.2	8.80	3.19		3.62
Age	0.11	-2.18	0.42	0.06		0.07
Neurological dysfunction	0.61	-26.9	25.8	7.06		6.38
Postinfarct VSR	1455	-87115	116173	11.0		11.6
Aorta manipulation	-16973	-157301	21317	11.4		11.0
BMI	0.50	-0.07	1.09	0.16		0.11
Patient height	0.10	-0.30	0.50	0.03		0.04
Multivessel disease	7.33	-10.1	25.7	4.12		4.52
Prev. CVA	-6.36	-25.8	13.9	6.68		6.94
Venous Anastomoses	-0.20	-4.57	4.03	1.67		1.60
Venous graft	-9.74	-21.9	1.48	3.77		3.89
Arterial graft	13.2	-10.6	36.8	4.86		4.62
Conversion	-9506	-214508	218248	11.0		11.3
Intercept GMM	69.4	68.3	70.4			

The intercept of the final model is 21mmHg as compared to 69mmHg in the GMM, meaning that the predictors in the final model can explain more than 70% of the LSBP during the operation. However, while the estimate of the GMM is fairly certain with a credibility interval (CI) of ±2mmHg, the intercept of the final model is much less certain with a CI of ±80

including zero. The random effects of anaesthetist, first surgeon and patient are very similar and seem large compared to the centre estimate but small compared to the CI. Experience has a small but certain effect with little variation between anaesthetists and patients. Specialisation negatively affects LSBP with uncertain effect size but considerable difference between anaesthetists and patients. Age, BMI and patient height have small positive effects with CIs including zero. Both the use of (a) venous graft(s) and the number of anastomoses negatively influenced LSBP, while the use of (an) arterial graft(s) increased LSBP. The use of (a) venous graft(s) had the largest net value. Conversion had a negative effect on LSBP, with considerable differences between anaesthetists and patients.

In the final model were both the logistic EuroSCORE and six individual variables of the score. The logistic EuroSCORE had better predictive value than the newer EuroSCORE II. The centre estimate is very small and close to zero, possibly due to the fact that some of the components in the model have positive effects while other are negative. Postinfarct ventricular septal rupture (VSR) had a large positive and aorta manipulation had a large negative effect, both highly uncertain. In the EuroSCORE postinfarct VSR and aorta manipulations are given a the two largest weightings, both positive however. Differences between anaesthetists and patients are highly similar. For the logistic EuroSCORE, these individual differences clearly exceed the centre estimate, which is almost zero. Thus how the EuroSCORE affects outcomes depends largely on the patient and the anaesthetist. Similar, for previous cardiac surgery and previous CVA, the differences between anaesthetists and patients are almost as large as the effects themselves. While these individual differences were large for conversion, the certainty of the effect is extremely low.

Operation duration (efficiency). For the duration of the operation (OD), a total of 73 models were estimated. The final model had the following formula:

Equation 2 Regression formula for final operation duration model

```
operationDuration ~ 1 +
        expECC + specialisation + eurolog + sex + urgency + BMI + weight +
        multiv + ven_anast + ven_graft + vengrdiff +
            (1 | firstSurgeon) +
            (1 + expECC + specialisation + eurolog + sex + urgency +
              BMI + weight + multiv + ven_anast + ven_graft + vengrdiff | patient) +
            (1 + expECC + specialisation + eurolog + sex + urgency +
              BMI + weight + multiv + ven_anast + ven_graft + vengrdiff |
               secondSurgeon) +
            (1 + expECC + specialisation + eurolog + sex + urgency +
              BMI + weight + multiv + ven_anast + ven_graft + vengrdiff | anaesthetist)
```

Table 6 shows the coefficient estimates, 95% confidence intervals and random factor SDs for the predictors of the final model and the GMM. The intercepts are 174 and 158 minutes respectively, meaning that all 14 predictors (11 fixed effects and 4 random effects) together explained about 9% of the operation duration. As in LSBP, the intercept was conditional on the first surgeon, while the fixed effects were not. Yet, the fixed effects were dependent on anaesthetist, second surgeon and patient. Again, the certainty for intercept of the GMM is better than for the intercept of the final model but the intercept of the final model is still certain enough to give a clear indication the true position. There are considerable differences between surgeons, anaesthetists and patients. For the duration of the operation, OPCAB experience was a better predictor than general CABG experience. However, this effect is exceedingly small and rather uncertain. Both experience and specialisation had negative effects, which was expected since a shorter duration can be interpreted as higher efficiency. An OPCAB-only surgeon can be around

34 minutes faster than a surgeon without OPCAB experience for the same procedure. Notably, individual effects of anaesthetist, second surgeon and patient are about one third of the effect.

Table 6

Coefficient estimates including 95% credibility intervals and standard deviations (SD) per random effect for operation duration model. The last line displays the estimation for the grand mean model (GMM) for comparison. BMI = body mass index

Coefficient	Centre	Lower 95% CI	Upper 95% CI	SD anaesthetist	SD first surgeon	SD second surgeon	SD patient
Intercept	158	100	216	6.53	12.3	8.18	12.4
OPCAB experience since 2015	-0.04	-0.14	0.07	0.05		0.05	0.06
Specialisation	-34.2	-57.0	11.8	7.75		10.8	8.98
Logistic EuroSCORE	0.09	-1.24	1.60	0.76		0.50	1.01
Female	-5.10	-52.7	15.6	6.17		16.2	9.52
Urgency: urgent	-1.07	-0.18	0.11	5.17		4.63	3.87
Urgency: emergency	-16.2	-91.2	76.9	12.5		25.7	12.6
BMI	0.96	-1.51	4.35	0.18		0.27	0.52
Patient weight	-0.12	-1.28	0.68	0.12		0.07	0.18
Multivessel disease	32.3	-1.12	70.7	5.57		9.61	19.3
Venous anastomoses	19.7	10.0	32.0	2.84		7.81	3.74
Venous graft	1236	-28228	20013	8.71		9.22	13.3
Difference between planned and executed venous graft	-1259	-20058	28200	4.10		6.37	6.54
Intercept GMM	174.39	171.71	177.04				

The logistic EuroSCORE, BMI and patient weight had small effects of less than one minute. The effect of being female is highly uncertain and had noticeable random effects SD

for anaesthetist, second surgeon, and patient. This indicates that team members have varying difficulty in applying their skills on female patients. Although being highly uncertain effects, higher urgency seems to lead to shorter operations. Again, for these operations the team has a high influence on the duration, especially for emergency operations a lot of variance depends on the second surgeon. As could be expected, operation time for patients with multiple diseased vessels is longer, the rather uncertain estimate is around half an hour. About two thirds of this effect varies by individual patients, one third by the second surgeon and one sixth by the anaesthetist. Every venous anastomosis increased operation duration for about 20 minutes, with a second surgeon SD of about 8 minutes. The use of one or more venous grafts and the difference between the number of planned and performed venous grafts were estimated to have a high influence on operation duration. However, these differences are highly uncertain and with opposite sign, thus they likely cancel each other out. These effects are also estimated to vary considerably by surgical team and patient.

Complication score (patient outcome). For the complications score, all 50 predictors were individually tested as predictors and not one model showed higher predictive accuracy than the GMM. To account for combinations of factors, the complication score has then been used in the final models of LSBP and operation duration, but still the GMM remained best fitting model. Therefore, no further models were estimated with this score. This means, that the best fitting model for the complication score contained no predictors.

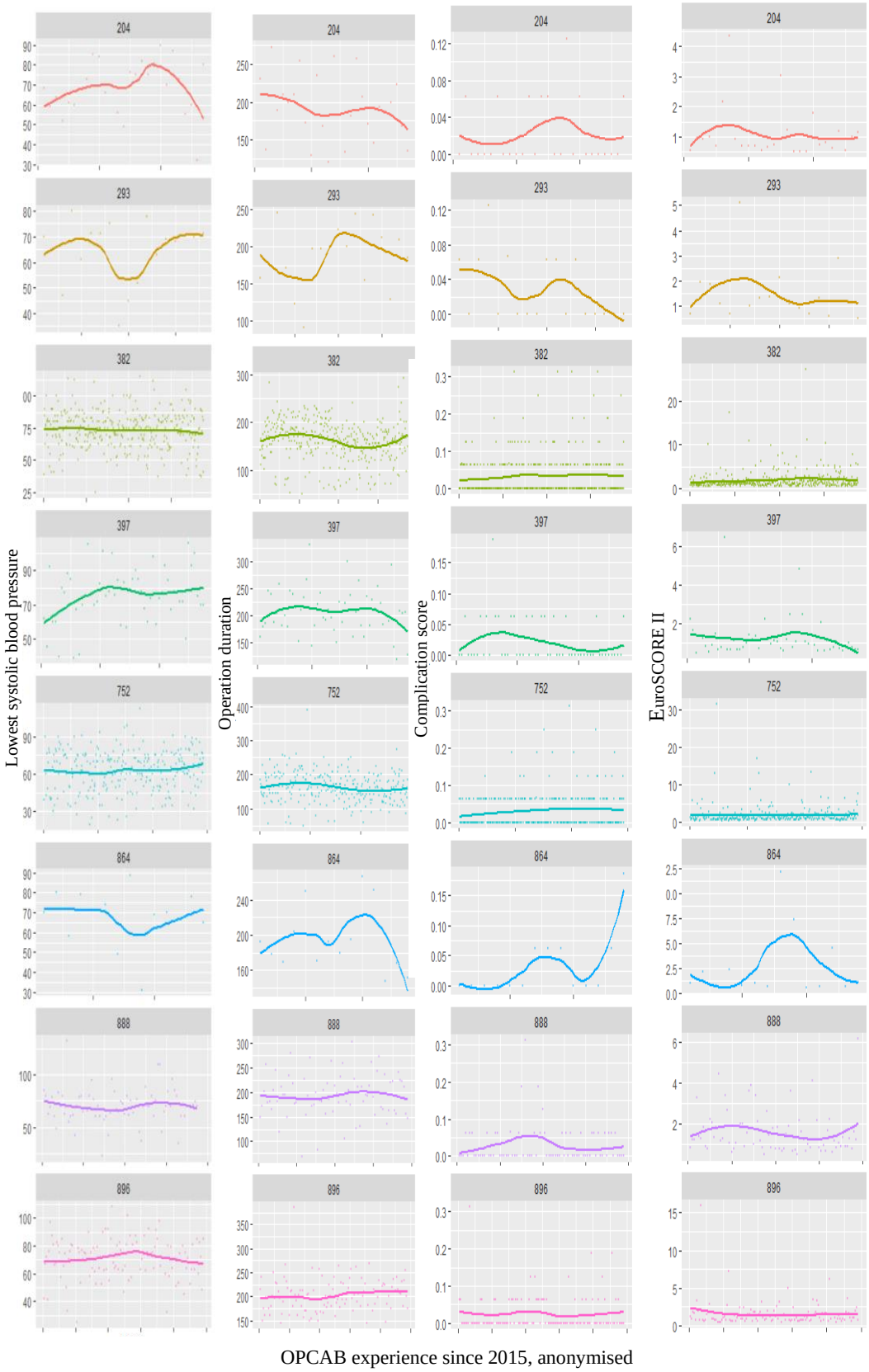
Learning curves of OPCAB

Basic visualizations of OPCAB learning curves

To get an impression if learning curves were present, the development of the selected outcomes was depicted over time for each surgeon. Figure 4 shows for eleven surgeons the development of the LSBP, operation duration, complication score; and the EuroSCORE II for reference. Five surgeons were excluded because they performed less than ten OPCABs in the given timeframe. The EuroSCORE II was added because it describes important case mix factors which supposedly explain most of the outcomes of CABG (O. Papachristofi et al., 2017). If learning occurs, a rising (LSBP) or falling (operation duration, complication score) trend would be expected, possibly influenced by the case mix (EuroSCORE II).

Figure 4

Graphs for each surgeon with OPCAB experience since 2015 on the x-axis, from left to right: lowest systolic blood pressure, operation duration, complication score, and EuroSCORE II on the y-axis. The rows/colours represent individual surgeons. Each case is represented by a point.



Generally, learning curves are monotonous, although there can be setbacks. Most curves in Figure 4, however, have at least once a change in slope. If the slope changes from upwards to downwards, or the other way, performance development is changing from improving to worsening or the other way round. Surgeon 204, for example, has an initial increase in patient risk with a simultaneous increase in LSBP and decrease of operation duration and complication score. This period of clear improvement is followed by first an increase in complications, then a decrease in patient risk, possibly to mitigate the performance dip, a short high in operation duration and a decrease of LSBP. It should be noted that surgeon 204 performed less than 50 OPCABs and therefore these fluctuations are not necessarily reason for concern. Similar trends can be seen for surgeons 293 and 864, who also have performed fewer OPCABs.

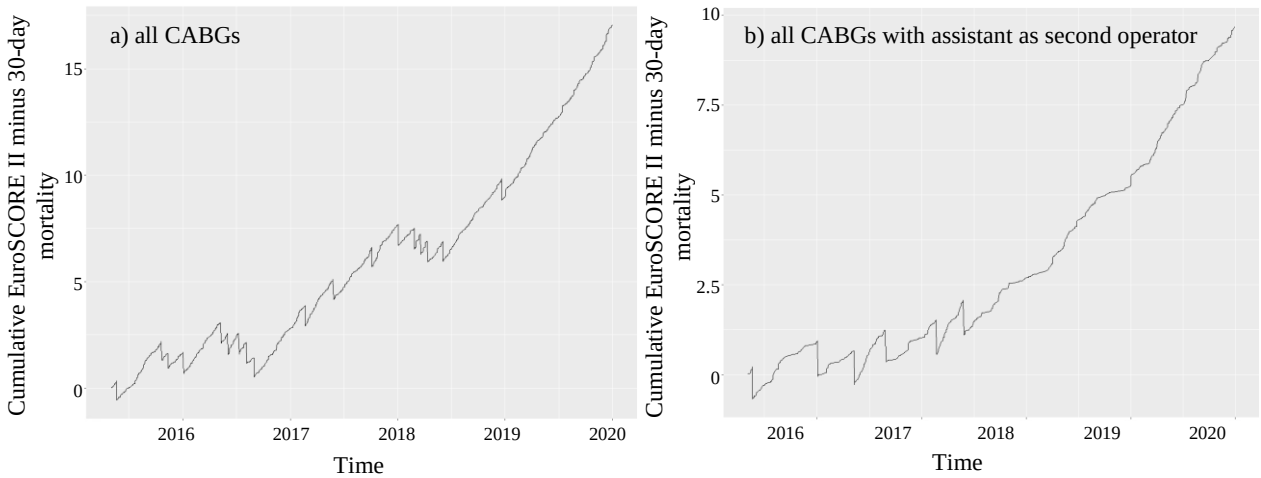
Surgeons with more cases have less fluctuations and a trend can be seen better. For example surgeon 382 had a period of increasing operation duration followed by a period of decrease and another period of increase. LSBP was rather stable throughout this period and the EuroSCORE II shows a slight increase. The complication rate also seems to have increased slightly and then stabilised. None of the curves display a monotonous learning curve.

CUSUM curves

Figure 5 shows the hospital wide CUSUM curves based on 30-day mortality and the EuroSCORE II. Panel a shows all CABGs during the period, while panel b shows only fully autonomous surgeons, meaning that the part of the second surgeon was fulfilled by a surgical assistant. With this selection, the procedures are limited to non-teaching procedures, where the first surgeon performed all main tasks. The EuroSCORE II has been found to overestimate 30-day mortality (Borracci et al., 2014), thus an upwards trend would be expected. The steepness

Figure 5

Hospital wide CUSUM curves, every step is calculated by the EuroSCORE II (risk) minus 30-day mortality; left panel shows all procedures, right panel shows only procedures with surgical assistant as second operator

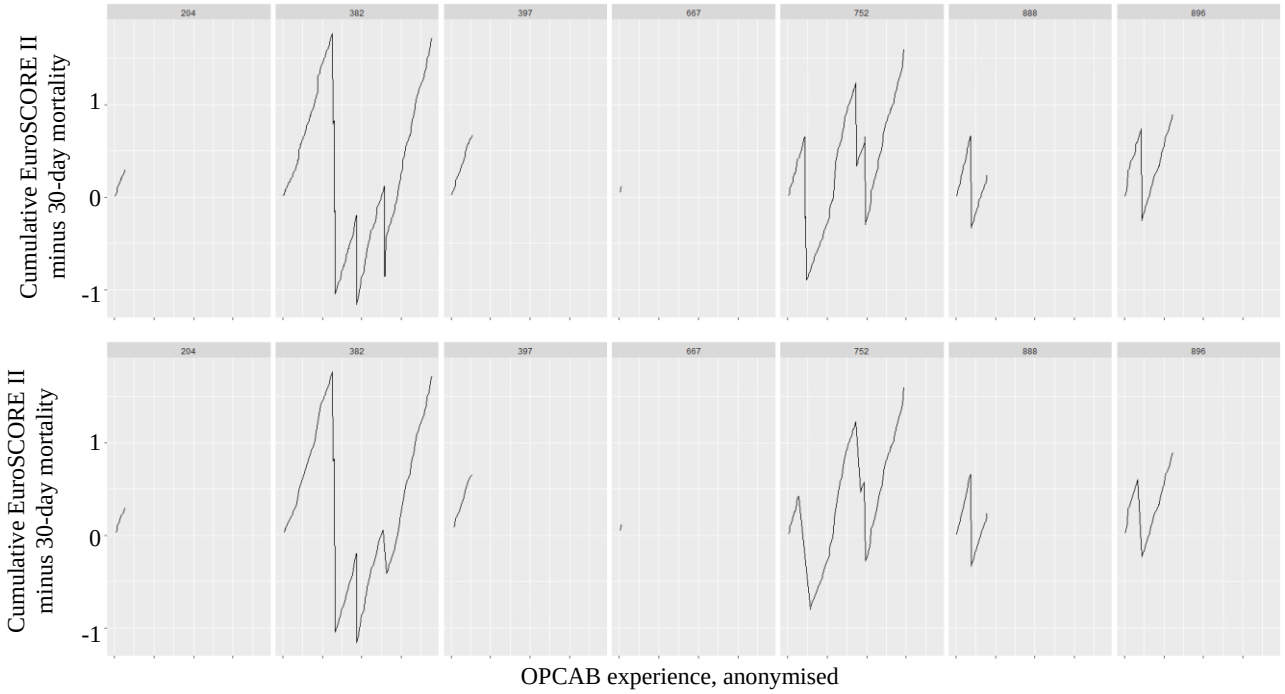


of the upwards trend depends on the calculated risk, the steeper upwards, the higher the risk of the patient. The steepness of the slope in general (including deaths) indicates the overall performance, where a steeper slope indicates higher performance. In both panels, the slope increases over time, indicating hospital wide improvements in 30-day mortality. No patients died within 30 days of their surgery since January 2019 and June 2017 for all CABGs and autonomous CABGs respectively.

Figure 6 displays the individual CUSUM curves for all surgeons performing at least one autonomous OPCAB. Excluded surgeons had less than 50 OPCABs total and no deaths within 30 days. The curves in figure 6 are based on each surgeons individual experience in OPCAB since 2015. The differences between teaching and autonomous surgeries (upper and lower panel respectively) is neglectable in individual surgeons. All surgeons show an upwards trend in general. Individual upwards trends are not as pronounced as the hospital-wide trend because the deaths occur only with surgeons who performed many surgeries and have to counterweight the deaths with successful surgeries on their own. Surgeons 382, 752, 888 and 896 had additional successful (no death within 30 days) cases in the role of second surgeon. Both surgeon 382 and 752 had a total number of 5 deaths, including a sequence of at least two deaths within few cases. However, the fact that deaths occur within a short period can be coincidence and does not necessarily reflect on the surgeon performance.

Figure 6

CUSUM curves per surgeon, calculated as cumulative difference between EuroSCORE II and 30-day mortality. Upper panel shows all OPCAB procedures, lower panel shows autonomous OPCAB procedures; Note: x-axis displays experience, not date. Values of the x-axis are removed to protect the surgeons' privacy. Surgeons that did not perform autonomously and with another surgeon were excluded from this figure.



Calculation of exponential learning curves

It was expected that surgeons would learn to perform OPCAB according to exponential learning curves. To fit an exponential learning curve, a monotonous increase or decrease in values is required. Figure 6 shows that none of the surgeons fulfils this basic requirement, let alone having a curve that follows an exponential shape. Therefore, it was impossible to calculate exponential learning curves.

Discussion

Outcomes of OPCAB

The first research question was about the suitability of outcome measures of OPCAB. Ten outcome variables have been investigated. MACCE and mortality with various follow-up periods (30/60/120 days, 1 year) are dichotomous rare events, which makes them less suitable for statistical analysis. To use these values in a training evaluation, a long series of training is needed for a reliable analysis. This renders these variables less useful for timely intervention, adaptation or evaluation (Olympia Papachristofi, Jenkins, & Sharples, 2016; Ramsay et al., 2001). Length of stay is a commonly used outcome of OPCAB (Mishra et al., 2005; Shinjo & Fushimi, 2015; Toumpoulis, Anagnostopoulos, Swistel, & Derose, 2005) but has been linked to hospital policies and financial considerations (Almashrafi et al., 2016). Thus, length of stay could be a useful outcome measure in single-centre studies but not for larger comparison. It should be further investigated how well length of stay can be predicted with commonly available information about the patient, surgeon and procedure.

The unweighted complication score, which was created with the intention of having a distribution similarly useful for statistical analyses as operation duration and LSBP, seemed to be unpredictable by all 50 available variables. Additionally, the complication score has been entered into the final models of both LSBP and operation duration, but the GMM still had the best predictive accuracy. Thus, with the available patient, surgeon and case characteristics, 0% of this score could be predicted. This is a surprising result, as one could expect that any of these predictors should be able to predict the occurrence of complications to some extent. A possible explanation is that the various complications have different causes and can thus not be combined. Weighting in severity might also help, so that the score represents the effect the intervention had on the wellbeing of the patient. The textbook outcome was created to represent freedom of the most severe complications, while also being a score that has a range of possible values and variation, making it more useful for statistical analyses (Hasper & Gourie, n.d.). However, the distribution of the score seemed to have two peaks, which might explain that neither of the EuroSCOREs had any predictive value. In future research, the score could be adapted to have a unimodal distribution while remaining valid for the patient. Alternatively, polynomial regression could be applied for the score.

Operation duration seems a reasonable choice to measure the efficiency of the surgeon. Duration of the operation is easily recorded, has a suitable distribution for statistical analysis (Ramsay et al., 2001) but is not often used as an outcome in itself. The duration of the operation

is likely of little relevance to the patient compared to complications or mortality. For the hospital, on the other hand, operation duration is a cost factor since staff and facilities are not available for other patients. It has been found that ONCAB has longer operation durations than OPCAB (Ji et al., 2014; Shroyer et al., 2009), but within OPCAB the variance in duration has not yet been explored. The available predictors were able to explain only about 13% of the variance in operation duration, which suggests that operation is largely dependent on factors not investigated in this project. In further research, it could be investigated which factors do have influence on the duration of the operation. The results of such an investigation might help hospitals safe costs and resources, which are especially scarce now during a pandemic.

Hypotension was measured here as lowest systolic blood pressure. It was chosen as an indication for the accuracy of the surgeon because the surgeon has to manipulate the heart to make anastomoses and this manipulation could disturb haemodynamics (Chassot et al., 2004). However, the surgeon is not alone responsible for haemodynamic changes but has to collaborate closely with the anaesthetist to keep the patient stable (Chassot et al., 2004). Keeping haemodynamic stability is considered a factor that makes OPCAB more technically demanding than ONCAB (Kirmani, Guo, Ahmadyur, & Bittar, 2019), therefore making it an attractive surgeon performance measure. Hypotension could also indirectly be considered a patient outcome since it is a common cause of intra-operative conversion (Jadhav et al., 2007; Shahzad G. Raja, 2016). Non-elective conversion has been found to have worse outcomes than either OPCAB or ONCAB (Hemli, Patel, & Subramanian, 2012; Jadhav et al., 2007; Landoni et al., 2007; Mukherjee et al., 2012; Novitzky et al., 2011). Thus, if risk factors for LSBP can be identified, a more informed decision towards ONCAB or OPCAB can be made. LSBP could largely (>70%) be explained by the available factors. Thus, LSBP is a useful outcome variable, because many predictors are now known and can be taken into account. LSBP can provide information on the performance of the surgical team. Predictability could even be increased by comparing LSBP to the systolic blood pressure before the surgery. Using this as a baseline, the change in blood pressure, which is likely also dependent on the blood pressure the patient has in a resting state before the surgery.

OPCAB is a highly complex procedure and multiple factors influence various outcomes. Variables not investigated in this paper might be considered as well, for example conversion has been treated as a procedural predictor, while it could also be seen as a negative outcome. Graft patency, which was not available in the current project, might also be an option for direct assessment of the surgeons performance (Becit et al., 2007; Hossein Almassi et al., 2015).

Therefore, it is important for a researcher or practitioner to make a well-informed decision based on the research question, availability of measurements and proposed statistical analysis. Patient outcomes should always be taken into account as they are the purpose of the procedure, but the researcher has to choose an operationalisation (Myles, 2014; Ramsay et al., 2001).

Predicting performance in OPCAB

The final models for both LSBP and operation duration have a large number of predictors. This highlights that OPCAB is a highly complex procedure and outcomes are influenced by various factors. For a comprehensive model possibly more factors are needed, especially for operation duration where only 13% of variance could be explained by the predictors. For both models, patient characteristics play the largest part in predicting outcomes, which confirms the findings by Papachristofi and colleagues (O. Papachristofi et al., 2017). Note, that patient random effects were considerable, indicating that the fixed effects are conditional on the patient at hand, and that possibly not all relevant patient characteristics were measured. Patient characteristics are only as good as their measurements. A trade-off has to be made in hospitals between the administrative burden, and accuracy and completeness of records. Therefore, only common and well-researched risk factors are measured and recorded. However, other less common or less researched risk-factors might have an independent influence on the course of the disease, but are not measured. An example of which is lipoprotein(a), which is a mostly genetically determined independent risk factor for cardio vascular diseases (Mellwig & Vogt, 2019).

While only the intercept was conditional on the first surgeon, most fixed effects are to some extent conditional on the anaesthetist (operation duration and LSBP) and second surgeon (operation duration only). This might indicate that the operation time depends more on the anaesthetist and second surgeon than on the first surgeon. This could indicate that depending on with whom the first surgeon operates, more or less time is being spent on explanations and therefore the total duration might vary, whereas a surgeon is likely faster with a surgical assistant because task allocation is pre-defined and likely little explanation has to be given. In future research, the experience of other team members, i.e. second surgeon and anaesthetist, should be taken into account when analysing team constellations (Elbardissi, Duclos, Rawn, Orgill, & Carty, 2013).

Experience of the surgeon had little influence on both operation duration and LSBP. Specialisation, however, had a considerable effect on both LSBP and operation duration. This

indicates that surgeons who specialise in OPCAB perform higher on both precision and accuracy. Thus, it is desired that OPCAB surgeons mostly perform CABGs off-pump to achieve and sustain a high skill level. Other predictors describing the procedure, like the amount of grafts or anastomoses, also relate to the patient. Depending on the severity of the disease more or less is needed to achieve complete revascularization. It was found that the number of venous (as compared to arterial) grafts and anastomoses had a negative effect on LSBP and a positive (increasing) effect on operation duration. While it has been stated before that arterial grafts have better long-term patency (Mariani, D'Alfonso, & Grandjean, 2004), perioperative outcomes improve as well.

Information criteria (ICs) an easily reproducible way of deciding which predictors to keep in the model, however some predictors had coefficients that were either unrealistically high or neglectably low. A different approach would be to investigate coefficients at every stage and make a decision based on both IC and coefficients. This approach would require considerably more time and careful definition on how to interpret coefficients but might result in more practical models.

Learning curves

The basic visualisations of learning curves showed that large numbers of cases are needed to see a trend and not reflect short-term fluctuations in outcomes. However, the surgeons with large numbers of cases might also have been established and experienced, meaning that there actually was less fluctuation in outcomes. Most surgeons had periods of both improvement and deterioration, which should be closely monitored as to whether these trends become long-term. Two surgeons showed a slight increase and stabilisation in complication scores, in both cases this happened simultaneously with slight increases in EuroSCORE II.

Cases in which the second surgeon was a surgical assistant had less deaths within 30 days than all cases together. This result might suggest that the quality of care is reduced when the surgeon teaches. However, this finding is contradicted by the fact that beginning surgeons who have low experience did not experience any deaths. Two possible explanations are that the difficulty of the chosen case could be higher if the teaching surgeon remains in control (i.e. first surgeon) or the teaching surgeon might take responsibility for mistakes made under his or her supervision, similar to a driving instructor who is responsible for the trainee. These propositions are speculative and further research should be conducted.

Based on the literature (e.g. Tsugawa et al., 2018), long learning curves were expected. A clear trend of improving performance for individual surgeons over time could not be replicated with the current data. The surgeons' performance development seemed to be multimodal in almost all cases (figure 6). In previous research, innovations in procedural technique have been a driving factor in performance improvements (H. K. Song et al., 2003). If innovation were the driving factor of performance change, it would be expected that the intervention date had an influence on outcomes. However, neither of the final GLMs included intervention date as a predictor. The multimodality could also be due to a change in case allocation for experienced surgeons, which was not investigated in the current analysis. With polynomial modelling, one could investigate which factors influence the change in slope.

The study period covered 5 years and at most 381 procedures by the surgeon with the highest throughput. In difficult procedures, lifelong learning might be applicable (Tsugawa et al., 2018) and thus, the timeframe of this study might have been too short to identify larger progress and only intermediate fluctuations in outcomes were detected for most surgeons. Further, experience in the CUSUM curves excluded previous experience, leaving the interpreter clueless as to where on a learning curve a surgeon is.

Strengths and Limitations

This research project was about exploring the performance and performance development of OPCAB surgeons at the MST hospital in Enschede. A large number of variables were included and therefore complex models could be built for hypotension and operation duration. Theses variables are mostly measured in a standardized way, as prescribed by the Dutch Heart Registry (NHR, 2018). The definitions are well-recorded, stable and therefore easily comparable to other heart centres in the Netherlands. When investigating the data very few quality issues were found, confirming the high quality of the available data. According to Ramsay (2001), the study was well set up for a thorough learning curve analysis: all cases performed by the surgeons in the study period were included, and previous experience was taken into account by including CABG experience since 2004.

However, the lack of clear differentiation between tasks that are performed by the first and second surgeon respectively might have led to a distorted picture of the learning curves. A problem with investigating between-surgeon differences is that it was not recorded which tasks exactly were performed by the first and second surgeon respectively. Thus, a surgery as first surgeon can be of varying autonomy and complexity depending on which tasks are taken over

by the second surgeon. Therefore, the tasks of the first and second surgeon should be recorded and controlled for. Forestier and colleagues conducted a research where all tasks were recorded exactly and could subsequently be analysed (Forestier, Riffaud, Petitjean, Henaux, & Jannin, 2018). A randomization of fixed delegation of tasks cannot be desired because the resident should learn and be gradually exposed to more tasks and responsibility.

Furthermore, the model building process was built entirely on the loo information criterion and during the building process no attention was paid to coefficients. While it is more difficult to have clear decision rules for coefficients, taking them into account might have led to more useful models without predictors with an almost non-existent effect size.

Suggestions for further research

To the knowledge of the author, LSBP or hypotension have not yet been investigated as outcomes of OPCAB but should be considered in future research, as it describes surgeon and anaesthetist performance as being a relevant outcome for the patient. Future research should test the model on hospital data from other hospitals to confirm its validity. Possibly further improvement could be achieved by comparing LSBP to a baseline of the patient. To fully incorporate the complexity of the situation, a Bayesian network could be created. Bayesian Networks have been used to create models that describe the complexity of liver disorder (Onisko, Druzdzel, & Wasyluk, 1999) and could similarly be used to describe the complexity of OPCAB or possibly cardio-vascular disease predictors, risk-factors and outcomes. The resulting network can then be used for aid in decision making and training.

Since learning curves could not be found in the current outcome variables, it is a possibility that experienced surgeons chose well which case a trainee is allowed to operate on and which tasks the trainee is allowed to perform (H. K. Song et al., 2003). Thus, future research should investigate what cases are chosen at which point of experience. Additional to that, one could explore task distribution (Forestier et al., 2018), which might interact with case allocation. A patient who needs a distal graft can have this performed by both experienced surgeon or trainee, depending on the skills of the trainee. Therefore, these variables should be explored together.

Recommendations

Based on the results, recommendations can be made for OPCAB training and evaluation. All evaluations of surgeons should be made in a team context because a surgeon is not solely responsible for all outcomes. Hypotension can be used as an indicator of the accuracy

of a surgeon, however it should be viewed in context of the surgical team and patient. Presurgical hypotension can further be useful in the decision on whether to use the heart-lung machine, as hypotension is a risk factor for conversion and the negative consequences of conversions should be avoided. The duration of the operation should be used carefully as a surgical outcome, since very little of its variance can actually be explained by common factors. It is advised to ensure up-to-date developments of the OPCAB procedure are incorporated into daily practice. At the MST, aortic manipulation is avoided, which might prevent complications (J. D. Puskas et al., 2016). Similarly, venous grafts have been shown to have worse outcomes than arterial grafts, which could be replicated in terms of intraoperative hypotension. Furthermore, the use venous grafts significantly increased operation duration, thus using arterial grafts can safe hospital resources.

The highest priority for OPCAB surgeon training is patient safety. If possible, OPCAB training should be done on simulators to guarantee patient safety and give trainees the opportunity to make mistakes in a safe environment and learn from them (Heskin, Simms, Holland, Traynor, & Galvin, 2019). OPCAB simulators have been created, but to date are lacking in validity and feasibility for many repetitions (de Vries, 2018). Before a surgeon decides to learn OPCAB, s/he should be aware that high specialisation in OPCAB leads to better results. It is thus desired that a surgeon who performs OPCAB does so for most patients to achieve and sustain a high skill level. A lot of experience also decreases operation duration, which in turn decreases hospital costs. A balance should be found between learning with various teams and thus learning to work with different surgical colleagues on the one hand and improving collaboration with one specific team.

Patient characteristics have a large influence on outcomes through fixed and random factors, thus a training/simulator should be as varied as possible. The trainee should learn to effectively deal with as many different aspects and scenarios of OPCAB as possible. For case allocation, it is not only important who first surgeon is, but careful attention should be paid to the combination of first, and second surgeon and anaesthetist. Measures should be taken to ensure that team collaboration works well, possibly by introducing clear communication rules (Bougioukakis et al., 2014). It should be taken into account that the team constellation has more influence on operation duration than the first surgeon.

Abbreviations, medical vocabulary, translation of Dutch variable names

Table 7

(Medical) Abbreviations and vocabulary

Medical term	Explanation
Anastomosis	"a surgical technique used to make a new connection between two body structures that carry fluid" ("Surgical anastomosis," 2019)
Angina pectoris	" chest pain or pressure, usually due to not enough blood flow to the heart muscle" ("Angina," 2013)
Aorta	Main artery directly ascending out of the left ventricle of the heart and providing the whole body with oxygenated blood ("Aorta," 2020)
Atrium	'entry halls'/chambers of the heart, filled with blood during diastole and pump the blood to the ventricles during systole ("Atrium (heart)," 2020)
Atrial fibrillation	"Abnormal heart rhythm […] with rapid and irregular [contracting atria]" ("Atrial fibrillation," 2020)
CABG	Coronary Artery Bypass Grafting
Cardiopulmonary bypass (CPB)	= ECC, use of heart-lung machine (thus bypassing the heart and lungs)
CCS class	Class in Canadian Cardiovascular Classification System
Coagulation	"[Also] known as clotting, is the process by which blood changes from a liquid to a gel, forming a blood clot" ("Coagulation," 2020)
Comorbidity	People suffering from one disease who have one or more other conditions have comorbidities ("Comorbidity," 2020)
CVA	Cerebrovascular accident, stroke
Distal	Located far from the point of reference, for the heart: on the side of the back (Gilroy, MacPherson, & Ross, 2008)
EuroSCORE	European System for Cardiac Operative Risk Evaluation, the first score was published with an additive formula only (Nashef et al., 1999)
EuroSCORE, logistic	EuroSCORE I calculated with the original logistic regression formula instead of the additive formula (Roques, Michel, Goldstone, & Nashef, 2003)
EuroSCORE II	Updated second version of the EuroSCORE (the logistic EuroSCORE is not counted since it is based on the same formula) (Nashef et al., 2012)
Extracorporal circulation (ECC)	= CPB, use of heart-lung machine
Graft	A graft in CABG is a blood vessel taken from elsewhere in the body and used to create a bypass of a coronary artery (Society for Cardiothoracic Surgery (SCTS), n.d.)

Hemodynamics	Dynamics of blood flow
Inflammation	"[Protective] response involving immune cells, blood vessels, and molecular mediators […] to eliminate the initial cause of cell injury […] and initiate tissue repair" ("Inflammation," 2021)
ICU	Intensive care unit
Intraoperative	"The intraoperative care period begins with the transfer of the patient to the operating room bed and ends with his admission to the [ICU]" ("Intraoperative Care," n.d.)
Ischemia	"[Restriction] in blood supply to tissues, causing a shortage of oxygen that is needed for cellular metabolism (to keep tissue alive)" ("Ischemia," 2021).
LIMA	left internal mammary artery (artery that is vertical through breast)
MIDCAB	minimally invasive direct coronary artery bypass (type of OPCAB)
NYHA-class	New York Heart Association Functional Classification for heart failure; the more symptoms the higher the class
ONCAB	On-Pump Coronary Artery Bypass
OPCAB	Off-Pump Coronary Artery Bypass, CABG without use of the heart-lung machine
Pancreatitis	inflammation of the pancreas
PCI	percutane coronaire interventie; treatment of narrowed coronary arteries using catheters
Perfusion	passage of fluid through the circulatory system ("Perfusion," 2020)
Pericardium	container of the heart, like a sac where there is little/no friction when the heart moves (Marieb & Hoehn, 2019)
Perioperative	"time period of a patient's surgical procedure. It commonly includes ward admission, [anaesthesia], surgery, and recovery. Perioperative may refer to the three phases of surgery: preoperative, intraoperative, and postoperative, though it is a term most often used for the first and third of these only" ("Perioperative," 2021)
Pneumonia	an inflammatory condition of the lung affecting primarily the small air sacs known as alveoli ("Pneumonia," 2020)
Recent myocardinfarction	Heart attack, part of the heart tissue dies off through lack of oxygen supply ("Myocardial infarction," 2021)
Resident surgeon	Surgeon in training
Revascularization	"revascularization is the restoration of perfusion to a body part or organ that has suffered ischemia" ("Revascularization," 2021)
Savenous vein	"a large, subcutaneous, superficial vein of the leg. It is the longest vein in the body, running along the length of the

	lower limb, returning blood from the foot, leg and thigh" ("Great Saphenous Vein," 2020)
Shunt (for anastomosis)	A shunt is a small pipe-like thing that can be inserted into the blood vessel that needs an anastomosis while the stitches are being made. It lets the blood flow continue while the surgeon operates without bleeding; a shunt can also refer to a moving hole or passage allowing fluid to flow from one part of the body to another, but this meaning of the word is not used in this thesis
Sputum	the coughed-up material (phlegm) from the lower airways ("Sputum," 2020)
Stable angina pectoris	symptoms when heart has to work hard, decrease when resting ("Angina," 2020)
Stay sutures	"temporary surgical sutures which are placed during operation to hold or manipulate the operating area" ("Stay Sutures," 2019)
Stent	"a metal or plastic tube inserted into the lumen of an anatomic vessel or duct to keep the passageway open" ("Stent," 2021)
Sternotomy	"surgical procedure in which a vertical inline incision is made along the sternum, after which the sternum itself is divided, or "cracked"" ("Median Sternotomy," 2020)
TIA	transient ischemic attack; temporary closing of a blood vessel in the brain caused by a blood clot that dissolves (Hartstichting, n.d.)
Unstable angina pectoris	symptoms are unpredictable and more intense as compared to stable angina pectoris ("Angina," 2020)
Ventricle septum rupture	Defect at intraventricular septum by rupture after myocardiac infarction (NHR, 2018)

Table 8

(Dutch) Variable names and translations

(Dutch) Variable name	**Translation, measurement unit**
XXXpat	Patient number, pseudonymized number
XXXeerste operateur	First surgeon, pseudonymized number
XXXtweede operateur	Second surgeon, pseudonymized number
XXXanesthesist	Anaesthetist, pseudonymized number
Interv_datum	Intervention date
Accept_datum	Date of acceptance for surgery
XXXopnameduur	Length of stay (nights between surgery and discharge)
Operatieduur	Operation duration in minutes starting at incision
Start operatie	Time of incision

Eind operatie	Time of closure of the thorax
euroI	Additive EuroSCORE I
Eurolog	Logistic EuroSCORE I
euroII	EuroSCORE II
Leeftijd	Age in years
Geslacht	Patient sex (m/f)
Chronische longziekte	chronic lung disease, dichotomous
Art_vaatpathologie	Extracardiac arteriopathy, dichotomous
Neuro_disfunctie	Neurological disfunction, dichotomous
Cardiochir_eerder	Previous cardiac surgery, dichotomous
Kreatinine_gehalte	Creatinine level, µmol/l
Endocarditis	Endocarditis, dichotomous
Krit_preop_toestand	Critical preoperative condition, dichotomous
Instabiele_AP	Non-stable angina pectoris, dichotomous
LVEF	Left ventricle ejection fraction, percentage
Recent_MI	Recent myocardial infarct, dichotomous
PA_druk	Pressure in pulmonary artery, mmHg
Thorac_aortachir	Surgery on aorta, dichotomous
Postinfarct_VSR	Operation is due to a defect at the intraventricular septum caused by rupture due to a myocardial infarct, dichotomous
NYHA	New York Heart Association functional classification for heart failure (can be class I through IV)
CCS_IV	Canadian Cardiovascular Classification System class IV, dichotomous: class IV or lower
Diabetes	Diabetes mellitus; distinctions: no treatment, unknown treatment, diet, oral medication, insulin, other, unknown, no diabetes
Slechte_mobiliteit	Poor mobility, neurological or musculoskeletal dysfunction severely affecting mobility, dichotomous
Nierfalen	Kidney failure, dichotomous according to STS criteria
Dialyse	Dialysis, dichotomous
Interv_gewicht	Weight of intervention, dichotomous: isolated CABG or not
Lengte	Height of patient, cm
Gewicht	Weight of patient, kg
BMI	Body mass index
Preop_ris_roker	Smoker, dichotomous
Preop_ris_rooktnu	Current smoker, dichotomous
CVA_eerder	Previous cardio vascular accident, dichotomous
Multiv	Multiple diseased vessels, dichotomous: at least 70% stenosis in 2 or more native vessels at first intervention, or 1 or more native vessels for patients after recent PCI/CABG

AF	Atrium fibrillation, dichotomous
Coronairchir_overig	Additional cardiac surgery to improve blood flow to the myocardium without grafts, dichotomous
ECC	Extra-cardiac circulation/cardio pulmonary bypass/heart-lung machine, dichotomous
Art_graft	Use of arterial graft(s) as bypass, dichotomous
Art_anast	Number of distal arterial anastomoses excluding Y-grafts and T-grafts
Ven_graft	Use of venous graft(s) as bypass, dichotomous
Ven_anast	Number of distal venous anastomoses excluding Y-grafts and T-grafts

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Appendix A: Data management plan

4TU. CENTRE FOR RESEARCH DATA

Data Management Plan

Data Management Plan

Name of group/project	Learning curve of surgeons performing OPCAB in the MST
Name of researcher(s)/student(s)	Stephanie Olbrich
Description of your research	*Investigation of the learning curves of surgeons performing OPCAB. Data is used from one centre (Thoraxcentrum Twente) for the heart surgeons in the period 2004-2019.*
Funding body(ies)	N/A
Grant number	*N/A*
Partner organisations	Medisch Spectrum Twente (MST) University of Twente (UT)
Project duration	Start: ***2020-04-13*** End: ***2020-10-31***
Date DMP created	***2020-03-24***
Date last update	**2020-08-13**

Version	*1.10*
Name of researcher(s) with roles/responsibilities for data management	*Van der Velde, Frank (supervisor)* *Groenier, Marleen (second supervisor)* *Halfwerk, Frank (external supervisor)*

This plan is in accordance with the EU General Data Protection Regulation, the Netherlands Code of Conduct for Research Integrity, the VSNU (Vereniging van Samenwerkende Nederlandse Universiteiten) Code of Conduct, the UT BMS research data management policy. An overview of the data flow and access of different parts is presented in figure 8 at the end of this document.

Abbreviations

SO	Stephanie Olbrich
FH	Frank Halfwerk
MG	Marleen Groenier
FvdV	Frank van der Velde
OPCAB	Off-pump coronary artery bypass
MST	Medisch spectrum Twente
TCT	Thoraxcentre Twente
UT	University of Twente
BMS	Faculty of behavioural, management and social sciences of the University of Twente
BMSlab	Service providing facilities for research at the BMS faculty

1. Raw Data Collection

- Reason for collecting data: The results of this project will be input for a training in OPCAB, which ensures safety of patients. This is of general interest to the whole population, because anyone might need this surgery themselves as they grow older.
- Collection: Electronic Patient and Employee Databases of MST
- Data Type: Existing data, observational health and occupation related data derived or compiled from databases (special category of personal data)

- File formats: .xls or .csv
- Reproducibility: Hospitals are required to store their data on employees, patients and procedures, therefore other hospitals should be able to use my analysis on their databases with minimal adjustments.
- Owner of data: The data is owned by the MST, the UT is allowed to use the data for the current research project; SO is owner of the analyses and results
- Estimated size of data: <1GB (8000 cases with 70 variables, 16000 cases with 4 variables)
- Pseudonymization:
    - Before data is obtained: only variables essential to the project are being included (i.e. name, patient number etc. are removed)
    - Pseudonymization: surgeon and patient numbers will be coded by the data manager of the TCT before transferring the data. The table for de-coding will remain with the data manager. The data will be password protected, thus for identifying individuals, both password and de-coding table are needed. After completion of the project, the password for the data will be handed over to a surgeon member of the board of the TCT. Thus, to identify individuals the surgeon with the password and the data manager are both needed.
    - Before (results of) analyses are published/shown to anyone besides FvdV and MG: Graphs, tables and other visualizations are anonymized, so that no single surgeon or patient can be identified even by employees of the MST

Anonymization: The research question does not allow for complete anonymization, therefore pseudonymization is used. The variables needed to answer the research question could be traced back to individuals if additional information were available. With, for example the combination of disease details and date of operation, individuals might be identified. However, both disease information and dates are essential to the project. Disease details can have a significant impact on various outcomes, but are not under the control of the surgeon. Since the portion of the outcomes that is controlled by the surgeon is main focus of the experiment, it is important to control for other influences. The date of surgery will be used to calculate the experience (all previous OPCABs/CABGs/operations) and specialization at the time (previous OPCABs divided by previous CABGs/all operations) and for the time span between procedures. To prevent identifying individuals, figures and tables used for publication or discussion of the project will be anonymized.

- Version control: The original files are stored separately from the processed ones. Documentation of all processing will be done with RMarkdown (output can be Word-document or PDF). Versions will be

named v1.1 with the first number changing for major adjustments and the second for minor adjustments. For each major adjustment, documents with previous minor adjustments will be deleted.

- Software to be used: R, Microsoft Office Excel, possibly SPSS

2. Data Storage and Back-up

- Handing over of data from MST to SO: ZIVVER/SURFfilesender (with encryption)
- Raw data storage and back-up: Raw data will be stored on a secure BMSlab server.A back-up will be stored as read-only in a SURFdrive folder shared between FvdV, MG and SO. The link for sharing the SURFdrive folder with SO will have an expiry date. Both the BMSlab server, and SURFdrive conform to ISO/IEC 27001 and NEN 7510 standards.
- Processed data storage and back-up: Processed data and analyses will be stored on a secure server of the BMSlab of the University of Twente.Back-ups are being made in a SURFdrive folder shared between FvdV, MG and SO. Both the BMSlab server, and SURFdrive conform to ISO/IEC 27001 and NEN 7510 standards. Anonymized results/analyses will be in a separate folder to avoid confusion, e.g. when discussing results with FH or other employees of the MST, because otherwise individual surgeons could be identified by the respective MST employee.
- Storage media: BMSlab server (UT), SURFdrive server (UT); both conform to ISO/IEC 27001 and NEN 7510 standards
- Backup frequency: weekly
- Backup locations: SURFdrive folder, encrypted
- Protection of computer system: Computer system and used programs are kept up to date, anti-virus software is being used. No public WIFI is being used. Computer is never left unlocked, has password protection and is only used by SO. If possible the computer is secured with a laptop lock.

3. Data Documentation

- Metadata: Most variables are described in the publicly accessible manual of the Netherlands Heart Registry (Nederlandse Hartstichting), all other variables will be explained in the documentation. A password-protected file with information for de-pseudonymizing the raw data (de-pseudonymization key) will be stored by the data manager of the thorax centre and not be shared with the researchers.
- Documentation during research and long-term storage: version numbers will be used for data/analysis files, changes between versions will be tracked in separate logbook. All steps of data processing and analysis will be documented in a Rscript.

- File naming convention: every document will receive a descriptive title (e.g. surgeonData), followed by an underscore and version number. Folders will specify type of documents, e.g. data or analysis.
- Data identifiers: none; might be added later

4. Data Access

- Copyright and IP: University of Twente owns the pseudonymized data. (Anonymized) analyses and outputs are intellectual property of SO, but can be re-used within the Thoraxcentrum Twente with permission of SO.
- Limitations on access of data: SO manages the database. FvdV and MG have access to the raw data and analyses. Results will be anonymized before being shared or discussed with FH or any other person.
- Access criteria for data: pseudonymized data can be accessed by SO, MG, FvdV. All anonymized output can also be accessed by FH. Access to the keys for de-pseudonymization will be under supervision by the TCT board. SO will not be able to access the original patient and surgeon codes.

5. Data Sharing and Reuse

- Data sharing method: On request the script of the analyses can be shared.
- Sharing requirements: raw data and non-anonymized results cannot be shared with the public in order to protect the subjects of the study. Metadata and documentation will be described in the thesis (the product of this project) and made public after 2 years.
- Audience for reuse: researchers and surgeons interested in topic and methods, other hospitals
- Publish information: (Results of the) analyses will be published as master thesis in the online open access depository of the UT (after a 2 year embargo), possibly research article
- Software requirements: R for analyses, PDF/word for reports

6. Data Preservation and Archiving

- Person responsible for archiving: data manager of Thoraxcentrum Twente
- Criteria for archiving and long-term access: transparency of research/research integrity
- Time span data preservation: 2 years (until publication of master thesis)

- File formats: data will be stored in .xls or .csv, analysis reports will be stored in .pdf
- Storage location: MST Thorax centre
- Access: FvdV and MG are allowed continued access to the data of the project after completion. They have no access to the key for de-pseudonymizing.

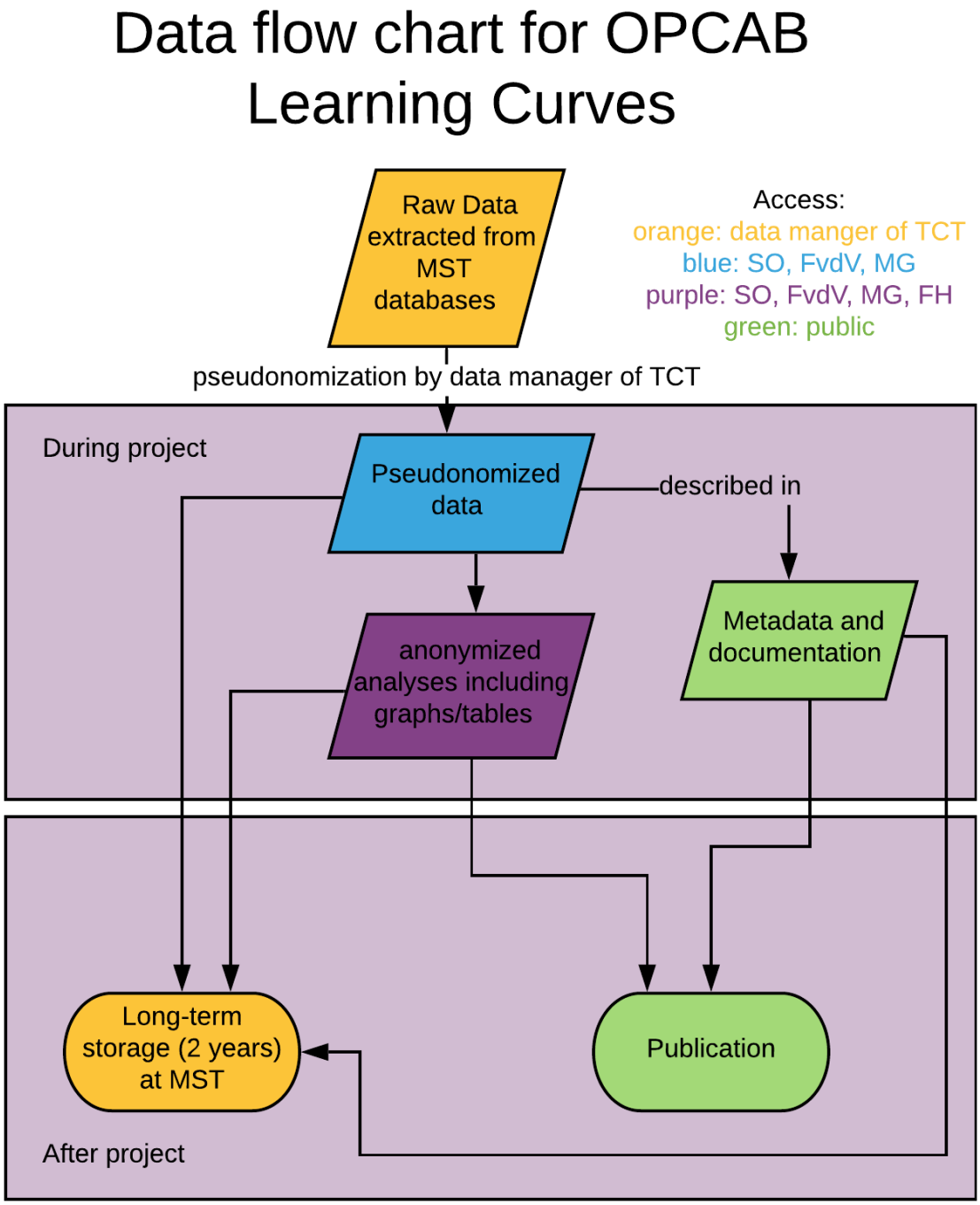


Figure 5 Data flow chart for during and after the project

Appendix B: Ethical approval

Ethical approval of the faculty ethical committee (BMS)

UNIVERSITY OF TWENTE.

FACULTY BMS

200114 REQUEST FOR ETHICAL REVIEW

Request nr: 200114
Researcher: Olbrich, S.L.
Supervisor: Schmettow, M.
Reviewer: Lubbe, R.H.J. van der
Status: Approved by commission
Version: 2

1. START

A. TITLE AND CONTEXT OF THE RESEARCH PROJECT

1. What is the title of the research project? (max. 100 characters)

Learning curves of OPCAB surgeons at the MST

2. In which context will you conduct this research?

Master's Thesis

3. Date of the application

08-05-2020

5. Is this research project closely connected to a research project previously assessed by the BMS Ethics Committee?

No/Unknown

B. CONTACT INFORMATION

6. Contact information for the lead researcher

6a. Initials:

S.L.

6b. Surname:

Olbrich

6c. Education/Department (if applicable):

M-BA

6d. Staff or Student number:

1572288

6e. Email address:

s.l.olbrich@student.utwente.nl

6f. Telephone number (during the research project):

Approval board of the hospital MST

Medisch Spectrum Twente

Postbus 50 000
7500 KA Enschede

Koningsplein 1
7512 KZ Enschede

www.mst.nl

Aan mevrouw S. Olbrich, Bsc.
Stagiaires pat bewon func.
Cardiothoracale Chirurgie
Medisch Spectrum Twente

Datum	Ons kenmerk	Pagina
22-09-2020	RvB/ljvdp/2081-20/73.0	1 van 2

Uw kenmerk
Leercurves van OPCAB-chirurgen

Contactpersoon

Onderwerp
Goedkeuring onderzoeksproject niet-WMO-plichtige studie

Geachte mevrouw Olbrich,

De Raad van Bestuur gaat akkoord met het starten van de studie *Leercurves van off-pump CABG van hartchirurgen in het MST*, bij ons bekend onder nummer K20-29.

De lokale adviescommissie uitvoerbaarheid heeft vastgesteld dat uw projectvoorstel niet-WMO-plichtig is en dat ook verder aan gestelde voorwaarden is voldaan.

Wij wensen u veel succes met de uitvoering van dit onderzoek en worden te zijner tijd graag geïnformeerd over de uitkomsten.

Met vriendelijke groet,
namens de Raad van Bestuur*,

Mw. C. Pinners,
Bedrijfskundig manager

I.a.a.:
RVE-management de heer H. Krijgsman
de heer drs. F. Halfwerk, Technisch Geneeskundige Cardio-Thoracale Chirurgie, Medisch Spectrum Twente
Adviescommissie lokale uitvoerbaarheid

*Bij mandaat van de Raad van Bestuur d.d. 31-10-2017

Confirmation for non-medical scientific research (nwmo verklaring)

Adviescommissie lokale uitvoerbaarheid MST

Secretariaat Wetenschapsbureau, Medical School Twente, Instituut voor Toegepast Wetenschappelijk Onderzoek, Postbus 50.000, 7500 KA Enschede Telefoon +31(0)53 487 30 11 Email: nietwmo@mst.nl
Website: https://www.mst.nl/over-mst/wetenschap-en-onderzoek/onderzoek-indienen-en-uitvoeren/niet-wmo-plichtig-onderzoek/ Mw. drs. M.A. Zhu-Chung, secretaris, telefoon: +31(0)53 487 20 46

Mevrouw S. Olbrich, Bsc.
Stagiaires pat bewon func
Cardiothoracale Chirurgie
Medisch Spectrum Twente

Enschede, 22-09-2020

Briefnummer: Adviescommissie/20059.olb

Titel: Leercurves van off-pump CABG van hartchirurgen in het MST
Korte titel: Leercurves van OPCAB-chirurgen
Kenmerk adviescommissie: K20-29

Geachte mevrouw Olbrich,

De Adviescommissie lokale uitvoerbaarheid van Medisch Spectrum Twente te Enschede, verklaart dat uw studie getiteld: <*Leercurves van off-pump CABG van hartchirurgen in het MST*>, volgens de Nederlandse wet niet voldoet aan de criteria, die vereisen dat de studie door een Medisch Ethische ToetsingsCommissie beoordeeld moet worden.

Deze criteria zijn als volgt:
1) De studie moet een Medisch Wetenschappelijke doelstelling hebben EN
2) Mensen worden handelingen of gedragingen opgelegd.

Het eerste is van toepassing, maar het tweede niet omdat uw studie een observationele studie zonder enige procedurele interventie is. Er worden voor dit onderzoek data uit bestaande registraties gebruikt. In strikte zin, volgens de WMO, is het niet nodig dat een METC een oordeel velt over dit studieprotocol. Het betreft een helder onderzoeksvoorstel, en ook de andere documenten zijn helder geformuleerd.

De volgende documenten zijn daarbij betrokken:

A1	Aanbiedingsbrief:	E-mail d.d. 14-07-2020 en aanbiedingsbrief d.d. augustus 2020 (versie 6 d.d. 14-09-2020);
A1	Aanmeldingsformulier	d.d. 09-07-2020;
C1	Het onderzoeksprotocol:	OPCABLC onderzoeksprotocol versie 6 d.d. 01-09-2020;
K6	Overige documenten:	Datamanagementplan d.d. Juli 2016.

De Adviescommissie lokale uitvoerbaarheid wijst u erop dat nog een akkoord van de Raad van Bestuur nodig is voordat met de uitvoering van het onderzoek kan worden gestart. Wij verwijzen u hiervoor naar de procedure niet WMO-plichtige studies, te vinden op onze website www.metstwente.nl.

Hoogachtend,
Namens de Adviescommissie lokale uitvoerbaarheid

Samenstelling adviescommissie:
Van der Valk, dhr. dr. P.D.L.P.M., arts-lid
Van der Palen, dhr. prof. dr. J.A.M., methodoloog
Zhu-Chung, mw. drs. M.A., secretaris

dr. P.D.L.P.M. van der Valk, voorzitter

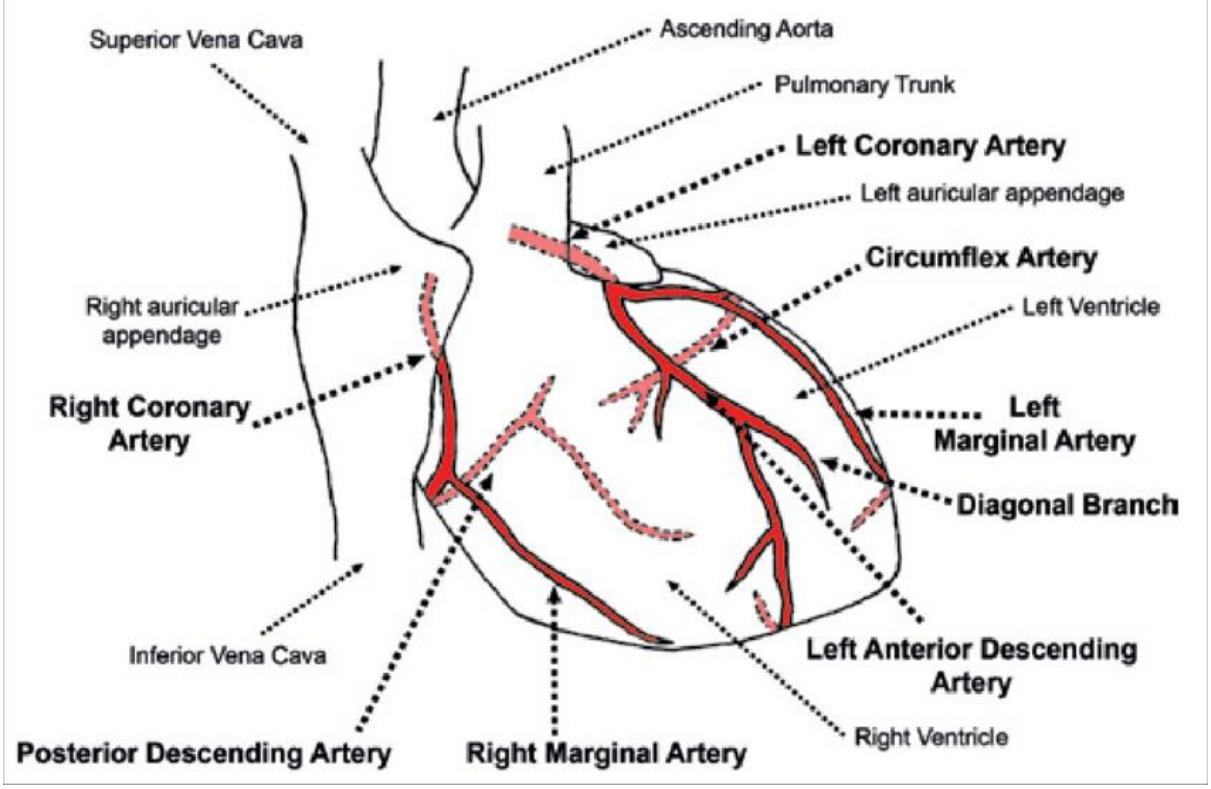
Supplementary material I: Medical background for non-medical readers

Anatomy of the heart and coronary artery disease (CAD)

The heart is about fist-size and pumps blood through the body. The blood provides tissue cells with oxygen and nutrients and transports waste away. The heart as a muscle demands a lot of blood for itself (1/20 of the body's supply), however, it cannot use the blood that is pumped through it because of its thick walls. Instead there are three main coronary arteries supplying the heart, which arise directly from the base of the aorta (Marieb & Hoehn, 2019). As can be seen in **Figure *6***, there are two main coronary arteries, called the right (RCA) and left coronary arteries (LCA). The LCA splits into the left anterior descending artery (LAD) and the left circumflex coronary artery (RCX). This is a schematic presentation, the exact placement and distribution of the coronary arteries can vary considerably between people (Saffitz, 2015).

Figure 6

Coronary Arteries (Beed, Khadaroo, Singh, & Brindley, 2015)

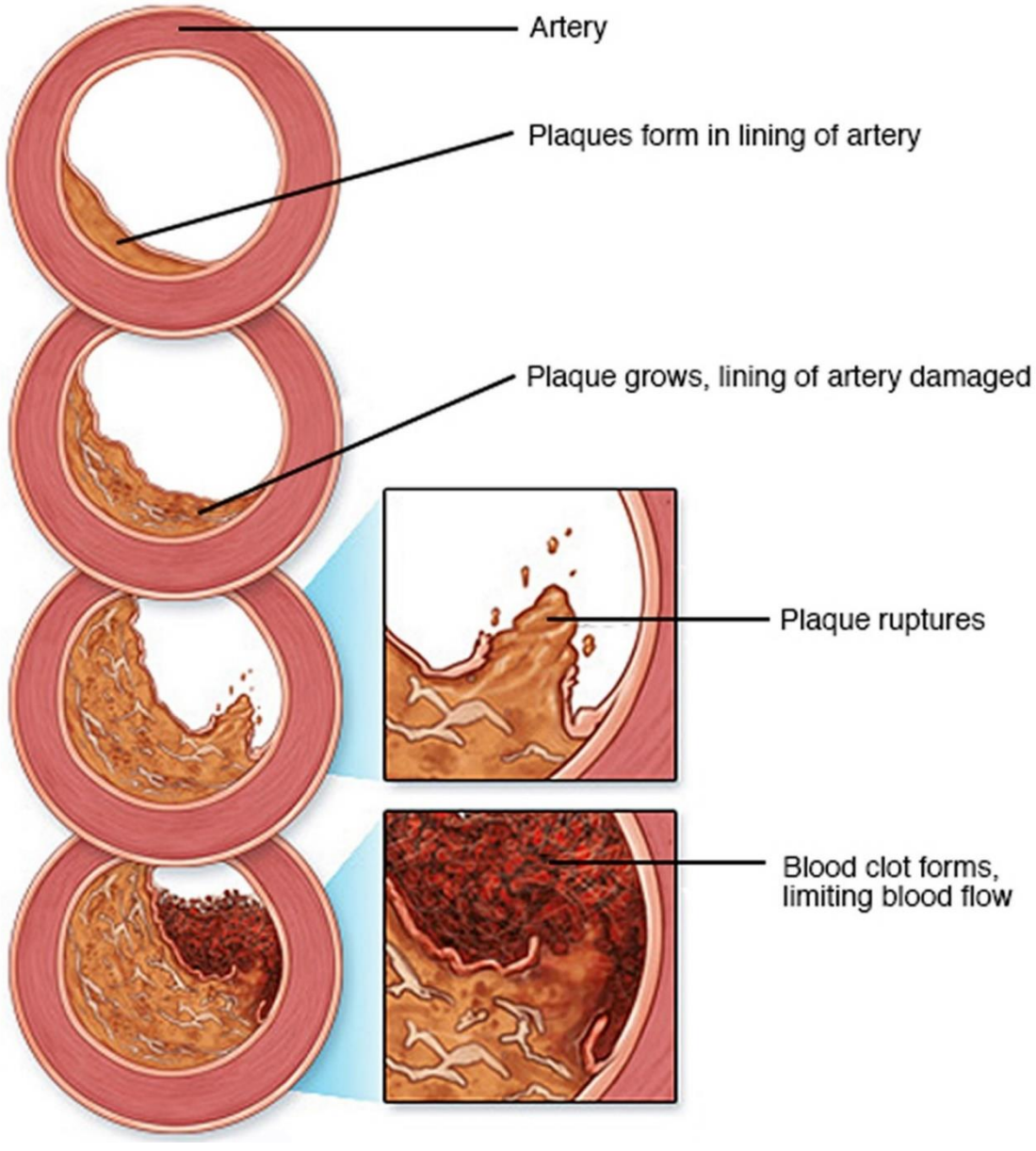


Over time, plaque can build up in these arteries and cause them to become narrower, also referred to as coronary artery disease (CAD, see Figure 10). The plaque decreases the effective diameter of the artery and thus obstructs the blood flow to the heart. There is a thin

layer separating the plaque from the so-called lumen (the volume of the blood vessel). The layer of plaque can rupture and blood can clot around the point of breach. The discharged material or blood clot can form an obstruction of the artery, so that very little or no blood can flow beyond that point. Multiple risk factors are well-known and can be put in two categories: fixed and potentially changeable. Fixed risk factors include age, sex, and family history. Potentially changeable risk factors include amongst others smoking, hypertension, diabetes, lack of exercise, fatty diets, overweight/obesity, personality, stress, and alcohol consumption (Bunce & Camm, 2012). Since CAD is a very common disease, it is well researched and treatments are available (Nederlandse Vereniging voor Cardiologie (NVVC), n.d.-b, n.d.-a).

Figure 7

Schematic display of possible course of coronary artery disease: plaque builds up in an artery and ruptures, a blood clot forms at the rupture and limits blood flow (taken from: https://healthjade.com/myocardial-ischemia/)



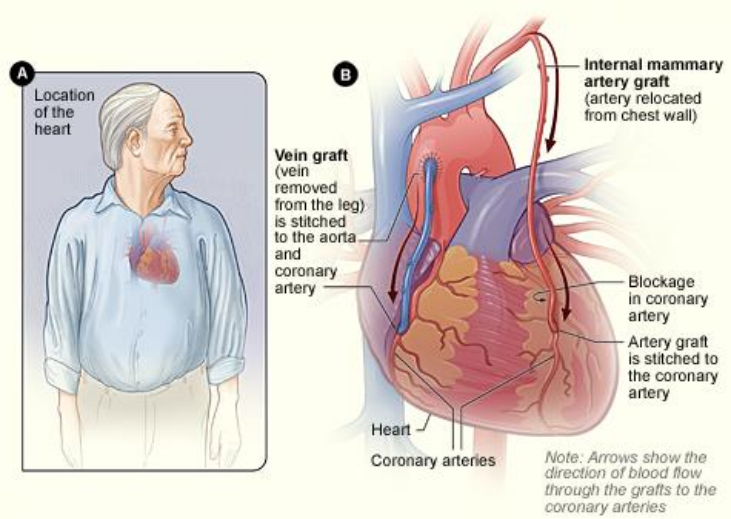
Treatments of CAD

The treatments for CAD can be ordered according to their invasiveness. Medical therapy relies entirely on medicinal help for the heart and can be combined with other, more invasive procedures. The least invasive surgical treatment is percutaneous coronary intervention (PCI). PCI is no open heart surgery and involves inserting a catheter into an artery, usually through an incision at the wrist. First, a catheter with a small balloon is used to open the artery (increase its diameter) at the narrowing. Then, a stent can be placed to keep the artery open. A stent is a small tube that stabilizes the blood vessel. Newer versions of stents can discharge drugs to prevent adverse bodily reactions to the stent (Nederlandse Vereniging voor Cardiologie (NVVC), n.d.-b). Although patients recover rather quickly from PCI, it has a high rate of reintervention, meaning that the benefits of PCI are not always for the long term (Kulik, 2017).

In cases when PCI is not suitable, coronary artery bypass surgery (CABG) is often used. CABG is an open heart operation, where a blood vessel from elsewhere in the body (usually chest, arm or leg) is used to bypass the occluded vessel(s). Bypass configurations are shown in Figure 11. Usually the breastbone will be sawed through, in order to access the heart, making CABG much more invasive than PCI, where the operation requires only a small incision in the skin. CABG has been used for more than 40 years and has become a very common, well-documented and researched procedure; risks of complications are low and the chance for at least 10 symptom-free years are 60% (Nederlandse Vereniging voor Cardiologie (NVVC), n.d.-a). For CABG there are two main ways to operate, namely with a heart-lung machine (on-pump, ONCAB) or without (off-pump, OPCAB), also called cardio-pulmonary bypass (CPB). If the heart-lung machine is used, it takes over the pumping of the blood through the body and therefore has to be connected to the heart with multiple tubes. Often, the heart is stopped chemically, so the surgeon can make anastomoses (connections between the bypassing and the bypassed vessel) on a non-moving target (Sellke et al., 2005). Without the heart-lung machine, the heart continues to pump blood through the body. The surgeon has to sew the grafts (bypasses) onto a moving target. Especially distal (on the back side of the heart) anastomoses are challenging because the heart has to be tilted without disturbing the blood flow (Sellke et al., 2005). Therefore, OPCAB is often considered to be more technically demanding and takes more time to learn (Elahi, Khan, & Matata, 2006).

Figure 8

Schematic heart with bypasses (taken from https://maryomedical.com/tag/coronary-circulation/)



ONCAB vs. OPCAB

Clinical trials and their shortcomings

The procedural and beneficial differences between ONCAB and OPCAB have been extensively researched and discussed in the literature, however clear conclusions are still lacking (Sellke et al., 2005). Clinical trials, the gold standard of comparing treatments, suffer from patient selection bias, surgical treatment bias and neglection of the learning process (Chassot et al., 2004). The learning curve is important, because ONCAB is a very old and common surgery, whereas OPCAB is often less prevalent and supposedly more difficult. Thus, surgeons included in studies might have lots of experience with ONCAB - performing on a high level, but very little experience with OPCAB – performing on a lower level (Shroyer et al., 2009). Furthermore, some studies or hospitals use clamping of the aorta when performing OPCAB , which leads to worse results than if the aorta is not manipulated (Jongman et al., 2014; Mishra et al., 2005). These differences in technique and experience make it more difficult to adequately compare the two methods (Shroyer et al., 2009).

ONCAB and completeness of revascularization

For ONCAB, the heart has to be connected to the heart-lung machine with multiple tubes. This means that blood circulation and oxygen provision are outside the body. Possible complications due to CPB are systemic inflammatory response, coagulation (blood-clotting) disorders, and multiple organ dysfunction (Chassot et al., 2004). When using CPB, the heart is usually stopped, so the surgeon can operate on a non-moving target. Because operating on a non-moving target is easier, ONCAB has been found to have complete revascularization (laying

all necessary/planned bypasses) more often than OPCAB (Kirmani et al., 2019), although this might be due to selection bias and not all studies could replicate this finding (Diegeler et al., 2019). With sufficient experience, the completeness of revascularization in OPCAB can be as high as in ONCAB (J. Puskas et al., 2005; Yadava & Taggart, 2020). In one trial, incomplete revascularization led to higher morbidity and mortality in both OPCAB and ONCAB and occurred about equally often (Diegeler et al., 2019). Therefore, incomplete revascularization might be "considered as the manifestation rather than the cause of a worse patient prognosis", meaning the patient's condition made complete revascularization harder to achieve (Diegeler et al., 2019).

OPCAB

OPCAB is considered the more difficult procedure for both surgeon and anaesthesiologist (Chassot et al., 2004). Yet, studies have shown that the length of stay in both ICU (intensive care unit) and the hospital in general, and the duration of ventilatory support are shorter after OPCAB, leading to lower short-term costs (Atluri et al., 2011; Chassot et al., 2004; J. D. Puskas et al., 2001). With off-pump techniques, clamping of the aorta may be completely avoided, which decreases risks of complications, like stroke (Chassot et al., 2004; Doenst et al., 2019). Especially elderly patients (Chassot et al., 2004) and those with left ventricular (LV) dysfunction (Chassot et al., 2004) or renal (kidney) impairment (Chassot et al., 2004; Ueki et al., 2018) can benefit from OPCAB. Other studies found OPCAB to benefit high-risk patients in general (Ji et al., 2014). The fact that benefits for low-risk patients have been less pronounced, might be due to the difficulty of finding significant differences in those already low numbers. However, OPCAB can only be a reasonable option for the majority of patients if it can provide complete revascularization (Anyanwu et al., 2002). Complete revascularization with OCPAB is related to the skill level of the surgeon (Farina et al., 2019; Shahzad G. Raja, 2016). Other benefits of OPCAB seem to be related to surgeon skill and technique as well (Smith, 2014). Studies with less experienced surgeons have found OPCAB to be result in inferior outcomes for patients (Shroyer et al., 2009).

Conversion

The surgeon has to be able to expose all sites of the heart for anastomoses (connections between blood vessels) and protect the heart from ischaemia (lack of blood supply). Tilting the heart results in haemodynamic (blood flow) changes and decrease in cardiac output (Chassot et al., 2004). In some cases, executing the whole operation without CPB is impossible, and a conversion to ONCAB has to take place. In the literature reported conversion rates vary

between 1.1% and 16.3%. Mortality for converted surgeries was 18% versus 2.7% in planned ONCABs in one study (Edgerton et al., 2003). Multiple studies observed worse outcomes after conversion (Anyanwu et al., 2002; Landoni et al., 2007; Mukherjee et al., 2011, 2012; Novitzky et al., 2011). Conversions usually become less often and better timed (earlier) with surgeon experience (Edgerton et al., 2003). Reasons for conversion are mostly hemodynamic instability (Edgerton et al., 2003; Hemli et al., 2012), anatomic, or electrical disturbance (Edgerton et al., 2003). Impaired LV function is an indicator for conversion, but from patient data, conversion cannot be well predicted (Hemli et al., 2012). A distinction can be made between elective, planned, urgent-emergent and reactive conversions, which are increasingly late in the process. The later in the process the conversion takes place, the higher are risks of complications (Edgerton et al., 2003; Hemli et al., 2012). Complications with increased likelihood after conversion are vascular complications, cardiac arrest, multi-system organ failure and coma for >24h (Edgerton et al., 2003). The complications during conversion are similar for all levels of surgeon experience (Hemli et al., 2012). With adequate preparations, a surgeon can shift from ONCAB only to mostly OPCAB with low conversion rates (Anyanwu et al., 2002).

Table 9

Comparison of OPCAB and ONCAB

OPCAB	ONCAB
Intra- and postoperative morbidity (Atluri et al., 2011; Bainbridge, Cheng, Martin, & Novick, 2007; Boyd et al., 1999; Chassot et al., 2004; J. D. Puskas et al., 2001; S.G. Raja & Benedetto, 2014; Wijeysundera et al., 2005)	Less intra- and postoperative morbidity (Arom et al., 2000)
Improved short-term (Wijeysundera et al., 2005) and long-term (Kirmani et al., 2019) mortality	Fewer reinterventions (Arom et al., 2000; Wijeysundera et al., 2005)
Shorter length of stay (Atluri et al., 2011; Bainbridge et al., 2007; Kirmani et al., 2019; Mishra et al., 2005; J. D. Puskas et al., 2001)	Generally lower difficulty (Arom et al., 2000; Elahi et al., 2006)
Lower hospital costs (Bainbridge et al., 2007; Boyd et al., 1999; Chassot et al., 2004; J. D. Puskas et al., 2001)	Easier achievement of haemodynamic stability (Chassot et al., 2004)
Improvements for high-risk patients (Arom et al., 2000; Chassot et al., 2004; Ji et al., 2014; Ueki et al., 2018)	Less explicit experience and expertise needed by surgeon and team (S.G. Raja & Benedetto, 2014; Sellke et al., 2005; Smith, 2014)

Equivalent or better graft-patency (Atluri et al., 2011; Boyd et al., 1999; Chassot et al., 2004; S.G. Raja & Benedetto, 2014; Shahzad G. Raja & Dreyfus, 2006)	Shorter duration of learning curve (Caputo et al., 2002; Farina et al., 2019; Mishra et al., 2005; S.G. Raja & Benedetto, 2014; Shahzad G. Raja, 2016; Shahzad G. Raja & Dreyfus, 2006; Yadava & Taggart, 2020)
Equivalent or better rate of completeness of revascularisation (Atluri et al., 2011; Diegeler et al., 2019; Mishra et al., 2005; J. Puskas et al., 2005; S.G. Raja & Benedetto, 2014; Shahzad G. Raja & Dreyfus, 2006; Yadava & Taggart, 2020)	More complete revascularisation (Chikwe et al., 2018; Gaudino et al., 2018; Hlavička et al., 2018; Kirmani et al., 2019)
Risk of conversion (Anyanwu et al., 2002; Chassot et al., 2004; Edgerton et al., 2003; Hemli et al., 2012; Landoni et al., 2007)	

Reconciliation and conclusion of critique

From the previous can be seen that OPCAB has the potential to be beneficial for patients, but the technique has to be good and surgeons should be either well-experienced or under supervision of a well-experienced surgeon. Also, since conversions have been shown to lead to worse patient outcomes, the rate should be kept low. An official statement of the American Heart Association on the OPCAB/ONCAB discussion said that both procedures have excellent outcomes, but the success of an individual case depends on other factors as well (e.g. surgeon skill, quality of institution). It has also been mentioned, that the benefits of OPCAB relate more to the outcomes for the patients, whereas the benefits of ONCAB are more related to the difficulty of the procedure (Sellke et al., 2005).

Focus shift to individual case

Besides the discussion about which method is more beneficial in general, some surgeons shifted their focus more to the individual patient, since the highest benefit for each patient is the ultimate goal (Sabik, 2015; Yadava & Taggart, 2020). High-risk patients benefit more from OPCAB, and OPCAB is the more difficult procedure, thus, the logical consequence would be that the surgeon should be able to perform well on all patients. If only high-risk patients were operated on off-pump, only the difficult patients would receive the difficult treatment, which would result in worse outcomes and patients could not benefit from off-pump (Yadava & Taggart, 2020). There are, however, patients benefitting from CPB for example due to a dilated heart, and those should be operated on with ONCAB (Diegeler et al., 2019; Yadava & Taggart, 2020). Thus, the surgeon should consider each patient as a new case and with all information

available about the disease and risk factors, a well-founded decision can be made towards OPCAB or ONCAB. One could conclude that the optimal case would be that most patients are operated on off-pump with investment in surgeon and team skill, while CPB is used when it benefits the specific patient. While a lot of authors focus on comparing ONCAB and OPCAB for certain patient groups, this report concentrates on the improvements of OPCAB.

Need for OPCAB training

The percentage of CABGs that has been performed off-pump has been decreasing in recent years (Mack & Taggart, 2019). Due to the high skill demand of OPCAB, there has been critique on making it a common procedure. Experts have asked for specialized teams and centres for OPCAB, as it is not a suitable procedure for every heart surgeon (Yanagawa & Puskas, 2015). Another expert declared that a procedure that can only be performed by "super-experts is not a good solution to a health problem the size of coronary disease" (Smith, 2015). There are no legal and often also no organisational specialization requirements for a cardiac surgeon to perform conventional CABG (ONCAB), in fact the specialization between ONCAB surgeon varied in a US sample between 0.1% and 43% (Sahni, Dalton, Cutler, Birkmeyer, & Chandra, 2016). Specialization refers to how many surgeries of one type (here CABG) a surgeon performs in relation to other types of surgeries. In 2003, Jenkins and colleagues called for structured trainings and gave reports of how they conducted training, concluding that training could be done safely if under supervision of an experienced senior surgeon (Jenkins et al., 2003). Heart surgeons can be trained to become experts in OPCAB and distribute across various hospitals, and train the other surgeons there. Then being an OPCAB expert becomes the norm and patients can benefit from being treated by an experienced or adequately supervised surgeon. Additionally, training a surgeon in OPCAB can have benefits regarding all heart operations. OPCAB requires more attention to the safe manipulation of the heart, better awareness of patient haemodynamics, and a need for efficiency in performing anastomoses. If a surgeon is trained in these aspects his general surgical skill shall improve (Jenkins et al., 2003). While it has been argued that OPCAB should be included in the training of every heart surgeon (Caputo et al., 2002), other argue to make it a subspecialisation, so only specialized surgeons can perform it (Mack & Taggart, 2019).

Current trainings

For the surgeon there is a dilemma between providing the best possible care and training young surgeons (Murzi et al., 2012). However, it has been shown that with proper supervision, even the distal (on the back of the heart) anastomoses can be performed by residents (surgeons

in training) without compromising patient safety, and even conversion rates can be kept the same (Hossein Almassi et al., 2015). For PCI, teaching hospitals have better outcomes than non-teaching hospitals (Sandhu et al., 2013). At Harefield, a high volume OPCAB-focused hospital, OPCAB has been performed since 1996 with continually good outcomes by both surgeons and trainees (Shahzad G. Raja, 2016). The total amount of OPCAB cases that needs to be performed for accreditation varies between 35 in the US and about 100 in the UK, while studies reported 'accepted' boundaries between <28 and >200 cases (Murphy et al., 2005). This high variance asks for a rigorous study of the learning curves in a local context, in order to capture the variance within one institution.

Evaluation of training and learning

Various OPCAB trainings have been evaluated and can be used to inform future trainings or adaptations in trainings. Murzi and colleagues (2012) report that patients showed similar outcomes for trainees and senior surgeons and conclude that their way of training is safe. Similarly, Hossein Almassi et al. (2015) describe that residents perform anastomoses equally well as surgeons, given good guidance and proper supervision. No differences in conversion rates could be found. However, trainees received cases with low risk, while senior surgeons operated on high-risk cases (Murzi et al., 2012). The low-risk cases should have better outcomes than high-risk ones. Similarly, one surgeon who learned OPCAB for half a year at a heart centre, but then continued without supervision found that adverse events for patients happened less than half as often after two years of practice. Both time and amount of cases influenced the difference in patient outcomes. After 290 cases performance was better than for ONCAB, but this might have been biased through the selection of easy cases (Bougioukakis et al., 2014). During a training a learning curve should be visible as little as possible in the patient outcomes and as much as possible in case allocation to the trainee, who should be supervised. When interpreting the results, risk and difficulty of the case should be taken into account (Hasan, Pozzi, & Hamilton, 2000).

Simulators and teaching sequence

Careful patient selection for trainees can help uphold a high quality of care (Mack et al., 2002). However, with simulators surgeons in training can learn the essential skills in a low-risk environment before applying them on a patient. On a simplistic simulator for anastomoses without haemodynamics, performance in terms of both speed and accuracy plateaued within 30-40 trials (Ito et al., 2013). Thus, the trainee gets the chance to learn one of the crucial skills to a high level, before performing it on a patient. Simulators can be used to teach essential skills

with the possibility for errors. On a real patient errors have to be avoided at all cost, whereas on a simulator a trainee can make mistakes and learn from them (Halkos & Puskas, 2009). Therefore, simulator training as an addition to training on real patients would be desirable (Heskin et al., 2019).

Various reports about the teaching sequence have been published. The coronary arteries can be seen in **Figure *6***. The typical order of teaching is to start with the LAD to allow for perfusion of the anterior (breast-sided) wall of the heart, and then moving towards posterior (back-sided) coronary arteries for which the heart must be manipulated more extensively (Anyanwu et al., 2002; Caputo et al., 2002; Halkos & Puskas, 2009; Murphy et al., 2005; Murzi et al., 2012; Yadava & Taggart, 2020). In Bristol, there is a structured system where trainees rotate every 6 months to a different supervisor, where they learn OPCAB as described above. After the first 3 years, 30-40 cases are done as 1st surgeon and proficiency is deemed to be achieved at about 80-100 cases (Murzi et al., 2012). For a beginning surgeon, easy cases should be selected, thus complicating factors like impaired ventricular function, left main stem or three-vessel disease are excluded in the beginning and gradually introduced until almost all cases can be done off-pump. A surgeon in training might be exposed to OPCAB and ONCAB simultaneously, shunts can help make the anastomoses unhurried (Halkos & Puskas, 2009; Murphy et al., 2005). Multiple factors should be considered when selecting a patient: the clinical condition, urgency, and ventricular function. The resident should be taught not only to perform the anastomoses, but the whole operation process, including creating a back-up plan, collateralizing vessels, judge complexity of disease and size of targets, sequence of grafting, usage of shunts, effective communication and usage of tools for exposure (Halkos & Puskas, 2009).

Learning curves

The performance of a surgeon is highly dependent on surgeon skill and case allocation (Bonchek, 2002). Thus, the cases should be allocated in a way that the surgeon is never overburdened and skill development can take place. A structured training has to be well-founded in previous experiences with training OPCAB. Learning curves are one way to quantify experience and find parameters of learning that can be used as input for a training. Especially if data about an individual surgeon can be collected, it can be used for adaptation and individualization of the curriculum (Gao et al., 2020; Ramsay et al., 2001). When calculating a learning curve, not only the moments of performance are of interest, but also the amount of rest can influence the progress (Savion-Lemieux & Penhune, 2005). “The importance of

understanding and managing the learning curve cannot be overemphasized" (Bougioukakis et al., 2014).

Learning curves described in the literature

Results of learning analyses vary widely, for both OPCAB and conventional CABG. For ONCAB, the found lengths of learning curves ranges between no learning after the training phase (Burt et al., 2015) and 15 years (Maruthappu et al., 2015) or 800 cases (Novick et al., 2006). However, it is not clear what the relation between ONCAB and OPCAB learning curves is. OPCAB learning curves are often inadequately described in the literature. Some authors assume a long learning curve without backing of the information in data or previous research (Atluri et al., 2011; Farina et al., 2019). Another method has been to average results and compare one period to another (Anyanwu et al., 2002). Averaging outcomes can give an indication of performance, but it does not provide information about developments through time (i.e. learning) and differences between surgeons. Visual investigations of learning curves have also been used, as they are useful to describe trends (Bougioukakis et al., 2014; H. K. Song et al., 2003). However, visual analyses cannot provide quantitative statements neither can they be used for prediction, thus more advanced methods are required to analyse the learning curve of OPCAB (Pusic et al., 2015; Ramsay et al., 2001).

Supplementary material II: Variable selection

To ensure validity of the analyses, variable choice is of crucial importance. A selection must be made from the large number of available variables. The criteria for selection of variables are availability, usefulness and suitability. The variables used can be categorized in predictors, outcomes, and control variables.

Predictors relating to the surgeon

Experience

A review about heart surgery in 2018 concluded that skill and precision of a surgeon have a large influence on long-term outcomes (Doenst et al., 2019). An experienced surgeon of the MST hospital claimed that hand eye coordination and insecurity are the most important predictors of performance of a trainee. Insecurity leads to nervousness and performance is worse than the technical skills of the surgeon would allow (Grandjean, 2020). However, skill, precision, hand eye coordination and insecurity are not measured and thus experience is being used as a proxy. Prof. dr. Grandjean confirmed that insecurity declines with experience and skill; precision and hand-eye coordination are also expected to improve with experience. Experience can be measured in years of practice or number of operations executed. Both were expected to correlate highly, but higher performance might be expected if the same amount of operations has been performed in less time. Surgeons in training might practice their skills in their own time, which might have a positive effect on their outcomes (Mack & Taggart, 2019), but is not measured. During training, the resident is increasingly challenged with more (difficult) tasks and responsibility. However, it has not been documented which tasks exactly were executed by the first or second surgeon. This might lead to constant outcomes, if the trainee is only given tasks s/he can execute well (Murzi et al., 2012). Years of practice has been found to predict aorta cross-clamp times in ONCAB (Burt et al., 2015; Maruthappu et al., 2015) and might also influence performance in OPCAB.

Specialisation

Additional to the amount of practice, specialisation might also play a role in the performance of a surgeon. If most of a surgeons procedures are OPCAB, performance might be better than another surgeon who also performs many other procedures, even though the total amount of experience is the same (Sahni et al., 2016). Experienced surgeons have called to make OPCAB a specialized procedure, so that those surgeons who perform OPCAB can focus on this procedure (Mack & Taggart, 2019).

Table 10

Surgeon related predictor variables

Variable	Measurement	Reference(s)
Experience	Number of operations (OPCAB/CABG)	(Burt et al., 2015; Mack & Taggart, 2019; Murzi et al., 2012; Sahni et al., 2016)
Specialisation	Amount of all CABGs divided by amount of OPCABs	(Sahni et al., 2016)

Control variables

Outcome measures related to the procedure or patient are dependent on not only the surgeon, but other factors play a role as well. These should be considered and adjusted for (Ramsay et al., 2001). Every operation is different, which is mainly due to patient (e.g. age, comorbidities) and disease (e.g. amount of diseased vessels, urgency of operation) characteristics. These variables together are called 'case mix' and have been found to predict about 95% of patient outcomes (O. Papachristofi et al., 2017, 2016). Due to the differences in cases, the exact experience of two surgeons cannot be the same and the case selection is highly important during training of a surgeon. This section describes all available variables that potentially impact the outcomes.

Risk score: EuroSCORE

The risk of an operation varies for each patient. In order to assess this risk easily, composite scores have been invented. The EuroSCORE has first been published in 1999 (Nashef et al., 1999) and updated in 2003 (logistic EuroSCORE, Roques, Michel, Goldstone, & Nashef, 2003) and 2012 (EuroSCORE II, S.A.M. Nashef et al., 2012). The difference between the first and the logistic score is only the formula (additive vs. logistic), they are based on the same data and analysis. For the latest version, data of hospitals in 43 countries has been used, making it a widely applicable score. The data for the EuroSCORE II is also more recent and thus fits the current techniques and technologies better than the old score. The main changes in the data were the decrease in mortality rate and simultaneous increase in risk scores, indicating that CABG has been improved through the years. EuroSCORE II also includes a different set of variables, which have not been collected before its introduction, so for some patients EuroSCORE I is the only one available, while patients operated on since 2015 have both scores available. All EuroSCOREs estimate the risk of dying within 30 days of an operation for multiple cardiac surgical procedures, including CABG which is the procedure with the lowest risk (Nashef et al., 2012). When calculating the EuroSCORE, no distinction has

been made between ONCAB and OPCAB. Therefore, applicability of the EuroSCORE for OPCAB has been questioned (Bonchek, 2002) and therefore the individual variables are explored as well as the scores.

Variables of the EuroSCORE:

(logistic) EuroSCORE: age, sex, chronic pulmonary disease, extracardiac arteriopathy, neurological dysfunction, previous cardiac surgery, serum creatinine, active endocarditis, critical preoperative state, unstable angina, left ventricular (LV) dysfunction, recent myocardial infarct, pulmonary hypertension, emergency, other than isolated CABG, surgery on thoracic aorta, postinfarct septal rupture

EuroSCORE II: New York Heart Association (NYHA) score, Canadian Cardiovascular Society 4 (CCS) score, insulin-dependent diabetes mellitus, age, female, extracardiac arteriopathy, chronic pulmonary dysfunction, neurological or musculoskeletal dysfunction severely affecting mobility, previous cardiac surgery, renal dysfunction, active endocarditis, critical preoperative state, LV function, recent myocardial infarct (MI), pulmonary artery systolic pressure, urgency, weight of procedure, thoracic aorta and a constant

Table 11

EuroSCORE variables

Variable	Measurement	Reference(s)
EuroSCORE Iogistic	MST calculation	(Roques et al., 2003)
EuroSCORE II	MST calculation	(Nashef et al., 2012)
Age	Years	(Nashef et al., 2012; Roques et al., 2003)
Sex	Categorical (M/F/unknown)	(Nashef et al., 2012; Roques et al., 2003)
Chronic pulmonary disease	Categorical (yes/no/unknown)	(Nashef et al., 2012; Roques et al., 2003)
Extracardiac arteriopathy	Categorical (yes/no/unknown)	(Nashef et al., 2012; Roques et al., 2003)
Neurological dysfunction	Categorical (yes/no/unknown)	(Roques et al., 2003)
Previous cardiac surgery	Categorical (yes/no/unknown)	(Nashef et al., 2012; Roques et al., 2003)
Serum Creatinine	µmol/l	(Roques et al., 2003)
Active endocarditis	Categorical (yes/no/unknown)	(Nashef et al., 2012; Roques et al., 2003)

Critical preoperative state	Categorical (yes/no/unknown)	(Nashef et al., 2012; Roques et al., 2003)
Unstable angina	Categorical (yes/no/unknown)	(Roques et al., 2003)
LF dysfunction	Categorical (yes/no/unknown)	(Nashef et al., 2012; Roques et al., 2003)
Recent MI	Categorical (yes/no/unknown)	(Nashef et al., 2012; Roques et al., 2003)
Pulmonary hypertension	mmHg	(Nashef et al., 2012; Roques et al., 2003)
Other than isolated CABG	Categorical (isolated CABG/1 non-CABG procedure/2 non-CABG procedures/3 or more non-CABG procedures/unknown)	(Roques et al., 2003)
Surgery thoracic aorta	Categorical (yes/no/unknown)	(Nashef et al., 2012; Roques et al., 2003)
Postinfarct septal rupture	Categorical (yes/no/unknown)	(Roques et al., 2003)
NYHA score	Categorical (class 1/2/3/4/ unknown)	(Nashef et al., 2012)
CCS4 score	Categorical (yes/no/unknown)	(Nashef et al., 2012)
Insulin-dependent diabetes mellitus	Categorical according to treatment	(Nashef et al., 2012)
Neurological or musculoskeletal dysfunction severely affecting mobility	Categorical (yes/no/unknown)	(Nashef et al., 2012)
Renal dysfunction	Categorical (yes/no/unknown)	(Nashef et al., 2012)
Urgency	Categorical (elective/urgent/ emergency/salvage/unknown)	(Nashef et al., 2012; Roques et al., 2003)
Weight of procedure	Categorical (isolated CABG/ 1/2/3 or more non-CABG procedures/unknown)	(Nashef et al., 2012)

Other patient characteristics

The EuroSCORE does not include all patient characteristics that might be of influence on surgical outcomes. A commonly used measure is the BMI, calculated from the height and weight of patients (weight in kg/[height in meters]^2) (Shahzad G. Raja et al., 2013). Smoking and alcohol consumption are also risk factors for CAD and might influence the risk for complications (Ji et al., 2015), however alcohol consumption was not recorded at the MST. Disease characteristics which are not included in the EuroSCORE but might be influencing CABG outcomes are multi-vessel disease (Murzi et al., 2012), atrial fibrillation (Michniewicz,

Mlodawska, Lopatowska, Tomaszuk-Kazberuk, & Malyszko, 2018) and previous cardio-vascular accident (CVA, Ascione, Reeves, Pano, & Angelini, 2004).

Table 12

Non-EuroSCORE patient variables

Variable	Measurement	Reference(s)
Height of patient	cm	(Shahzad G. Raja et al., 2013)
Weight of patient	kg	(Shahzad G. Raja et al., 2013)
BMI	weight in kg/[height in meters]^2	(Shahzad G. Raja et al., 2013)
Smoking currently	Categorical (yes/no/unknown)	(Ji et al., 2015)
Smoker	Categorical (yes/no/unknown)	(Ji et al., 2015)
Multi-vessel disease	Categorical (yes/no/unknown)	(Murzi et al., 2012)
Atrial fibrillation	Categorical (no/paroxysmal/ non-paroxysmal/unknown)	(Michniewicz et al., 2018)
Previous CVA	Categorical (yes/no/unknown)	(Ascione et al., 2004)

Time and timing

The year of operation is taken into account, because the technique and tools change and improve over time and therefore the procedure becomes better over time (Murzi et al., 2012; Nashef et al., 2012). Since actual changes in the procedure might be small or continuous and are not recorded, year of operation will serve as a proxy for the development of the procedure. Furthermore, surgeons might fatigue during their shifts and therefore the actual time of the operation might influence surgeon performance (Chan, Tang, & Chow, 2018).

Table 13

Time related variables

Variable	Measurement	Reference(s)
Development stage of procedure	Year of operation	(Murzi et al., 2012; Nashef et al., 2012)
Start of operation	Time	(Chan et al., 2018)

Team composition

Research on the influence of anaesthetists is inconclusive. In the US, anaesthetists are found to influence results, while in the UK no influence was found (O. Papachristofi et al., 2016). The difference might root in the care systems and responsibilities bore by anaesthetists. Together with the anaesthetist, the most important team members are the first and second surgeon. Various combinations are possible: A experienced surgeon might be second surgeon, while a resident is first. Another option is that the first surgeon is experienced and then the

second surgeon could be a resident, experienced surgeon, guest surgeon, surgery assistant or none at all.

Table 14

Team composition variables

Variable	Measurement	Reference(s)
1st surgeon	Random identifier number	(O. Papachristofi et al., 2016)
2nd surgeon	Random identifier number	(O. Papachristofi et al., 2016)
Anaesthetist	Random identifier number	(O. Papachristofi et al., 2016)

Procedure variables

During a bypass surgery, the surgeon has to make multiple anastomoses. The anastomoses vary in difficulty depending on their location relative to the heart. The further to the back of the patient (downside when patient is in lying position), the more difficult, because the heart has to be manipulated. Manipulation of the heart can lead to disturbances in haemodynamics (Sergeant, De Worm, Meyns, & Wouters, 2001). Furthermore, as bypass for a blocked coronary artery, a surgeon can use a vein or an artery. Veins are easier to process, but arteries have better long-term results (Alexander & Smith, 2016). The amount of proximal and distal, arterial and venous anastomoses were therefore taken into account as difficulty of the procedure

Table 15

Procedural variables

Variable	Measurement	Reference(s)
Distal venous grafts	Number	(Alexander & Smith, 2016; Sergeant et al., 2001)
Proximal venous grafts	Number	(Alexander & Smith, 2016; Sergeant et al., 2001)
Distal arterial grafts	Number	(Alexander & Smith, 2016; Sergeant et al., 2001)
Proximal arterial grafts	Number	(Alexander & Smith, 2016; Sergeant et al., 2001)

Outcome variables of CABG

CABG does not have one clear outcome that the surgeon is solely responsible for. Multiple outcomes are to some extent influenced by the surgeon and relevant to the project. Finding a suitable, available, valid and reliably measured outcome variables is difficult (Ramsay et al., 2001). Outcomes of CABG can be divided into two main categories: efficiency and accuracy. Efficiency relates to the resources (time, money, personal) used, while accuracy

relates more to the qualitative aspect of operating, mainly patient outcomes. Efficiency by itself is not a good measure, because a surgeon who operates fast need not have the best outcomes. On the other hand, patient outcomes are often rare, dichotomous events and are therefore difficult to analyse (Ramsay et al., 2001). To balance out the limitations, a combination of outcome variables has been used.

Time needed for intervention

The more skilled a surgeon is, the less time s/he is expected to need to finish the surgery (Maruthappu et al., 2015). In ONCAB, surgeons with high experience were found to have shorter CPB and aorta cross-clamping times (Burt et al., 2015). However, time needed for the operation is influenced by other factors, like the amount and type of anastomoses, mistakes that need to be corrected, or the difficulty of the case. Also the second operator might influence the time taken for an operation. An experienced surgeon might let an assistant perform certain tasks, which might not be reflected in the time or take the time to explain something to a resident, but still performing well. Further, one surgeon might be faster while having worse outcomes, with another surgeon being slower while having better outcomes. Time alone can thus not be a single good indicator.

Hypotension

When a surgeon lifts the heart to perform lateral (side) and distal anastomoses, blood pressure falls and hypotension occurs (Grandjean, 2020). Surgeon and anaesthetist have to work together to keep blood pressure as stable as possible. Hypotension can be defined by an absolute value of less than 60 mmHg or as a relative reduction of blood pressure by >30%, for the latter a baseline has to be established first (Weyland & Grüne, 2013). Hypotension of more than 10 minutes during an operation is associated with death and vascular events. This association was found even for patients with no prior coronary artery disease (Roshanov et al., 2019). However, causality has not been established (Weyland & Grüne, 2013). Due to availability of data, the overall lowest systolic blood pressure during the operation was used.

Conversion

If the procedure is started as OPCAB and during the process switched to ONCAB it is called conversion. Surgeons with less skills are expected to convert more often than highly skilled surgeons. Conversion rates of surgeons can vary between around 1% to around 16% of all OPCABs (Edgerton et al., 2003). A patient who was converted to on-pump has a much higher risk than an unconverted patient from either ONCAB or OPCAB (Edgerton et al., 2003;

Hassanein & El-Awady, 2016). The timing of a conversion also plays a role. An early conversion (before start of the operation) has little increased risk, a late (during operation) conversion on the other hand, has much higher risk. Experienced surgeons do not achieve better outcomes with converted patients than residents, but their conversions are earlier (better timed) and thus pose less of a risk (Edgerton et al., 2003). Conversions are rare and dichotomous.

Length of stay (ICU/hospital)

The length of stay (LOS) in the intensive care unit (ICU) and the hospital in general give a general indication of the quality of the patient's recovery. It is being used as a proxy for all perioperative processes (Myles, 2014). How long a patient remains in the ICU/hospital is highly dependent on social, administrative, economic factors and is often guided by hospital rules. Since this project is only about one hospital, no differences in this process have to be taken into account. A short LOS is cheaper, but a readmission due to insufficient recovery time is even more expensive than a longer initial stay (Myles, 2014).

Comparison of planned and executed intervention (revascularization)

Before every operation, a plan is made for the intervention. The actual placement of grafts and anastomoses might be different to what was planned. It is seen as good quality to follow up on the plan and perform all anastomoses as planned. It is expected that less experienced surgeons have more deviance from the plan. On study found that trainees make fewer anastomoses, while the relation between distal anastomoses and diseased vessels was similar to the ones of experienced surgeons (Murzi et al., 2012).

Mortality

Mortality is one of the most important outcomes of CABG. Common options for measuring mortality are within the hospital and after 30/60/90/120 and 365 days. Within hospital mortality is highly dependent on discharge guidelines of a hospital (Siregar et al., 2013). According to Siregar (2013), the survival chance of isolated CABG becomes stable after 60 days. Meaning that 60 days of follow-up should be sufficient for analysing mortality. However, mortality with longer follow-up has been explored as well.

Complications

In the literature, multiple definitions of complications are being used (Dindo, Demartines, & Clavien, 2004). For the current project, availability was used to select variables for initial exploration. To account for various possible complications, a score has been made. The score is based on major adverse cardiac event and major adverse cardiac or cerebrovascular

event scores. MACCE occurs if the patient has at least one of the following complications: mortality within 1 year, cardiovascular accident, myocardial infarction, or revascularization (Halbersma et al., 2009). Another score was created which extended to non-cardiac complications that might arise after CABG and might be due to surgeon actions. The complications included were: reintervention, MI, arm-/leg-wound problems, lung infection, artificial respiration for more than 24h, readmission to ICU, CVA, renal failure, gastro-intestinal complication, vascular complication, rhythm problem, re-thoracotomy, refixation sternum, and deep sternum wound infection.

Table 16

Outcome/Performance variables

Variable	Measurement	Reference(s)
Duration of surgery	Minutes	(Burt et al., 2015; Maruthappu et al., 2015)
Hypotension	Lowest systolic blood pressure, mmHg	(Grandjean, 2020; Roshanov et al., 2019; Weyland & Grüne, 2013)
Conversion	Dichotomous (yes/no)	(Edgerton et al., 2003; Hassanein & El-Awady, 2016)
Length of stay hospital	Days	(Myles, 2014)
Revascularization	Difference between planned and executed anastomoses	(Murzi et al., 2012)
Mortality	In hospital, after 30/60/120 days, one year	(Siregar et al., 2013)
Complications	Percentage score of all recorded complications	(Ramsay et al., 2001)
MACCE	Any of the following: 1 year mortality, cardio vascular accident, perioperative myocardial infarction, revascularisation within 30 days	(Dindo et al., 2004; Diodato & Chedrawy, 2014; Novick et al., 2006)

Supplementary material III: R script

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Data import and cleaning

```
knitr::opts_chunk$set(warning = FALSE)
library(readxl)
library(brms)

## Loading required package: Rcpp

## Loading 'brms' package (version 2.14.0). Useful instructions
## can be found by typing help('brms'). A more detailed introduction
## to the package is available through vignette('brms_overview').

##
## Attaching package: 'brms'

## The following object is masked from 'package:stats':
##
##     ar

library(reshape2)
library(tidyverse)

## -- Attaching packages ----------------------- tidyverse 1.3.0 --

## v ggplot2 3.3.2     v purrr   0.3.4
## v tibble  3.0.4     v dplyr   1.0.2
## v tidyr   1.1.2     v stringr 1.4.0
## v readr   1.3.1     v forcats 0.5.0

## -- Conflicts -------------------------- tidyverse_conflicts() --
## x dplyr::filter() masks stats::filter()
## x dplyr::lag()    masks stats::lag()

library(bayr)

## Registered S3 methods overwritten by 'bayr':
##   method          from
##   coef.brmsfit    brms
##   predict.brmsfit brms

##
## Attaching package: 'bayr'

## The following objects are masked from 'package:brms':
##
##     fixef, ranef

library(scales)

##
## Attaching package: 'scales'
```

```
## The following object is masked from 'package:purrr':
##
##     discard

## The following object is masked from 'package:readr':
##
##     col_factor

library(gridExtra)

##
## Attaching package: 'gridExtra'

## The following object is masked from 'package:dplyr':
##
##     combine

#setwd("//t4pfs01.ad.utwente.nl/T4P-DATA/Projects/OPCAB-LC")
options(mc.cores = 30)
#read data in, exclude cases with unrealistic values and sort out variable
 types. Some variables are simplified to boolean types
d <- read_excel("OPCABLC.xlsx", na = c("NULL","-1",-1))
df <- d %>% #only explicit first surgeons are of interest, all others are
excluded
  arrange(interv_datum, `start operatie`) %>%
  filter(`XXXeerste operateur` != "NULL" &
           `XXXeerste operateur` != "Onbekend" &
           `XXXeerste operateur` != "Cardioloog",
         # cases are selected that are either only CABG or CABG and unknow
n if another procedure took place
         art_graft ==1 | ven_graft ==1,
         (is.na(graft1) &
            is.na(graft2) &
            is.na(graft3) &
            is.na(graft4) &
            is.na(graft5) &
            is.na(graft6))==F,
         is.na(interv_gewicht) |
           interv_gewicht != 11 &
           interv_gewicht != 20 &
           interv_gewicht != 30,
         graft1 != "Venegraft",
         is.na(graft2) |
           graft2 != "venegraft",
         XXXopnameduur <= 200)
df <- df %>%
  mutate(XXXpat = as.factor(XXXpat),
         eersteOperateur = as.factor(`XXXeerste operateur`),
         tweedeOperateur = as.factor(`XXXtweede operateur`),
         anesthesist = as.factor(XXXanesthesist),
         interv_datum = as.Date(interv_datum),
         accept_datum = as.Date(accept_datum),
         start_operatie = `start operatie`,
         euroI = as.numeric(`EuroSCORE I`),
         euroII = as.numeric(`EuroSCORE II`),
```

```
        geslacht = fct_recode(as.factor(`geslacht patient`),
                              "vrouwelijk" = "V",
                              "mannelijk" = "M"),
        chron_longziekte = as.logical(`chronische longziekte`),
        art_vaatpathologie = as.logical(art_vaatpathologie),
        neuro_disfunctie = as.logical(neuro_disfunctie),
        cardiochir_eerder = as.logical(cardiochir_eerder),
        endocarditis = as.logical(endocarditis),
        krit_preop_toestand = as.logical(krit_preop_toestand),
        instabiele_AP = as.logical(instabiele_AP),
        recent_MI = as.logical(recent_MI),
        aortachirurgie = as.logical(thorac_aortachir),
        postinfarct_VSR = as.logical(postinfarct_VSR),
        NYHA = as.factor(NYHA),
        CCS_IV = as.logical(CCS_IV),
        diabetes = fct_recode(as.factor(diabetes),
                              "geen" = "0",
                              "Diabetes, behandeling onbekend" = "1",
                              "Diabetes, geen behandeling" = "2",
                              "Diabetes, dieet" = "10",
                              "Diabetes, orale medicatie" = "20",
                              "Diabetes, insuline" =  "30"),
        slechte_mob = as.logical(slechte_mobiliteit),
        nierfalen = as.logical(nierfalen),
        dialyse = as.logical(dialyse),
        urgentie = fct_recode(as.factor(urgentie),
                              "electief" = "10",
                              "urgent" = "20",
                              "spoed" = "30",
                              "redding" = "40"),
        interv_gewicht = as.factor(interv_gewicht),
        gewicht = as.numeric(gewicht),
        roker = as.logical(fct_recode(as.factor(preop_ris_roker),
                           "TRUE" = "J",
                           "FALSE" = "N")),
        rooktnu = as.logical(fct_recode(as.factor(preop_ris_rooktnu),
                           "TRUE" = "J",
                           "FALSE" = "N")),
        CVA_eerder = as.logical(CVA_eerder),
        multiv = as.logical(multiv),
        AF = as.logical(fct_recode(as.factor(AF),
                        "FALSE" = "0",
                        "TRUE" = "10",
                        "TRUE" = "20")),
        coronairchir_overig = as.logical(coronairchir_overig),
        ECC = as.logical(ifelse(ECC==10|ECC==20|ECC==30,"TRUE","FALSE")),
        ECC_canulatie = fct_recode(as.factor(ECC_canulatie),
                                   "Geen" = "0",
                                   "canulatie soort onbekend" = "1",
                                   "klassieke canulatie" = "10",
                                   "links-links bypass" = "20",
                                   "overige canulatie" = "90"),
        circ_arrest = as.logical(circ_arrest),
        art_graft = as.logical(art_graft),
```

```
        ven_graft = as.logical(ven_graft),
        LIMA = as.logical(LIMA),
        RIMA = as.logical(RIMA),
        radialis = as.logical(radialis),
        GEA = as.logical(GEA),
        LMvoorstel = ifelse(LMvoorstel=="J","TRUE","FALSE"),
        LMvoorstel = as.logical(LMvoorstel),
        LADvoorstel = ifelse(LADvoorstel=="J","TRUE","FALSE"),
        LADvoorstel = as.logical(LADvoorstel),
        DIAGvoorstel = ifelse(DIAGvoorstel=="J","TRUE","FALSE"),
        DIAGvoorstel = as.logical(DIAGvoorstel),
        ALvoorstel = ifelse(ALvoorstel=="J","TRUE","FALSE"),
        ALvoorstel = as.logical(ALvoorstel),
        MOvoorstel = ifelse(MOvoorstel=="J","TRUE","FALSE"),
        MOvoorstel = as.logical(MOvoorstel),
        LPLvoorstel = ifelse(LPLvoorstel=="J","TRUE","FALSE"),
        LPLvoorstel = as.logical(LPLvoorstel),
        RPLvoorstel = ifelse(RPLvoorstel=="J","TRUE","FALSE"),
        RPLvoorstel = as.logical(RPLvoorstel),
        RCAvoorstel = ifelse(RCAvoorstel=="J","TRUE","FALSE"),
        RCAvoorstel = as.logical(RCAvoorstel),
        RDPvoorstel = ifelse(RDPvoorstel=="J","TRUE","FALSE"),
        RDPvoorstel = as.logical(RDPvoorstel),
        VENGRvoorstel = ifelse(VENGRvoorstel=="J","TRUE","FALSE"),
        VENGRvoorstel = as.logical(VENGRvoorstel),
        ARTGRvoorstel = ifelse(ARTGRvoorstel=="J","TRUE","FALSE"),
        ARTGRvoorstel = as.logical(ARTGRvoorstel),
        graft1 = fct_collapse(as.factor(graft1),
                              AL = c("Al","AL","IM"),
                              D = c("D", "D1","D2","D3", "Diagonaal"),
                              LAD = c(
                                "LAD (lange ana over perif. stenose)",
                                "LAD apicaal","LAD distaal",
                                "LAD intramyocardiaal",
                                "LAD med", "LAD mid",  "LAD prox",
                                "LAD2", "LADprox", "LAD proximaal"),
                              MO = c("MO", "Mo","MO1", "MO2","MOCx"),
                              RPL = c("PLCx"),
                              RCA = c("rRCA"),
                              RDP = c("vene-RDP")),
        graft2 = fct_collapse(as.factor(graft2),
                              AL = c("Al", "IM", "IMA"),
                              D = c("D1", "D1B", "D2",
                                    "D3", "Diagonaal", "Graft"),
                              LAD = c("LAD (RCA)", "LAD apicaal","
                                      LAD dist", "LAD distaal",
                                      "LAD intramyocardiaal",
                                      "LAD mid","LAD prox","LDP"),
                              MO = c("MA","Mo","MO (Cx)","MO 2",
                                     "MO1","MO1A","Mo2","MO2",
                                     "MOCx","MOCx1","MOCx1b","MOCx2"),
                              LPL = c("LPL 1", "CX"),
                              RPL = c("PlCx","PLCx"),
                              RCA = c("PlRCA","RCA crux","/RCA")),
```

```
        graft3 = fct_collapse(as.factor(graft3),
                              AL = c("Al","AL b","Ala", "IM", "IMB"),
                              D = c("D1","D distaal","D1A", "D2",
                                    "D3", "Diagonaal", "Graft"),
                              LAD = c("LAD dist", "LDP"),
                              LPL = c("LPL1","LPL2"),
                              MO = c("MA","MA (RCA)","MO1", "MO1A",
                                     "MO1b","MO1B","MO1C","MO2",
                                     "MO3","MOCx","MOCx2"),
                              RPL = c("PLCx", "PL", "PLR", "RPL(Cx)",
                                      "RPL crux"),
                              RCA = c("PlRCA","RCA crux","/RCA",
                                      "RCA-RDP", "RCA bifurcatie"),
                              RDP = c("RDP (van links)", "RDP (van linksL
",
                                      "RDP(Cx)")),
        graft4 = fct_collapse(as.factor(graft4),
                              AL = c("Al","ALb","Ala", "IM", "IMB"),
                              D = c("D1","D distaal","D1A", "D2",
                                    "D3", "Diagonaal", "Graft"),
                              LAD = c("LAD dist", "LDP",
                                      "LAD te klein, dubbel systeem"),
                              LPL = c("LPL1","LPL2"),
                              MO = c("Ma","MA (Dx)", "MA","MA (RCA)",
                                     "MO1", "MO1A", "MO1b","MO1B",
                                     "MO1C","MO2","MO3","MOCx","MOCx2",
                                     "MOCx3"),
                              RPL = c("PLCx", "PL", "PLR", "RPL(Cx)",
                                      "RPL crux", "PLCx1", "PLRCA"),
                              RCA = c("PlRCA","RCA crux","/RCA",
                                      "RCA-RDP", "RCA bifurcatie"),
                              RDP = c(".", "RDP (van links)",
                                      "RDP (van linksL", "RDP(Cx)",
                                      "RDP (crux)", "RDP (Cx)",
                                      "RDP (van Cx)", "RDP van links",
                                      "RDP/MA")),
        graft5 = fct_collapse(as.factor(graft5),
                              AL = c("Al","ALb","Ala", "IM", "IMB"),
                              D = c("D1","D distaal","D1A", "D2",
                                    "D3", "Diagonaal", "Graft"),
                              LAD = c("LAD dist", "LDP",
                                      "LAD te klein, dubbel systeem"),
                              LPL = c("LPL1","LPL2"),
                              MO = c("Ma","MA (Dx)", "MA","MA (RCA)",
                                     "MO1", "MO1A", "MO1b","MO1B",
                                     "MO1C","MO2","MO3","MOCx","MOCx2",
                                     "MOCx3"),
                              RPL = c("PLCx", "PL", "PLR", "RPL(Cx)",
                                      "RPL crux", "PLCx1", "PLRCA",
                                      "PLCX", "PLCx2"),
                              RCA = c("PlRCA","RCA crux","/RCA",
                                      "RCA-RDP", "RCA bifurcatie"),
                              RDP = c(".", "RDP (van links)",
                                      "RDP (van linksL", "RDP(Cx)",
```

```
                                      "RDP (crux)", "RDP (Cx)",
                                      "RDP (van Cx)", "RDP van links",
                                      "RDP/MA")),
         graft6 = fct_collapse(as.factor(graft6),
                               LAD = c("LAD dist")),
         conversie = ifelse(Conversie_HLM=="Ja","TRUE","FALSE"),
         conversie = as.logical(conversie),
         laagste_druk_syst = as.numeric(laagste_druk_syst),
         hoogste_druk_syst = as.numeric(hoogste_druk_syst),
         hoogste_druk_diast = as.integer(hoogste_druk_diast),
         mort_status = as.logical(mort_status),
         mort_status_datum = as.Date(mort_status_datum),
         mort30d = as.numeric(ifelse(
           ((mort_status_datum - interv_datum) <= 30) &
             (mort_status==1), T,F)),
         mort60d = as.numeric(ifelse(
           ((mort_status_datum - interv_datum) <= 60) &
             (mort_status==1), T,F)),
         mort120d = as.numeric(ifelse(
           ((mort_status_datum - interv_datum) <= 120) &
             (mort_status==1), T,F)),
         mort1j = as.numeric(ifelse(
           ((mort_status_datum - interv_datum) <= 365) &
             (mort_status==1),T,F)),
         nieuwe_interv_tijdens_opname = as.logical(nieuwe_interv_tijdens_o
pname),
         periop_MI = as.logical(periop_MI),
         arm_beenwond = as.logical(arm_beenwond),
         longinfectie = as.logical(longinfectie),
         resp_insuff = as.logical(resp_insuff),
         beademing = as.logical(beademing),
         heropname_IC = as.logical(heropname_IC),
         CVA_restletsel = as.logical(CVA_restletsel),
         CVA_zonder_restletsel = as.logical(CVA_zonder_restletsel),
         gastroint_compl = as.logical(gastroint_compl),
         vasc_compl_opname = as.logical(vasc_compl_opname),
         ritmeprobleem = as.logical(ritmeprobleem),
         revasc_30d = as.logical(rethorac_30d == "20"),
         rethorac_30d = as.logical(ifelse (rethorac_30d==10|
                                             rethorac_30d==20|
                                             rethorac_30d==90,
                                           "TRUE","FALSE")),
         herfixatie_30d = as.logical(herfixatie_30d),
         DSWI_30d = as.logical(DSWI_30d))

# CVA cannot be with AND without residual damage, therefore those who have
 both are considered missing values
df$CVA_restletsel[df$CVA_restletsel == T &
                    df$CVA_zonder_restletsel == T] <- NA
df$CVA_zonder_restletsel[is.na(df$CVA_restletsel)] <- NA
# highly unrealistic values are recoded as missing values
df$`eind operatie`[df$`eind operatie` == 5145] <- NA
df$lengte[df$lengte == 1170] <- NA
df$lengte[df$lengte == 18] <- NA
```

```
df$lengte[df$lengte == 88] <- NA
df$gewicht[df$gewicht==887] <- NA
df$XXXopnameduur[df$XXXopnameduur==0] <- NA
# for a few patients, it seems as if height and weight are swapped, the fo
llowing code reverses that
df$gewicht[df$lengte ==46] <- 46
df$lengte[df$lengte==46] <- 160
df$gewicht[df$lengte ==70] <- 70
df$lengte[df$lengte==70] <- 170
df$gewicht[df$lengte ==75] <- 75
df$lengte[df$lengte==75] <- 170
df$gewicht[df$lengte ==87] <- 87
df$lengte[df$lengte==87] <- 185
df$gewicht[df$lengte ==98] <- 98
df$lengte[df$lengte==98] <- 183
df$gewicht[df$lengte ==103] <- 103
df$lengte[df$lengte==103] <- 180
df$gewicht[df$lengte ==109] <- 109
df$lengte[df$lengte==109] <- 180
#quality control for blood pressure
df$laagste_druk_syst[df$laagste_druk_syst >
                       df$hoogste_druk_syst] <- NA
df$laagste_druk_diast[df$laagste_druk_diast >
                        df$hoogste_druk_diast] <- NA
#logistic euroscore (values taken from Roques et al, 2003)
df$eurolog <- exp(-4.789594 +
                    0.0666354 * df$leeftijd +
                    0.3304052 * ifelse(df$geslacht == "vrouwelijk",
                                       1, 0) +
                    0.6521653 * ifelse(df$kreatinine_gehalte > 200,
                                       1, 0) +
                    0.6558917 * ifelse(df$art_vaatpathologie == "TRUE",
                                       1, 0) +
                    0.4931341 * ifelse(df$chron_longziekte == "TRUE",
                                       1, 0) +
                    0.841626 * ifelse(df$neuro_disfunctie == "TRUE",
                                      1, 0) +
                    1.002625 * ifelse(df$cardiochir_eerder == "TRUE",
                                      1, 0) +
                    0.5460218 * ifelse(df$recent_MI == "TRUE",
                                       1, 0) +
                    0.4191643 * ifelse(df$LVEF >= 30 & df$LVEF <= 50,
                                       1, 0) +
                    1.094443 * ifelse(df$LVEF < 30, 1, 0) +
                    0.7676924 * ifelse(df$PA_druk > 60, 1, 0) +
                    1.101265 * ifelse(df$endocarditis == "TRUE",
                                      1, 0) +
                    0.5677075 * ifelse(df$instabiele_AP == "TRUE",
                                       1, 0) +
                    0.7127953 * ifelse(df$urgentie != "electief" &
                                         is.na(df$urgentie) == F,
                                       1, 0) +
                    0.9058132 * ifelse(df$krit_preop_toestand == "TRUE",
                                       1, 0) +
```

```
                    1.462009 * ifelse(df$postinfarct_VSR == "TRUE",
                                      1, 0) +
                    0.5420364 * ifelse(df$interv_gewicht != 10,
                                       1, 0) +
                    1.159787 * ifelse(df$aortachirurgie == "TRUE",
                                      1, 0))
# the calculations below are not executed in the initial setup, because al
l value changes should be performed before using them for calculations
df$BMI <- round(df$gewicht / ((df$lengte/100) ^2), 2)
df <- df %>% rowwise() %>% mutate(
  allcomps = mean(c(mort1j, nieuwe_interv_tijdens_opname, periop_MI,
                    DSWI_30d, herfixatie_30d, rethorac_30d, ritmeprobleem,
                    vasc_compl_opname, gastroint_compl, CVA_restletsel,
                    CVA_zonder_restletsel, heropname_IC, beademing,
                    resp_insuff, longinfectie, arm_beenwond), na.rm=T),
  textbout = weighted.mean(c(mort30d, mort120d, mort1j, DSWI_30d,
                             CVA_restletsel, nieuwe_interv_tijdens_opname,
                             periop_MI),
                           c(0.109,0.144,0.188,0.067,0.090,0.212,0.190), n
a.rm=T),
  totalgrafts = if(!is.na(graft6)){6} else if
  (!is.na(graft5)){5} else if
  (!is.na(graft4)){4} else if
  (!is.na(graft3)){3} else if
  (!is.na(graft2)){2} else if
  (!is.na(graft1)){1} else {0},
  voorstellen = sum(c(LMvoorstel,LADvoorstel,DIAGvoorstel,ALvoorstel,
                      MOvoorstel,LPLvoorstel,RPLvoorstel,RCAvoorstel,
                      RDPvoorstel)))
#MACCE has partly shorter follow up than in Halbersma et al. (2009), Hilli
s et al. (2011) difference between MACE and MACCE not clear, overlapping d
efinitions especially since both have no clear definition
df$MACCE <- df %>%
  rowwise() %>%
  summarise(MACCE = any(mort1j, CVA_restletsel,CVA_zonder_restletsel,
                        periop_MI, revasc_30d, na.rm=T))

## `summarise()` ungrouping output (override with `.groups` argument)

df$MACCE <- as.numeric(pull(df$MACCE,MACCE))

# difference between proposed grafts and actual grafts
df <- df %>%
  rowwise() %>%
  mutate(vengrdiff = diff(c(VENGRvoorstel,ven_graft), na.rm=F),
         artgrdiff = diff(c(ARTGRvoorstel,art_graft), na.rm=F),
         planvsuitg = diff(c(voorstellen,totalgrafts),na.rm=T))
df <- df %>%
  mutate(LADdone = if(graft1 == "LAD" |
                      (!is.na(graft2) & graft2 == "LAD") |
                      (!is.na(graft3) & graft3 == "LAD") |
                      (!is.na(graft4) & graft4 == "LAD") |
                      (!is.na(graft5) & graft5 == "LAD") |
                      (!is.na(graft6) & graft6 == "LAD")){TRUE} else
```

```
                        {FALSE},
                    LADdvp = as.factor(diff(c(LADvoorstel,LADdone),
                                            na.rm=T)),
                    Ddone = if(graft1 == "D" |
                                (!is.na(graft2) & graft2 == "D") |
                                (!is.na(graft3) & graft3 == "D") |
                                (!is.na(graft4) & graft4 == "D") |
                                (!is.na(graft5) & graft5 == "D") |
                                (!is.na(graft6) & graft6 == "D")){TRUE} el
se
                                  {FALSE},
                    Ddvp = as.factor(diff(c(DIAGvoorstel,Ddone),
                                          na.rm=T)),
                    ALdone = if(graft1 == "AL" |
                                (!is.na(graft2) & graft2 == "AL") |
                                (!is.na(graft3) & graft3 == "AL") |
                                (!is.na(graft4) & graft4 == "AL") |
                                (!is.na(graft5) & graft5 == "AL") |
                                (!is.na(graft6) & graft6 == "AL")){TRUE} e
lse
                                  {FALSE},
                    ALdvp = as.factor(diff(c(ALvoorstel,ALdone),
                                           na.rm=T)),
                    MOdone = if(graft1 == "MO" |
                                (!is.na(graft2) & graft2 == "MO") |
                                (!is.na(graft3) & graft3 == "MO") |
                                (!is.na(graft4) & graft4 == "MO") |
                                (!is.na(graft5) & graft5 == "MO") |
                                (!is.na(graft6) & graft6 == "MO")){TRUE} e
lse
                                  {FALSE},
                    MOdvp = as.factor(diff(c(MOvoorstel,MOdone),
                                           na.rm=T)),
                    LPLdone = if(graft1 == "LPL" |
                                (!is.na(graft2) & graft2 == "LPL") |
                                (!is.na(graft3) & graft3 == "LPL") |
                                (!is.na(graft4) & graft4 == "LPL") |
                                (!is.na(graft5) & graft5 == "LPL") |
                                (!is.na(graft6) & graft6 == "LPL")){TRUE}
else
                                  {FALSE},
                    LPLdvp = as.factor(diff(c(LPLvoorstel,LPLdone),
                                           na.rm=T)),
                    RPLdone = if(graft1 == "RPL" |
                                (!is.na(graft2) & graft2 == "RPL") |
                                (!is.na(graft3) & graft3 == "RPL") |
                                (!is.na(graft4) & graft4 == "RPL") |
                                (!is.na(graft5) & graft5 == "RPL") |
                                (!is.na(graft6) & graft6 == "RPL")){TRUE}
else
                                  {FALSE},
                    RPLdvp = as.factor(diff(c(RPLvoorstel,RPLdone),
                                           na.rm=T)),
                    RCAdone = if(graft1 == "RCA" |
```

```
                                (!is.na(graft2) & graft2 == "RCA") |
                                (!is.na(graft3) & graft3 == "RCA") |
                                (!is.na(graft4) & graft4 == "RCA") |
                                (!is.na(graft5) & graft5 == "RCA") |
                                (!is.na(graft6) & graft6 == "RCA")){TRUE}
else
                                  {FALSE},
                    RCAdvp = as.factor(diff(c(RCAvoorstel,RCAdone),
                                            na.rm=T)),
                    RDPdone = if(graft1 == "RDP" |
                                (!is.na(graft2) & graft2 == "RDP") |
                                (!is.na(graft3) & graft3 == "RDP") |
                                (!is.na(graft4) & graft4 == "RDP") |
                                (!is.na(graft5) & graft5 == "RDP") |
                                (!is.na(graft6) & graft6 == "RDP")){TRUE}
else
                                  {FALSE},
                    RDPdvp = as.factor(diff(c(RDPvoorstel,RDPdone),
                                            na.rm=T)),)
levels(df$LADdvp)<- c("as planned","unplanned","planned & not done")
levels(df$Ddvp)<- c("as planned","unplanned","planned & not done")
levels(df$ALdvp)<- c("as planned","unplanned","planned & not done")
levels(df$MOdvp)<- c("as planned","unplanned","planned & not done")
levels(df$LPLdvp)<- c("as planned","unplanned","planned & not done")
levels(df$RPLdvp)<- c("as planned","unplanned","planned & not done")
levels(df$RCAdvp)<- c("as planned","unplanned","planned & not done")
levels(df$RDPdvp)<- c("as planned","unplanned","planned & not done")



# calculate experience and specialisation as 1st surgeon and select datase
t for 2015 and later only
df <- df %>%
  group_by(eersteOperateur) %>%
  mutate(CABGexp04 = row_number()) %>%
  ungroup()
d15 <- df %>%
  filter(interv_datum > as.Date("2015-05-01"))
d15 <- d15 %>%
  group_by(eersteOperateur) %>%
  mutate(CABGexp15 = row_number()) %>%
  ungroup()
d15 <- d15 %>%
  group_by(ECC,eersteOperateur) %>%
  mutate(expECC = row_number(),
         specialisatie = expECC/CABGexp15) %>%
  ungroup()

#Martins functions for model selection
IC <- function (ic) {
  ic$estimates %>%
  as_tibble(rownames = "IC") %>%
  mutate(Model = attr(ic, "model_name")) %>%
```

```
  select(Model, IC, Estimate, SE)}
compare_IC <- function(ic_list,
                       include = c("looic", "waic", "kfoldic")){
    ic_list %>%
    purrr::map_df(IC) %>%
    filter(IC %in% include) %>%
    group_by(IC) %>%
    mutate(diff_IC = Estimate - min(Estimate)) %>%
    ungroup() %>%
    arrange(IC, diff_IC)
}

dOACV <- d15 %>% filter(tweedeOperateur == "OACV")
```

Data analysis

Exploratory analysis

```
summary(df)
summary(d15)
d15 %>% filter(ECC == F) %>%
  group_by(eersteOperateur) %>%
  summarise(expECC = max(expECC))

d15 %>% filter(ECC == F) %>%
  summary()
d15 %>% filter(ECC == T) %>%
  summary()

d15 %>%
  group_by(ECC) %>%
  summarise(sd = sd(leeftijd, na.rm=T))
d15 %>%
  filter(interv_datum >= as.Date("2019-01-01"),
         interv_datum <= as.Date("2019-12-31"),
         ECC ==T) %>%
  view()
d15 %>%
  filter(MACCE == T,
         ECC == F) %>%
  view()
```

Outcome variables

Operation duration (operatieduur)

```
summary(df$operatieduur)
summary(d15$operatieduur)
df %>%
  count(eersteOperateur,wt = operatieduur) %>%
  ggplot(aes(x = eersteOperateur,y = n)) +
  geom_col() +
  scale_y_continuous(labels = comma)  #the amount of minutes each surgeon
has been operating in total. Not important but interesting
df %>%
```

```
  group_by(eersteOperateur) %>%
  summarise(count = n(),
            min = min(operatieduur, na.rm=T),
            first_q = quantile(operatieduur,.25, na.rm=T),
            median = median(operatieduur, na.rm=T),
            med_abs_dev = mad(operatieduur, na.rm=T),
            mean = mean(operatieduur,na.rm=T),
            third_q = quantile(operatieduur,.75,na.rm=T),
            iqr = IQR(operatieduur,na.rm=T),
            max = max(operatieduur,na.rm=T))
d15 %>%
  group_by(eersteOperateur) %>%
  summarise(count = n(),
            min = min(operatieduur, na.rm=T),
            first_q = quantile(operatieduur,.25, na.rm=T),
            median = median(operatieduur, na.rm=T),
            mean = mean(operatieduur,na.rm=T),
            third_q = quantile(operatieduur,.75,na.rm=T),
            max = max(operatieduur,na.rm=T))
df %>%
  ggplot(aes(x=operatieduur)) +
  geom_histogram(fill="darkgreen") +
  coord_cartesian(xlim=c(0,1000),ylim=c(0,5000))
d15 %>%
  ggplot(aes(x=operatieduur)) +
  geom_histogram() +
  coord_cartesian(xlim=c(0,550))

medianopd <- df %>%
  group_by(eersteOperateur) %>%
  summarise(median(operatieduur, na.rm=T))
medianopd %>%
  ggplot(aes(x=eersteOperateur,
             y=`median(operatieduur, na.rm = T)`)) +
  geom_col()
medianECCopd <- d15 %>%
  group_by(eersteOperateur,ECC) %>%
  summarise(median(operatieduur,na.rm=T))
medianECCopd %>%
  ggplot(aes(x=ECC,y=`median(operatieduur,
                             na.rm = T)`,fill=ECC)) +
  geom_col() +
  facet_wrap(~eersteOperateur)

df %>%
  ggplot(aes(x=eersteOperateur,y=operatieduur))+
  geom_boxplot() +
  coord_cartesian(ylim = c(0,1000))

d15 %>%
  ggplot(aes(x=eersteOperateur,y=operatieduur, fill = ECC))+
  geom_boxplot() +
  coord_cartesian(ylim = c(0,550))
```

Lowest systolic blood pressure

```
summary(df$laagste_druk_syst)
summary(d15$laagste_druk_syst)
df %>%
  ggplot(aes(x=laagste_druk_syst)) +
  geom_histogram(binwidth=1) # 2 values removed: 855, 900
d15 %>%
  ggplot(aes(x=laagste_druk_syst, fill=ECC)) +
  geom_histogram()
d15 %>%
  filter(ECC==F) %>%
  ggplot(aes(x=laagste_druk_syst)) +
  geom_histogram()

medianopd <- df %>%
  group_by(eersteOperateur) %>%
  summarise(median(laagste_druk_syst, na.rm=T))
medianopd %>%
  ggplot(aes(x=eersteOperateur,
             y=`median(laagste_druk_syst, na.rm = T)`)) +
  geom_col()
medianECCopd <- d15 %>%
  group_by(eersteOperateur,ECC) %>%
  summarise(median(laagste_druk_syst,na.rm=T))
medianECCopd %>%
  ggplot(aes(x=ECC,y=`median(laagste_druk_syst, na.rm = T)`,
             fill=ECC)) +
  geom_col() +
  facet_wrap(~eersteOperateur)

df %>%
  ggplot(aes(x=eersteOperateur,y=laagste_druk_syst)) +
  geom_boxplot()

d15 %>%
  ggplot(aes(x=eersteOperateur,y=laagste_druk_syst, fill = ECC)) +
  geom_boxplot()
```

MACCE (major adverse cerebrovasculaire or cardial event)

```
summary(df$MACCE)
#percentage of patients having any major adverse cerebrovascular or cardia
c event
sum(df$MACCE)/(sum(df$MACCE)+sum(df$MACCE==FALSE))
summary(d15$MACCE)
sum(d15$MACCE)/(sum(d15$MACCE)+sum(d15$MACCE==FALSE))
df %>%
  ggplot(aes(x=MACCE,fill=MACCE)) +
  geom_bar() +
  facet_wrap(~ eersteOperateur) +
  theme_bw()
d15 %>%
  ggplot(aes(x=MACCE, fill=MACCE)) +
  geom_bar() +
```

```
  theme_bw()

d15 %>%
  ggplot(aes(x=ECC, fill = ECC))+
  geom_bar() +
  facet_wrap(~eersteOperateur) +
  theme_bw()
d15 %>%
  ggplot(aes(x=eersteOperateur, fill = ECC))+
  geom_bar() +
  facet_wrap(~ECC) +
  theme_bw()

# 1 year mortality
summary(df$mort1j)
sum(df$mort1j,na.rm=T)/(sum(df$mort1j, na.rm=T) +
                          sum(df$mort1j==FALSE,na.rm=T))
summary(d15$mort1j)
sum(d15$mort1j)/(sum(d15$mort1j) +
                   sum(d15$mort1j==FALSE))
df %>%
  ggplot(aes(x=mort1j,fill=mort1j)) +
  geom_bar() +
  facet_wrap(~ eersteOperateur) +
  theme_bw()
d15 %>%
  ggplot(aes(x=mort1j, fill=mort1j)) +
  geom_bar() +
  facet_wrap(~ ECC) +
  theme_bw()

# CVA with and without residual damage
summary(df$CVA_restletsel)
sum(df$CVA_restletsel,na.rm=T)/
  (sum(df$CVA_restletsel, na.rm=T) +
     sum(df$CVA_restletsel==FALSE,na.rm=T))
summary(d15$CVA_restletsel)
sum(d15$CVA_restletsel)/
  (sum(d15$CVA_restletsel)+sum(d15$CVA_restletsel==FALSE))
df %>%
  ggplot(aes(x=CVA_restletsel,fill=CVA_restletsel)) +
  geom_bar() +
  facet_wrap(~ eersteOperateur) +
  theme_bw()
d15 %>%
  ggplot(aes(x=CVA_restletsel, fill=CVA_restletsel)) +
  geom_bar() +
  facet_wrap(~ ECC) +
  theme_bw()

summary(df$CVA_zonder_restletsel)
sum(df$CVA_zonder_restletsel,na.rm=T)/(sum(df$CVA_zonder_restletsel, na.rm
=T)+sum(df$CVA_zonder_restletsel==FALSE,na.rm=T))
summary(d15$CVA_zonder_restletsel)
```

```
sum(d15$CVA_zonder_restletsel)/
  (sum(d15$CVA_zonder_restletsel) +
     sum(d15$CVA_zonder_restletsel==FALSE))
df %>%
  ggplot(aes(x=CVA_zonder_restletsel,fill=CVA_zonder_restletsel)) +
  geom_bar() +
  facet_wrap(~ eersteOperateur) +
  theme_bw()
d15 %>%
  ggplot(aes(x=CVA_zonder_restletsel, fill=CVA_zonder_restletsel)) +
  geom_bar() +
  facet_wrap(~ ECC) +
  theme_bw()


# perioperative myocardial infarct
summary(df$periop_MI)
sum(df$periop_MI,na.rm=T)/(sum(df$periop_MI, na.rm=T)+sum(df$periop_MI==FA
LSE,na.rm=T))
summary(d15$periop_MI)
sum(d15$periop_MI, na.rm=T)/
  (sum(d15$periop_MI,na.rm=T) +
     sum(d15$periop_MI==FALSE,n.rm=T))
df %>%
  ggplot(aes(x=periop_MI,fill=periop_MI)) +
  geom_bar() + facet_wrap(~ eersteOperateur) +
  theme_bw()
d15 %>%
  ggplot(aes(x=periop_MI, fill=periop_MI)) +
  geom_bar() +
  facet_wrap(~ ECC) +
  theme_bw()

# revascularization within 30 days
summary(df$revasc_30d)
sum(df$revasc_30d,na.rm=T)/
  (sum(df$revasc_30d, na.rm=T) +
     sum(df$revasc_30d==FALSE,na.rm=T))
summary(d15$revasc_30d)
sum(d15$revasc_30d, na.rm=T)/
  (sum(d15$revasc_30d,na.rm=T) +
     sum(d15$revasc_30d==FALSE,n.rm=T))
df %>%
  ggplot(aes(x=revasc_30d,fill=revasc_30d)) +
  geom_bar() +
  facet_wrap(~ eersteOperateur) +
  theme_bw()
d15 %>%
  ggplot(aes(x=revasc_30d, fill=revasc_30d)) +
  geom_bar() +
  facet_wrap(~ ECC) +
  theme_bw()
```

Textbook outcome

```
#remember textbook outcome is calculated as weighted mean of various compl
ications, thus 0 means 'textbook' outcome and 1 a very unfortunate combina
tion of outcomes including death
summary(df$textbout)
summary(d15$textbout)
df %>%
  ggplot(aes(x=textbout)) +
  geom_histogram(binwidth=0.01)
d15 %>%
  ggplot(aes(x=textbout)) +
  geom_histogram(binwidth=0.01)

df %>%
  ggplot(aes(x=eersteOperateur,y=textbout))+
  geom_count()

d15 %>%
  ggplot(aes(x=eersteOperateur,y=textbout, col = ECC))+
  geom_count()

#those which have been exprored for MACCE already are not repeated
# 30 day mortality
summary(df$mort30d)
sum(df$mort30d,na.rm=T)/
  (sum(df$mort30d, na.rm=T) +
     sum(df$mort30d==FALSE,na.rm=T))
summary(d15$mort30d)
sum(d15$mort30d)/
  (sum(d15$mort30d) +
     sum(d15$mort30d==FALSE))
df %>%
  ggplot(aes(x=mort30d,fill=mort30d)) +
  geom_bar() +
  facet_wrap(~ eersteOperateur) +
  theme_bw()
d15 %>%
  ggplot(aes(x=mort30d, fill=mort30d)) +
  geom_bar() +
  facet_wrap(~ ECC) +
  theme_bw()

# 120 day mortality
summary(df$mort120d)
sum(df$mort120d,na.rm=T)/
  (sum(df$mort120d, na.rm=T) +
     sum(df$mort120d==FALSE,na.rm=T))
summary(d15$mort120d)
sum(d15$mort120d)/
  (sum(d15$mort120d) +
     sum(d15$mort120d==FALSE))
df %>%
  ggplot(aes(x=mort120d,fill=mort120d)) +
```

```
  geom_bar() +
  facet_wrap(~ eersteOperateur) +
  theme_bw()
d15 %>%
  ggplot(aes(x=mort120d, fill=mort120d)) +
  geom_bar() +
  facet_wrap(~ ECC) +
  theme_bw()

# deep sternum wound infection within 30 days
summary(df$DSWI_30d)
sum(df$DSWI_30d,na.rm=T)/
  (sum(df$DSWI_30d, na.rm=T) +
     sum(df$DSWI_30d==FALSE,na.rm=T))
summary(d15$DSWI_30d)
sum(d15$DSWI_30d)/
  (sum(d15$DSWI_30d) +
     sum(d15$DSWI_30d==FALSE))
df %>%
  ggplot(aes(x=DSWI_30d,fill=DSWI_30d)) +
  geom_bar() +
  facet_wrap(~ eersteOperateur) +
  theme_bw()
d15 %>%
  ggplot(aes(x=DSWI_30d, fill=DSWI_30d)) +
  geom_bar() +
  facet_wrap(~ ECC) +
  theme_bw()

# new intevention during hospital stay
summary(df$nieuwe_interv_tijdens_opname)
sum(df$nieuwe_interv_tijdens_opname,na.rm=T)/
  (sum(df$nieuwe_interv_tijdens_opname,na.rm=T) +
     sum(df$nieuwe_interv_tijdens_opname==FALSE,na.rm=T))
summary(d15$nieuwe_interv_tijdens_opname)
sum(d15$nieuwe_interv_tijdens_opname)/
  (sum(d15$nieuwe_interv_tijdens_opname) +
     sum(d15$nieuwe_interv_tijdens_opname==FALSE))
df %>%
  ggplot(aes(x=nieuwe_interv_tijdens_opname,
             fill=nieuwe_interv_tijdens_opname)) +
  geom_bar() +
  facet_wrap(~ eersteOperateur) +
  theme_bw()
d15 %>%
  ggplot(aes(x=nieuwe_interv_tijdens_opname,
             fill=nieuwe_interv_tijdens_opname)) +
  geom_bar() +
  facet_wrap(~ ECC) +
  theme_bw()

# perioperative myocardial infarct
summary(df$periop_MI)
sum(df$periop_MI,na.rm=T)/
```

```
  (sum(df$periop_MI, na.rm=T) +
     sum(df$periop_MI==FALSE,na.rm=T))
summary(d15$periop_MI)
sum(d15$periop_MI, na.rm=T)/
  (sum(d15$periop_MI, na.rm=T) +
     sum(d15$periop_MI==FALSE,na.rm=T))
df %>%
  ggplot(aes(x=periop_MI,fill=periop_MI)) +
  geom_bar() +
  facet_wrap(~ eersteOperateur) +
  theme_bw()
d15 %>%
  ggplot(aes(x=periop_MI, fill=periop_MI)) +
  geom_bar() +
  facet_wrap(~ ECC) +
  theme_bw()
```

All complications

```
summary(df$allcomps)
summary(d15$allcomps)
df %>%
  ggplot(aes(x=allcomps)) +
  geom_histogram(binwidth=0.01)
d15 %>%
  ggplot(aes(x=allcomps)) +
  geom_histogram(binwidth=0.01)

# mean is used instead of median, because the median is for most 0
meanac <- df %>%
  group_by(eersteOperateur) %>%
  summarise(mean(allcomps, na.rm=T))
meanac %>%
  ggplot(aes(x=eersteOperateur,y=`mean(allcomps, na.rm = T)`)) +
  geom_col()
meanac <- d15 %>%
  group_by(eersteOperateur,ECC) %>%
  summarise(mean(allcomps,na.rm=T))
meanac %>%
  ggplot(aes(x=ECC,y=`mean(allcomps, na.rm = T)`,fill=ECC)) +
  geom_col() +
  facet_wrap(~eersteOperateur)

df %>%
  ggplot(aes(x=eersteOperateur,y=allcomps)) +
  geom_boxplot()

d15 %>%
  ggplot(aes(x=eersteOperateur,y=allcomps, fill = ECC)) +
  geom_boxplot()

# herfixatie
summary(df$herfixatie_30d)
sum(df$herfixatie_30d,na.rm=T)/
  (sum(df$herfixatie_30d, na.rm=T) +
```

```
     sum(df$herfixatie_30d==FALSE,na.rm=T))
summary(d15$herfixatie_30d)
sum(d15$herfixatie_30d, na.rm=T)/
  (sum(d15$herfixatie_30d, na.rm=T) +
     sum(d15$herfixatie_30d==FALSE,na.rm=T))

# rethoracotomie
summary(df$rethorac_30d)
sum(df$rethorac_30d,na.rm=T)/
  (sum(df$rethorac_30d, na.rm=T) +
     sum(df$rethorac_30d==FALSE,na.rm=T))
summary(d15$rethorac_30d)
sum(d15$rethorac_30d, na.rm=T)/
  (sum(d15$rethorac_30d, na.rm=T) +
     sum(d15$rethorac_30d==FALSE,na.rm=T))

# ritmeprobleem
summary(df$ritmeprobleem)
sum(df$ritmeprobleem,na.rm=T)/
  (sum(df$ritmeprobleem, na.rm=T) +
     sum(df$ritmeprobleem==FALSE,na.rm=T))
summary(d15$ritmeprobleem)
sum(d15$ritmeprobleem, na.rm=T)/
  (sum(d15$ritmeprobleem, na.rm=T) +
     sum(d15$ritmeprobleem==FALSE,na.rm=T))
df %>%
  ggplot(aes(x=ritmeprobleem,fill=ritmeprobleem)) +
  geom_bar() +
  facet_wrap(~ eersteOperateur) +
  theme_bw()
d15 %>%
  ggplot(aes(x=ritmeprobleem, fill=ritmeprobleem)) +
  geom_bar() +
  facet_wrap(~ ECC) +
  theme_bw()

# vascular complication
summary(df$vasc_compl_opname)
sum(df$vasc_compl_opname,na.rm=T)/
  (sum(df$vasc_compl_opname, na.rm=T) +
     sum(df$vasc_compl_opname==FALSE,na.rm=T))
summary(d15$vasc_compl_opname)
sum(d15$vasc_compl_opname, na.rm=T)/
  (sum(d15$vasc_compl_opname, na.rm=T) +
     sum(d15$vasc_compl_opname==FALSE,na.rm=T))

# gastrointestinale complicatie tijdens opname
summary(df$gastroint_compl)
sum(df$gastroint_compl,na.rm=T)/
  (sum(df$gastroint_compl, na.rm=T) +
     sum(df$gastroint_compl==FALSE,na.rm=T))
summary(d15$gastroint_compl)
sum(d15$gastroint_compl, na.rm=T)/
  (sum(d15$gastroint_compl, na.rm=T) +
```

```
     sum(d15$gastroint_compl==FALSE,na.rm=T))

# cerebrovascular accident without residual damage
summary(df$CVA_zonder_restletsel)
sum(df$CVA_zonder_restletsel,na.rm=T)/
  (sum(df$CVA_zonder_restletsel, na.rm=T) +
     sum(df$CVA_zonder_restletsel==FALSE,na.rm=T))
summary(d15$CVA_zonder_restletsel)
sum(d15$CVA_zonder_restletsel, na.rm=T)/
  (sum(d15$CVA_zonder_restletsel, na.rm=T) +
     sum(d15$CVA_zonder_restletsel==FALSE,na.rm=T))

# heropname IC
summary(df$heropname_IC)
sum(df$heropname_IC,na.rm=T)/
  (sum(df$heropname_IC, na.rm=T) +
     sum(df$heropname_IC==FALSE,na.rm=T))
summary(d15$heropname_IC)
sum(d15$heropname_IC, na.rm=T)/
  (sum(d15$heropname_IC, na.rm=T) +
     sum(d15$heropname_IC==FALSE,na.rm=T))

# beademing
summary(df$beademing)
sum(df$beademing,na.rm=T)/
  (sum(df$beademing, na.rm=T) +
     sum(df$beademing==FALSE,na.rm=T))
summary(d15$beademing)
sum(d15$beademing, na.rm=T)/
  (sum(d15$beademing, na.rm=T) +
     sum(d15$beademing==FALSE,na.rm=T))

# respiratory insufficiency
summary(df$resp_insuff)
sum(df$resp_insuff,na.rm=T)/
  (sum(df$resp_insuff, na.rm=T) +
     sum(df$resp_insuff==FALSE,na.rm=T))
summary(d15$resp_insuff)
sum(d15$resp_insuff, na.rm=T)/
  (sum(d15$resp_insuff, na.rm=T) +
     sum(d15$resp_insuff==FALSE,na.rm=T))

# lung infection
summary(df$longinfectie)
sum(df$longinfectie,na.rm=T)/
  (sum(df$longinfectie, na.rm=T) +
     sum(df$longinfectie==FALSE,na.rm=T))
summary(d15$longinfectie)
sum(d15$longinfectie, na.rm=T)/
  (sum(d15$longinfectie, na.rm=T) +
     sum(d15$longinfectie==FALSE,na.rm=T))

# arm or leg wound
summary(df$arm_beenwond)
```

```
sum(df$arm_beenwond,na.rm=T)/
  (sum(df$arm_beenwond, na.rm=T) +
     sum(df$arm_beenwond==FALSE,na.rm=T))
summary(d15$arm_beenwond)
sum(d15$arm_beenwond, na.rm=T)/
  (sum(d15$arm_beenwond, na.rm=T) +
     sum(d15$arm_beenwond==FALSE,na.rm=T))
```

Length of stay (opnameduur)

```
summary(df$XXXopnameduur)
summary(d15$XXXopnameduur)
df %>%
  ggplot(aes(x=XXXopnameduur)) +
  geom_histogram(binwidth=1) +
  coord_cartesian(xlim=c(0,150))
d15 %>%
  ggplot(aes(x=XXXopnameduur)) +
  geom_histogram(binwidth=1) +
  coord_cartesian(xlim=c(0,150))

medianopnd <- df %>%
  group_by(eersteOperateur) %>%
  summarise(median(XXXopnameduur, na.rm=T))
medianopnd %>%
  ggplot(aes(x=eersteOperateur,y=`median(XXXopnameduur, na.rm = T)`)) +
  geom_col()
medianECCopnd <- d15 %>%
  group_by(eersteOperateur,ECC) %>%
  summarise(median(XXXopnameduur,na.rm=T))
medianECCopnd %>%
  ggplot(aes(x=ECC,y=`median(XXXopnameduur, na.rm = T)`,fill=ECC)) +
  geom_col() +
  facet_wrap(~eersteOperateur)

df %>%
  ggplot(aes(x=eersteOperateur,y=XXXopnameduur)) +
  geom_boxplot() +
  coord_cartesian(ylim = c(0,100))

d15 %>%
  ggplot(aes(x=eersteOperateur,y=XXXopnameduur, fill = ECC)) +
  geom_boxplot() +
  coord_cartesian(ylim = c(0,100))
```

60-day mortality

```
summary(df$mort60d)
sum(df$mort60d,na.rm=T)/
  (sum(df$mort60d, na.rm=T) +
     sum(df$mort60d==FALSE,na.rm=T))
summary(d15$mort60d)
sum(d15$mort60d)/
  (sum(d15$mort60d) +
     sum(d15$mort60d==FALSE))
```

```
df %>%
  ggplot(aes(x=mort60d,fill=mort60d)) +
  geom_bar() +
  facet_wrap(~ eersteOperateur) +
  theme_bw()
d15 %>%
  ggplot(aes(x=mort60d, fill=mort60d)) +
  geom_bar() +
  facet_wrap(~ ECC) +
  theme_bw()
```

Conversion from off-pump to on-pump

```
summary(df$conversie)
sum(df$conversie,na.rm=T)/
  (sum(df$conversie, na.rm=T) +
     sum(df$conversie==FALSE,na.rm=T))
summary(d15$conversie)
sum(d15$conversie, na.rm=T)/
  (sum(d15$conversie, na.rm=T) +
     sum(d15$conversie==FALSE,na.rm=T))
df %>%
  ggplot(aes(x=conversie,fill=conversie)) +
  geom_bar() +
  facet_wrap(~ eersteOperateur) +
  theme_bw()
d15 %>%
  ggplot(aes(x=conversie, fill=conversie)) +
  geom_bar() +
  facet_wrap(~ ECC) +
  theme_bw()
```

Correlations

```
d15 %>%
  select(operatieduur, laagste_druk_syst, textbout, allcomps,
         XXXopnameduur, conversie, expECC, CABGexp15, euroI,
         euroII, BMI, totalgrafts) %>%
  cor( use = "pairwise.complete.obs")
d15 %>%
  select(operatieduur, laagste_druk_syst, textbout, allcomps,
         XXXopnameduur, conversie, expECC, euroI, euroII, BMI,
         totalgrafts) %>%
  cor( use = "pairwise.complete.obs") %>%
  melt() %>%
  ggplot(aes(x=Var1,y=Var2,fill=value)) +
  geom_tile() +
  scale_fill_gradient2(low='red',mid='white',high='blue',
                       limit=c(-1,1), midpoint=0,
                       name="Pearson/ncorrelation") +
  theme_bw()
```

experience plots

```
d15 %>%
  filter(ECC == F,
```

```
         eersteOperateur != 355 &
           eersteOperateur != 759) %>%
  ggplot(aes(y = laagste_druk_syst, x = expECC,
             colour = eersteOperateur)) +
  geom_smooth(se = F) +
  geom_point(alpha = 0.4, size = 0.2) +
  theme(axis.text.x=element_blank(),
        legend.position = "none") +
  facet_wrap(eersteOperateur ~ .,
             scales = "free",
             ncol = 1)
d15 %>%
  filter(ECC == F,
         eersteOperateur != 355 &
           eersteOperateur != 759) %>%
  ggplot(aes(y = operatieduur, x = expECC, colour = eersteOperateur)) +
  geom_smooth(se = F) +
  geom_point(alpha = 0.4, size = 0.2) +
  theme(axis.text.x=element_blank(),
        legend.position = "none") +
  facet_wrap(eersteOperateur ~ .,
             scales = "free",
             ncol = 1)

d15 %>%
  filter(ECC == F,
         eersteOperateur != 355 &
           eersteOperateur != 759) %>%
  ggplot(aes(y = allcomps, x = expECC, colour = eersteOperateur)) +
  geom_smooth(se = F) +
  geom_point(alpha = 0.4, size = 0.2) +
  theme(axis.text.x=element_blank(),
        legend.position = "none") +
  facet_wrap(eersteOperateur ~ .,
             scales = "free",
             ncol = 1)

d15 %>%
  filter(ECC == F,
         eersteOperateur != 355 &
           eersteOperateur != 759) %>%
  ggplot(aes(y = euroII, x = expECC, colour = eersteOperateur)) +
  geom_smooth(se = F) +
  geom_point(alpha = 0.4, size = 0.2) +
  theme(axis.text.x=element_blank(),
        legend.position = "none") +
  facet_wrap(eersteOperateur ~ .,
             scales = "free",
             ncol = 1)

ep2 <- d15 %>%
  filter(ECC == F) %>%
  ggplot(aes(y = operatieduur, x = interv_datum, colour = eersteOperateur)
) +
```

```
  geom_smooth(se = F) +
  geom_point(alpha = 0.4, size = 0.2) +
  theme(axis.text.x=element_blank(),
        legend.position = "none")

ep3 <- d15 %>%
  filter(ECC == F) %>%
  ggplot(aes(y = allcomps, x = interv_datum, colour = eersteOperateur)) +
  geom_smooth(se = F) +
  geom_point(alpha = 0.4, size = 0.2) +
  theme(axis.text.x=element_blank(),
        legend.position = "none")

grid.arrange(ep2,ep3)
```

###CUSUM

```
#for CUSUM euroscore minus 30-day mortality
d15 <- d15 %>%
  rowwise() %>%
  mutate(euroIminmort = diff(c(mort30d, euroI/100)),
                                  euroIIminmort = diff(c(mort30d, euroII/1
00)))
df <- df %>%
  rowwise() %>%
  mutate(cusvalueI = diff(c(mort30d, euroI/100)),
                                  cusvalueII = diff(c(mort30d, euroII/100)
))
#CUSUM value for whole hospital (NA's are +0)
d15$cusumIhospital <- cumsum(replace_na(d15$euroIminmort,0))
d15$cusumIIhospital <- cumsum(replace_na(d15$euroIIminmort, 0))
df$cusIhospital <- cumsum(replace_na(df$cusvalueI,0))
df$cusIIhospital <- cumsum(replace_na(df$cusvalueII, 0))

#visualisation hospital wide cusum: what happened to change the trend so m
uch for euroscoreII?
p1 <- d15 %>%
  ggplot(aes(x= expECC,y=cusumIhospital)) +
  geom_line()
p2 <- d15 %>%
  ggplot(aes(x= expECC,y=cusumIIhospital)) +
  geom_line()
grid.arrange(p1,p2)

d15 <- d15 %>%
  group_by(eersteOperateur, ECC) %>%
  mutate(cusumIIsurgeon = cumsum(replace_na(euroIIminmort,0))) %>%
  ungroup()

d15 %>%
  filter(ECC==F) %>%
  ggplot(aes(x= expECC,y=cusumIIsurgeon,col=eersteOperateur)) +
  geom_line(show.legend=F) +
  theme_bw()
```

```
p3 <- d15 %>%
  filter(ECC==FALSE,
           eersteOperateur != 293 &
           eersteOperateur != 308 &
           eersteOperateur != 355 &
           eersteOperateur != 864 &
           eersteOperateur != 891 &
           eersteOperateur != 759) %>%
  ggplot(aes(x= expECC,y=cusumIIsurgeon)) +
  geom_line() +
  theme(axis.text.x = element_blank()) +
  facet_wrap(. ~ eersteOperateur, nrow = 1)
p4 <- d15 %>%
  filter(ECC==FALSE,
           eersteOperateur != 293 &
           eersteOperateur != 308 &
           eersteOperateur != 355 &
           eersteOperateur != 864 &
           eersteOperateur != 891 &
           eersteOperateur != 759,
         tweedeOperateur == "OACV") %>%
  ggplot(aes(x= expECC,y=cusumIIsurgeon)) +
  geom_line() +
  theme(axis.text.x = element_blank()) +
  facet_wrap(. ~ eersteOperateur, nrow = 1)
grid.arrange(p3, p4, nrow = 2)
```

###CUSUM OACV

```
#for CUSUM euroscore minus 30-day mortality
dOACV <- dOACV %>% rowwise() %>% mutate(euroIIminmort = diff(c(mort30d, eu
roII/100)))
#CUSUM value for whole hospital (NA's are +0)
dOACV$cusumIIhospital <- cumsum(replace_na(dOACV$euroIIminmort, 0))


p01 <- dOACV %>%
  ggplot(aes(x= expECC,y=cusumIIhospital)) +
  geom_line()
p01

#CUSUM per surgeon (NA's are +0)
dOACV <- dOACV %>%
  group_by(eersteOperateur, ECC) %>%
  mutate(cusumIIsurgeon = cumsum(replace_na(euroIIminmort,0))) %>%
  ungroup()
#visualise surgeon CUSUM
p02 <- dOACV %>%
  ggplot(aes(x= expECC,y=cusumIIsurgeon,col=eersteOperateur)) +
  theme(axis.text.x=element_blank()) +
  geom_line(show.legend=F) +
  facet_wrap(~ ECC) +
```

```
  theme_bw()
p02
p03 <- dOACV %>%
  filter(eersteOperateur != 293 &
           eersteOperateur != 308 &
           eersteOperateur != 864 &
           eersteOperateur != 873 &
           eersteOperateur != 888) %>%
  ggplot(aes(x= CABGexp15,y=cusumIIsurgeon, col=ECC)) +
  theme(axis.text.x=element_blank()) +
  geom_line() +
  facet_wrap(eersteOperateur ~ ECC)
p03
```

Outcome histograms

```
hg1 <- d15 %>%
    filter(ECC == F) %>%
    ggplot(aes(laagste_druk_syst)) +
  geom_histogram()
hg2 <- d15 %>%
    filter(ECC == F) %>%
    ggplot(aes(operatieduur)) +
  geom_histogram(binwidth = 5) +
  coord_cartesian(xlim = c(0,450))
hg3 <- d15 %>%
    filter(ECC == F) %>%
    ggplot(aes(allcomps)) +
  geom_histogram(binwidth = 0.01)
hg4 <- d15 %>%
    filter(ECC == F) %>%
    ggplot(aes(XXXopnameduur)) +
  geom_histogram(binwidth = 1) +
  coord_cartesian(xlim=c(0,100))
hg5 <- d15 %>%
    filter(ECC == F) %>%
    ggplot(aes(MACCE)) + geom_bar()
hg6 <- d15 %>%
    filter(ECC == F) %>%
    ggplot(aes(textbout)) +
  geom_histogram() +
  coord_cartesian(ylim=c(0,100))
hg7 <- d15 %>%
    filter(ECC == F) %>%
    ggplot(aes(mort30d)) +
  geom_bar()
hg8 <- d15 %>%
    filter(ECC == F) %>%
    ggplot(aes(mort60d)) +
  geom_bar()
hg9 <- d15 %>%
    filter(ECC == F) %>%
    ggplot(aes(mort120d)) +
  geom_bar()
```

```
hg10 <- d15 %>%
    filter(ECC == F) %>%
    ggplot(aes(mort1j)) +
  geom_bar()

grid.arrange(hg1,hg2,hg3,hg4,hg5,hg6,hg7,hg8,hg9,hg10, nrow = 5)
```

Model building

blood pressure

```
d15 %>%
  select(laagste_druk_syst, expECC, euroI, euroII, BMI,
         totalgrafts, ven_graft, art_graft, ven_anast, art_anast,
         specialisatie) %>%
  cor( use = "pairwise.complete.obs") %>%
  melt() %>%
  ggplot(aes(x=Var1, y=Var2,fill=value, fct_reorder(value))) +
  geom_tile() +
  scale_fill_gradient2(low='red',mid='white',high='blue',
                       limit=c(-1,1), midpoint=0,
                       name="Pearson/ncorrelation") +
  theme_bw()


# a GMM is estimated as reference. Any model that fits worse than that is
useless
M_bp0 <- d15 %>%
  filter(ECC == F) %>%
  brm(laagste_druk_syst ~ 1,
      family = skew_normal,
      data = .)
L_M_bp0 <- loo(M_bp0)

# first round of fittings, the various experience variables are compared,
then specialization is added to the best fitting
M_bp1 <- d15 %>%
  filter(ECC == F) %>%
  brm(laagste_druk_syst ~ 1 + CABGexp04,
      family = skew_normal,
      data = .)
L_M_bp1 <- loo(M_bp1)
M_bp2 <- d15 %>%
  filter(ECC == F) %>%
  brm(laagste_druk_syst ~ 1 + CABGexp15,
      family = skew_normal,
      data = .)
L_M_bp2 <- loo(M_bp2)
M_bp3 <- d15 %>%
  filter(ECC == F) %>%
  brm(laagste_druk_syst ~ 1 + expECC,
      family = skew_normal,
      data = .)
L_M_bp3 <- loo(M_bp3)
M_bp4 <- d15 %>%
```

```
  filter(ECC == F) %>%
  brm(laagste_druk_syst ~ 1 + CABGexp04 + specialisatie,
      family = skew_normal,
      data = .)
L_M_bp4 <- loo(M_bp4)
list(L_M_bp0,
     L_M_bp1,
     L_M_bp2,
     L_M_bp3,
     L_M_bp4) %>%
  compare_IC() #order: 4 1 0 2 3

# add euroscores
M_bp5 <- d15 %>%
  filter(ECC == F) %>%
  brm(laagste_druk_syst ~ 1 + CABGexp04 + specialisatie +
        euroI,
      family = skew_normal,
      cores = 4,
      inits = 0,
      data = .)
L_M_bp5 <- loo(M_bp5)
M_bp6 <- d15 %>%
  filter(ECC == F) %>%
  brm(laagste_druk_syst ~ 1 + CABGexp04 + specialisatie +
        eurolog,
      family = skew_normal,
      cores = 4,
      inits = 0,
      data = .)
L_M_bp6 <- loo(M_bp6)
M_bp7 <- d15 %>%
  filter(ECC == F) %>%
  brm(laagste_druk_syst ~ 1 + CABGexp04 + specialisatie +
        euroII,
      family = skew_normal,
      cores = 4,
      inits = 0,
      data = .)
L_M_bp7 <- loo(M_bp7)
list(L_M_bp0,
     L_M_bp4,
     L_M_bp5,
     L_M_bp6,
     L_M_bp7) %>%
  compare_IC() #order: 6, 5, 7, 4, 0

# add individual euroscore variables
M_bp8 <- d15 %>%
  filter(ECC == F) %>%
  brm(laagste_druk_syst ~ 1 + CABGexp04 + specialisatie +
        eurolog + leeftijd,
      family = skew_normal,
      cores = 4,
```

```
      inits = 0,
      data = .)
L_M_bp8 <- loo(M_bp8)
M_bp9 <- d15 %>%
  filter(ECC == F) %>%
  brm(laagste_druk_syst ~ 1 + CABGexp04 + specialisatie +
        eurolog + geslacht,
      family = skew_normal,
      cores = 4,
      inits = 0,
      data = .)
L_M_bp9 <- loo(M_bp9)
M_bp10 <- d15 %>%
  filter(ECC == F) %>%
  brm(laagste_druk_syst ~ 1 + CABGexp04 + specialisatie +
        eurolog + chron_longziekte,
      family = skew_normal,
      cores = 4,
      inits = 0,
      data = .)
L_M_bp10 <- loo(M_bp10)
M_bp11 <- d15 %>%
  filter(ECC == F) %>%
  brm(laagste_druk_syst ~ 1 + CABGexp04 + specialisatie +
        eurolog + art_vaatpathologie,
      family = skew_normal,
      cores = 4,
      inits = 0,
      data = .)
L_M_bp11 <- loo(M_bp11)
M_bp12 <- d15 %>%
  filter(ECC == F) %>%
  brm(laagste_druk_syst ~ 1 + CABGexp04 + specialisatie +
        eurolog + neuro_disfunctie,
      family = skew_normal,
      cores = 4,
      inits = 0,
      data = .)
L_M_bp12 <- loo(M_bp12)
M_bp13 <- d15 %>%
  filter(ECC == F) %>%
  brm(laagste_druk_syst ~ 1 + CABGexp04 + specialisatie +
        eurolog + cardiochir_eerder,
      family = skew_normal,
      cores = 4,
      inits = 0,
      data = .)
L_M_bp13 <- loo(M_bp13)
M_bp14 <- d15 %>%
  filter(ECC == F) %>%
  brm(laagste_druk_syst ~ 1 + CABGexp04 + specialisatie +
        eurolog + kreatinine_gehalte,
      family = skew_normal,
      cores = 4,
```

```
      inits = 0,
      data = .)
L_M_bp14 <- loo(M_bp14)
M_bp15 <- d15 %>%
  filter(ECC == F) %>%
  brm(laagste_druk_syst ~ 1 + CABGexp04 + specialisatie +
        eurolog + endocarditis,
      family = skew_normal,
      cores = 4,
      inits = 0,
      data = .)
L_M_bp15 <- loo(M_bp15)
M_bp16 <- d15 %>%
  filter(ECC == F) %>%
  brm(laagste_druk_syst ~ 1 + CABGexp04 + specialisatie +
        eurolog + krit_preop_toestand,
      family = skew_normal,
      cores = 4,
      inits = 0,
      data = .)
L_M_bp16 <- loo(M_bp16)
M_bp17 <- d15 %>%
  filter(ECC == F) %>%
  brm(laagste_druk_syst ~ 1 + CABGexp04 + specialisatie +
        eurolog + instabiele_AP,
      family = skew_normal,
      cores = 4,
      inits = 0,
      data = .)
L_M_bp17 <- loo(M_bp17)
M_bp18 <- d15 %>%
  filter(ECC == F) %>%
  brm(laagste_druk_syst ~ 1 + CABGexp04 + specialisatie +
        eurolog + LVEF,
      family = skew_normal,
      cores = 4,
      inits = 0,
      data = .)
L_M_bp18 <- loo(M_bp18)
M_bp19 <- d15 %>%
  filter(ECC == F) %>%
  brm(laagste_druk_syst ~ 1 + CABGexp04 + specialisatie +
        eurolog + recent_MI,
      family = skew_normal,
      cores = 4,
      inits = 0,
      data = .)
L_M_bp19 <- loo(M_bp19)
M_bp20 <- d15 %>%
  filter(ECC == F) %>%
  brm(laagste_druk_syst ~ 1 + CABGexp04 + specialisatie +
        eurolog + PA_druk,
      family = skew_normal,
      cores = 4,
```

```
      inits = 0,
      data = .)
L_M_bp20 <- loo(M_bp20)
M_bp21 <- d15 %>%
  filter(ECC == F) %>%
  brm(laagste_druk_syst ~ 1 + CABGexp04 + specialisatie +
        eurolog + thorac_aortachir,
      family = skew_normal,
      cores = 4,
      inits = 0,
      data = .)
L_M_bp21 <- loo(M_bp21)
M_bp22 <- d15 %>%
  filter(ECC == F) %>%
  brm(laagste_druk_syst ~ 1 + CABGexp04 + specialisatie +
        eurolog + postinfarct_VSR,
      family = skew_normal,
      cores = 4,
      inits = 0,
      data = .)
L_M_bp22 <- loo(M_bp22)
M_bp23 <- d15 %>%
  filter(ECC == F) %>%
  brm(laagste_druk_syst ~ 1 + CABGexp04 + specialisatie +
        eurolog + NYHA,
      family = skew_normal,
      cores = 4,
      inits = 0,
      data = .)
L_M_bp23 <- loo(M_bp23)
M_bp24 <- d15 %>%
  filter(ECC == F) %>%
  brm(laagste_druk_syst ~ 1 + CABGexp04 + specialisatie +
        eurolog + CCS_IV,
      family = skew_normal,
      cores = 4,
      inits = 0,
      data = .)
L_M_bp24 <- loo(M_bp24)
M_bp25 <- d15 %>%
  filter(ECC == F) %>%
  brm(laagste_druk_syst ~ 1 + CABGexp04 + specialisatie +
        eurolog + diabetes,
      family = skew_normal,
      cores = 4,
      inits = 0,
      data = .)
L_M_bp25 <- loo(M_bp25)
M_bp26 <- d15 %>%
  filter(ECC == F) %>%
  brm(laagste_druk_syst ~ 1 + CABGexp04 + specialisatie +
        eurolog + slechte_mob,
      family = skew_normal,
      cores = 4,
```

```
      inits = 0,
      data = .)
L_M_bp26 <- loo(M_bp26)
M_bp27 <- d15 %>%
  filter(ECC == F) %>%
  brm(laagste_druk_syst ~ 1 + CABGexp04 + specialisatie +
        eurolog + dialyse,
      family = skew_normal,
      cores = 4,
      inits = 0,
      data = .)
L_M_bp27 <- loo(M_bp27)
M_bp28 <- d15 %>%
  filter(ECC == F) %>%
  brm(laagste_druk_syst ~ 1 + CABGexp04 + specialisatie +
        eurolog + urgentie,
      family = skew_normal,
      cores = 4,
      inits = 0,
      data = .)
L_M_bp28 <- loo(M_bp28)
list(L_M_bp0,
     L_M_bp6,
     L_M_bp8,
     L_M_bp9,
     L_M_bp10,
     L_M_bp11,
     L_M_bp12,
     L_M_bp13,
     L_M_bp14,
     L_M_bp15,
     L_M_bp16,
     L_M_bp17,
     L_M_bp18,
     L_M_bp19,
     L_M_bp20,
     L_M_bp21,
     L_M_bp22,
     L_M_bp23,
     L_M_bp24,
     L_M_bp25,
     L_M_bp26,
     L_M_bp27,
     L_M_bp28) %>%
  compare_IC() #order: 13, 9, 8, 12, 15, 22, 21, 6, 26, 28, 25, 14, 16, 11
, 20, 17, 19, 10, 27, 24, 18, 23, 0

# multiple single risk factors contributing to the problem? tested are tho
se that added something to the previously best fitting model
M_bp29 <- d15 %>%
  filter(ECC == F) %>%
  brm(laagste_druk_syst ~ 1 + CABGexp04 + specialisatie +
        eurolog + cardiochir_eerder + geslacht,
      family = skew_normal,
```

```
      cores = 4,
      inits = 0,
      data = .)
L_M_bp29 <- loo(M_bp29)
M_bp30 <- d15 %>%
  filter(ECC == F) %>%
  brm(laagste_druk_syst ~ 1 + CABGexp04 + specialisatie +
        eurolog + cardiochir_eerder + geslacht + leeftijd,
      family = skew_normal,
      cores = 4,
      inits = 0,
      data = .)
L_M_bp30 <- loo(M_bp30)
M_bp31 <- d15 %>%
  filter(ECC == F) %>%
  brm(laagste_druk_syst ~ 1 + CABGexp04 + specialisatie +
        eurolog + cardiochir_eerder + geslacht + leeftijd +
        neuro_disfunctie,
      family = skew_normal,
      cores = 4,
      inits = 0,
      data = .)
L_M_bp31 <- loo(M_bp31)
M_bp32 <- d15 %>%
  filter(ECC == F) %>%
  brm(laagste_druk_syst ~ 1 + CABGexp04 + specialisatie +
        eurolog + cardiochir_eerder + geslacht + leeftijd +
        neuro_disfunctie + postinfarct_VSR,
      family = skew_normal,
      cores = 4,
      inits = 0,
      data = .)
L_M_bp32 <- loo(M_bp32)
M_bp33 <- d15 %>%
  filter(ECC == F) %>%
  brm(laagste_druk_syst ~ 1 + CABGexp04 + specialisatie +
        eurolog + cardiochir_eerder + geslacht + leeftijd +
        neuro_disfunctie + postinfarct_VSR + thorac_aortachir,
      family = skew_normal,
      cores = 4,
      inits = 0,
      data = .)
L_M_bp33 <- loo(M_bp33)
list(L_M_bp0,
     L_M_bp13,
     L_M_bp29,
     L_M_bp30,
     L_M_bp31,
     L_M_bp32,
     L_M_bp33) %>%
  compare_IC() #order: 33, 32, 31, 30, 29, 13, 0

#add non-euroscore patient characteristics
M_bp34 <- d15 %>%
```

```
  filter(ECC == F) %>%
  brm(laagste_druk_syst ~ 1 + CABGexp04 + specialisatie +
        eurolog + cardiochir_eerder + geslacht + leeftijd +
        neuro_disfunctie + postinfarct_VSR + thorac_aortachir +
        nierfalen,
      family = skew_normal,
      cores = 4,
      inits = 0,
      data = .)
L_M_bp34 <- loo(M_bp34)
M_bp35 <- d15 %>%
  filter(ECC == F) %>%
  brm(laagste_druk_syst ~ 1 + CABGexp04 + specialisatie +
        eurolog + cardiochir_eerder + geslacht + leeftijd +
        neuro_disfunctie + postinfarct_VSR + thorac_aortachir +
        lengte,
      family = skew_normal,
      cores = 4,
      inits = 0,
      data = .)
L_M_bp35 <- loo(M_bp35)
M_bp36 <- d15 %>%
  filter(ECC == F) %>%
  brm(laagste_druk_syst ~ 1 + CABGexp04 + specialisatie +
        eurolog + cardiochir_eerder + geslacht + leeftijd +
        neuro_disfunctie + postinfarct_VSR + thorac_aortachir +
        gewicht,
      family = skew_normal,
      cores = 4,
      inits = 0,
      data = .)
L_M_bp36 <- loo(M_bp36)
M_bp37 <- d15 %>%
  filter(ECC == F) %>%
  brm(laagste_druk_syst ~ 1 + CABGexp04 + specialisatie +
        eurolog + cardiochir_eerder + geslacht + leeftijd +
        neuro_disfunctie + postinfarct_VSR + thorac_aortachir +
        BMI,
      family = skew_normal,
      cores = 4,
      inits = 0,
      data = .)
L_M_bp37 <- loo(M_bp37)
M_bp38 <- d15 %>%
  filter(ECC == F) %>%
  brm(laagste_druk_syst ~ 1 + CABGexp04 + specialisatie +
        eurolog + cardiochir_eerder + geslacht + leeftijd +
        neuro_disfunctie + postinfarct_VSR + thorac_aortachir +
        CVA_eerder,
      family = skew_normal,
      cores = 4,
      inits = 0,
      data = .)
L_M_bp38 <- loo(M_bp38)
```

```
M_bp39 <- d15 %>%
  filter(ECC == F) %>%
  brm(laagste_druk_syst ~ 1 + CABGexp04 + specialisatie +
        eurolog + cardiochir_eerder + geslacht + leeftijd +
        neuro_disfunctie + postinfarct_VSR + thorac_aortachir +
        multiv,
      family = skew_normal,
      cores = 4,
      inits = 0,
      data = .)
L_M_bp39 <- loo(M_bp39)
M_bp40 <- d15 %>%
  filter(ECC == F) %>%
  brm(laagste_druk_syst ~ 1 + CABGexp04 + specialisatie +
        eurolog + cardiochir_eerder + geslacht + leeftijd +
        neuro_disfunctie + postinfarct_VSR + thorac_aortachir +
        AF,
      family = skew_normal,
      cores = 4,
      inits = 0,
      data = .)
L_M_bp40 <- loo(M_bp40)
M_bp41 <- d15 %>%
  filter(ECC == F) %>%
  brm(laagste_druk_syst ~ 1 + CABGexp04 + specialisatie +
        eurolog + cardiochir_eerder + geslacht + leeftijd +
        neuro_disfunctie + postinfarct_VSR + thorac_aortachir +
        coronairchir_overig,
      family = skew_normal,
      cores = 4,
      inits = 0,
      data = .)
L_M_bp41 <- loo(M_bp41)
M_bp42 <- d15 %>%
  filter(ECC == F) %>%
  brm(laagste_druk_syst ~ 1 + CABGexp04 + specialisatie +
        eurolog + cardiochir_eerder + geslacht + leeftijd +
        neuro_disfunctie + postinfarct_VSR + thorac_aortachir +
        roker,
      family = skew_normal,
      cores = 4,
      inits = 0,
      data = .)
L_M_bp42 <- loo(M_bp42)
M_bp43 <- d15 %>%
  filter(ECC == F) %>%
  brm(laagste_druk_syst ~ 1 + CABGexp04 + specialisatie +
        eurolog + cardiochir_eerder + geslacht + leeftijd +
        neuro_disfunctie + postinfarct_VSR + thorac_aortachir +
        rooktnu,
      family = skew_normal,
      cores = 4,
      inits = 0,
      data = .)
```

```
L_M_bp43 <- loo(M_bp43)
list(L_M_bp0,
     L_M_bp33,
     L_M_bp34,
     L_M_bp35,
     L_M_bp36,
     L_M_bp37,
     L_M_bp38,
     L_M_bp39,
     L_M_bp40,
     L_M_bp41,
     L_M_bp42,
     L_M_bp43) %>%
  compare_IC() #order: 37, 36, 35, 39, 38, 33, 34, 43, 40, 42, 41, 0

# BMI and its components were best fitting, various combinations are compa
red
M_bp44 <- d15 %>%
  filter(ECC == F) %>%
  brm(laagste_druk_syst ~ 1 + CABGexp04 + specialisatie +
        eurolog + cardiochir_eerder + geslacht + leeftijd +
        neuro_disfunctie + postinfarct_VSR + thorac_aortachir +
        BMI + gewicht,
      family = skew_normal,
      cores = 4,
      inits = 0,
      data = .)
L_M_bp44 <- loo(M_bp44)
M_bp45 <- d15 %>%
  filter(ECC == F) %>%
  brm(laagste_druk_syst ~ 1 + CABGexp04 + specialisatie +
        eurolog + cardiochir_eerder + geslacht + leeftijd +
        neuro_disfunctie + postinfarct_VSR + thorac_aortachir +
        BMI + lengte,
      family = skew_normal,
      cores = 4,
      inits = 0,
      data = .)
L_M_bp45 <- loo(M_bp45)
M_bp46 <- d15 %>%
  filter(ECC == F) %>%
  brm(laagste_druk_syst ~ 1 + CABGexp04 + specialisatie +
        eurolog + cardiochir_eerder + geslacht + leeftijd +
        neuro_disfunctie + postinfarct_VSR + thorac_aortachir +
        BMI + lengte + gewicht,
      family = skew_normal,
      cores = 4,
      inits = 0,
      data = .)
L_M_bp46 <- loo(M_bp46)
list(L_M_bp0,
     L_M_bp33,
     L_M_bp44,
     L_M_bp45,
```

```
     L_M_bp46) %>%
  compare_IC() #order: 45, 44, 46, 33, 0

#other non-euroscore patient characteristics that increased the fit are ad
ded
M_bp47 <- d15 %>%
  filter(ECC == F) %>%
  brm(laagste_druk_syst ~ 1 + CABGexp04 + specialisatie +
        eurolog + cardiochir_eerder + geslacht + leeftijd +
        neuro_disfunctie + postinfarct_VSR + thorac_aortachir +
        BMI + lengte + multiv,
      family = skew_normal,
      cores = 4,
      inits = 0,
      data = .)
L_M_bp47 <- loo(M_bp47)
M_bp48 <- d15 %>%
  filter(ECC == F) %>%
  brm(laagste_druk_syst ~ 1 + CABGexp04 + specialisatie +
        eurolog + cardiochir_eerder + geslacht + leeftijd +
        neuro_disfunctie + postinfarct_VSR + thorac_aortachir +
        BMI + lengte + multiv + CVA_eerder,
      family = skew_normal,
      cores = 4,
      inits = 0,
      data = .)
L_M_bp48 <- loo(M_bp48)
list(L_M_bp0,
     L_M_bp33,
     L_M_bp45,
     L_M_bp47,
     L_M_bp48) %>%
  compare_IC() #order: 47, 48, 45, 33, 0

# add individual case variables
M_bp49 <- d15 %>%
  filter(ECC == F) %>%
  brm(laagste_druk_syst ~ 1 + CABGexp04 + specialisatie +
        eurolog + cardiochir_eerder + geslacht + leeftijd +
        neuro_disfunctie + postinfarct_VSR + thorac_aortachir +
        BMI + lengte + multiv + CVA_eerder +
        interv_datum,
      family = skew_normal,
      cores = 4,
      inits = 0,
      data = .)
L_M_bp49 <- loo(M_bp49)
M_bp50 <- d15 %>%
  filter(ECC == F) %>%
  brm(laagste_druk_syst ~ 1 + CABGexp04 + specialisatie +
        eurolog + cardiochir_eerder + geslacht + leeftijd +
        neuro_disfunctie + postinfarct_VSR + thorac_aortachir +
        BMI + lengte + multiv + CVA_eerder +
        start_operatie,
```

```
      family = skew_normal,
      cores = 4,
      inits = 0,
      data = .)
L_M_bp50 <- loo(M_bp50)
M_bp51 <- d15 %>%
  filter(ECC == F) %>%
  brm(laagste_druk_syst ~ 1 + CABGexp04 + specialisatie +
        eurolog + cardiochir_eerder + geslacht + leeftijd +
        neuro_disfunctie + postinfarct_VSR + thorac_aortachir +
        BMI + lengte + multiv + CVA_eerder +
        art_graft,
      family = skew_normal,
      cores = 4,
      inits = 0,
      data = .)
L_M_bp51 <- loo(M_bp51)
M_bp52 <- d15 %>%
  filter(ECC == F) %>%
  brm(laagste_druk_syst ~ 1 + CABGexp04 + specialisatie +
        eurolog + cardiochir_eerder + geslacht + leeftijd +
        neuro_disfunctie + postinfarct_VSR + thorac_aortachir +
        BMI + lengte + multiv + CVA_eerder +
        art_anast,
      family = skew_normal,
      cores = 4,
      inits = 0,
      data = .)
L_M_bp52 <- loo(M_bp52)
M_bp53 <- d15 %>%
  filter(ECC == F) %>%
  brm(laagste_druk_syst ~ 1 + CABGexp04 + specialisatie +
        eurolog + cardiochir_eerder + geslacht + leeftijd +
        neuro_disfunctie + postinfarct_VSR + thorac_aortachir +
        BMI + lengte + multiv + CVA_eerder +
        ven_graft,
      family = skew_normal,
      cores = 4,
      inits = 0,
      data = .)
L_M_bp53 <- loo(M_bp53)
M_bp54 <- d15 %>%
  filter(ECC == F) %>%
  brm(laagste_druk_syst ~ 1 + CABGexp04 + specialisatie +
        eurolog + cardiochir_eerder + geslacht + leeftijd +
        neuro_disfunctie + postinfarct_VSR + thorac_aortachir +
        BMI + lengte + multiv + CVA_eerder +
        ven_anast,
      family = skew_normal,
      cores = 4,
      inits = 0,
      data = .)
L_M_bp54 <- loo(M_bp54)
M_bp55 <- d15 %>%
```

```
  filter(ECC == F) %>%
  brm(laagste_druk_syst ~ 1 + CABGexp04 + specialisatie +
        eurolog + cardiochir_eerder + geslacht + leeftijd +
        neuro_disfunctie + postinfarct_VSR + thorac_aortachir +
        BMI + lengte + multiv + CVA_eerder +
        conversie,
      family = skew_normal,
      cores = 4,
      inits = 0,
      data = .)
L_M_bp55 <- loo(M_bp55)
M_bp56 <- d15 %>%
  filter(ECC == F) %>%
  brm(laagste_druk_syst ~ 1 + CABGexp04 + specialisatie +
        eurolog + cardiochir_eerder + geslacht + leeftijd +
        neuro_disfunctie + postinfarct_VSR + thorac_aortachir +
        BMI + lengte + multiv + CVA_eerder +
        totalgrafts,
      family = skew_normal,
      cores = 4,
      inits = 0,
      data = .)
L_M_bp56 <- loo(M_bp56)
M_bp57 <- d15 %>%
  filter(ECC == F) %>%
  brm(laagste_druk_syst ~ 1 + CABGexp04 + specialisatie +
        eurolog + cardiochir_eerder + geslacht + leeftijd +
        neuro_disfunctie + postinfarct_VSR + thorac_aortachir +
        BMI + lengte + multiv + CVA_eerder +
        voorstellen,
      family = skew_normal,
      cores = 4,
      inits = 0,
      data = .)
L_M_bp57 <- loo(M_bp57)
M_bp58 <- d15 %>%
  filter(ECC == F) %>%
  brm(laagste_druk_syst ~ 1 + CABGexp04 + specialisatie +
        eurolog + cardiochir_eerder + geslacht + leeftijd +
        neuro_disfunctie + postinfarct_VSR + thorac_aortachir +
        BMI + lengte + multiv + CVA_eerder +
        planvsuitg,
      family = skew_normal,
      cores = 4,
      inits = 0,
      data = .)
L_M_bp58 <- loo(M_bp58)
M_bp59 <- d15 %>%
  filter(ECC == F) %>%
  brm(laagste_druk_syst ~ 1 + CABGexp04 + specialisatie +
        eurolog + cardiochir_eerder + geslacht + leeftijd +
        neuro_disfunctie + postinfarct_VSR + thorac_aortachir +
        BMI + lengte + multiv + CVA_eerder +
        artgrdiff,
```

```
      family = skew_normal,
      cores = 4,
      inits = 0,
      data = .)
L_M_bp59 <- loo(M_bp59)
M_bp60 <- d15 %>%
  filter(ECC == F) %>%
  brm(laagste_druk_syst ~ 1 + CABGexp04 + specialisatie +
        eurolog + cardiochir_eerder + geslacht + leeftijd +
        neuro_disfunctie + postinfarct_VSR + thorac_aortachir +
        BMI + lengte + multiv + CVA_eerder +
        vengrdiff,
      family = skew_normal,
      cores = 4,
      inits = 0,
      data = .)
L_M_bp60 <- loo(M_bp60)
list(L_M_bp0,
     L_M_bp47,
     L_M_bp49,
     L_M_bp50,
     L_M_bp51,
     L_M_bp52,
     L_M_bp53,
     L_M_bp54,
     L_M_bp55,
     L_M_bp56,
     L_M_bp57,
     L_M_bp58,
     L_M_bp59,
     L_M_bp60) %>%
  compare_IC() #order: 54, 55, 60, 53, 59, 51, 49, 47, 57, 52, 56, 50, 58,
 0

# combination of venous variables
M_bp61 <- d15 %>%
  filter(ECC == F) %>%
  brm(laagste_druk_syst ~ 1 + CABGexp04 + specialisatie +
        eurolog + cardiochir_eerder + geslacht + leeftijd +
        neuro_disfunctie + postinfarct_VSR + thorac_aortachir +
        BMI + lengte + multiv + CVA_eerder +
        ven_anast + vengrdiff,
      family = skew_normal,
      cores = 4,
      inits = 0,
      data = .)
L_M_bp61 <- loo(M_bp61)
M_bp62 <- d15 %>%
  filter(ECC == F) %>%
  brm(laagste_druk_syst ~ 1 + CABGexp04 + specialisatie +
        eurolog + cardiochir_eerder + geslacht + leeftijd +
        neuro_disfunctie + postinfarct_VSR + thorac_aortachir +
        BMI + lengte + multiv + CVA_eerder +
        ven_anast + ven_graft,
```

```
      family = skew_normal,
      cores = 4,
      inits = 0,
      data = .)
L_M_bp62 <- loo(M_bp62)
M_bp63 <- d15 %>%
  filter(ECC == F) %>%
  brm(laagste_druk_syst ~ 1 + CABGexp04 + specialisatie +
        eurolog + cardiochir_eerder + geslacht + leeftijd +
        neuro_disfunctie + postinfarct_VSR + thorac_aortachir +
        BMI + lengte + multiv + CVA_eerder +
        vengrdiff + ven_graft,
      family = skew_normal,
      cores = 4,
      inits = 0,
      data = .)
L_M_bp63 <- loo(M_bp63)
M_bp64 <- d15 %>%
  filter(ECC == F) %>%
  brm(laagste_druk_syst ~ 1 + CABGexp04 + specialisatie +
        eurolog + cardiochir_eerder + geslacht + leeftijd +
        neuro_disfunctie + postinfarct_VSR + thorac_aortachir +
        BMI + lengte + multiv + CVA_eerder +
        ven_anast + vengrdiff + ven_graft,
      family = skew_normal,
      cores = 4,
      inits = 0,
      data = .)
L_M_bp64 <- loo(M_bp64)
list(L_M_bp0,
     L_M_bp47,
     L_M_bp49,
     L_M_bp53,
     L_M_bp54,
     L_M_bp60,
     L_M_bp61,
     L_M_bp62,
     L_M_bp63,
     L_M_bp64) %>%
  compare_IC() #order: 62, 61, 54, 64, 63, 60, 53, 49, 47, 0



M_bp65 <- d15 %>%
  filter(ECC == F) %>%
  brm(laagste_druk_syst ~ 1 + CABGexp04 + specialisatie +
        eurolog + cardiochir_eerder + geslacht + leeftijd +
        neuro_disfunctie + postinfarct_VSR + thorac_aortachir +
        BMI + lengte + multiv + CVA_eerder +
        ven_anast + ven_graft + artgrdiff + art_graft,
      family = skew_normal,
      cores = 4,
      inits = 0,
      data = .)
```

```
L_M_bp65 <- loo(M_bp65)
M_bp66 <- d15 %>%
  filter(ECC == F) %>%
  brm(laagste_druk_syst ~ 1 + CABGexp04 + specialisatie +
        eurolog + cardiochir_eerder + geslacht + leeftijd +
        neuro_disfunctie + postinfarct_VSR + thorac_aortachir +
        BMI + lengte + multiv + CVA_eerder +
        ven_anast + ven_graft + artgrdiff,
      family = skew_normal,
      cores = 4,
      inits = 0,
      data = .)
L_M_bp66 <- loo(M_bp66)
M_bp67 <- d15 %>%
  filter(ECC == F) %>%
  brm(laagste_druk_syst ~ 1 + CABGexp04 + specialisatie +
        eurolog + cardiochir_eerder + geslacht + leeftijd +
        neuro_disfunctie + postinfarct_VSR + thorac_aortachir +
        BMI + lengte + multiv + CVA_eerder +
        ven_anast + ven_graft + art_graft,
      family = skew_normal,
      cores = 4,
      inits = 0,
      data = .)
L_M_bp67 <- loo(M_bp67)
list(L_M_bp0,
     L_M_bp47,
     L_M_bp51,
     L_M_bp59,
     L_M_bp62,
     L_M_bp65,
     L_M_bp66,
     L_M_bp67) %>%
  compare_IC() #order: 67, 66, 62, 65, 59, 51, 47, 0

M_bp68 <- d15 %>%
  filter(ECC == F) %>%
  brm(laagste_druk_syst ~ 1 + CABGexp04 + specialisatie +
        eurolog + cardiochir_eerder + geslacht + leeftijd +
        neuro_disfunctie + postinfarct_VSR + thorac_aortachir +
        BMI + lengte + multiv + CVA_eerder +
        ven_anast + ven_graft + art_graft + conversie,
      family = skew_normal,
      cores = 4,
      inits = 0,
      data = .)
L_M_bp68 <- loo(M_bp68)
M_bp69 <- d15 %>%
  filter(ECC == F) %>%
  brm(laagste_druk_syst ~ 1 + CABGexp04 + specialisatie +
        eurolog + cardiochir_eerder + geslacht + leeftijd +
        neuro_disfunctie + postinfarct_VSR + thorac_aortachir +
        BMI + lengte + multiv + CVA_eerder +
        ven_anast + ven_graft + art_graft + conversie +
```

```
        interv_datum,
      family = skew_normal,
      cores = 4,
      inits = 0,
      data = .)
L_M_bp69 <- loo(M_bp69)
list(L_M_bp0,
     L_M_bp65,
     L_M_bp68,
     L_M_bp69) %>%
  compare_IC() #order: 68, 69, 65, 0

M_bp70 <- d15 %>%
  filter(ECC == F) %>%
  brm(laagste_druk_syst ~ 1 + CABGexp04 + specialisatie +
        eurolog + cardiochir_eerder + geslacht + leeftijd +
        neuro_disfunctie + postinfarct_VSR + thorac_aortachir +
        BMI + lengte + multiv + CVA_eerder +
        ven_anast + ven_graft + art_graft + conversie +
        (1 | eersteOperateur),
      family = skew_normal,
      cores = 4,
      inits = 0,
      data = .)
L_M_bp70 <- loo(M_bp70)
M_bp71 <- d15 %>%
  filter(ECC == F) %>%
  brm(laagste_druk_syst ~ 1 + CABGexp04 + specialisatie +
        eurolog + cardiochir_eerder + geslacht + leeftijd +
        neuro_disfunctie + postinfarct_VSR + thorac_aortachir +
        BMI + lengte + multiv + CVA_eerder +
        ven_anast + ven_graft + art_graft + conversie +
        (1 + CABGexp04 + specialisatie +
        eurolog + cardiochir_eerder + geslacht + leeftijd +
          neuro_disfunctie + postinfarct_VSR + thorac_aortachir +
        BMI + lengte + multiv + CVA_eerder +
        ven_anast + ven_graft + art_graft + conversie| eersteOperateur),
      family = skew_normal,
      cores = 4,
      inits = 0,
      data = .)
L_M_bp71 <- loo(M_bp71)
list(L_M_bp0,
     L_M_bp68,
     L_M_bp70,
     L_M_bp71) %>%
  compare_IC() #order: 70, 68, 71, 0

M_bp72 <- d15 %>%
  filter(ECC == F) %>%
  brm(laagste_druk_syst ~ 1 + CABGexp04 + specialisatie +
        eurolog + cardiochir_eerder + geslacht + leeftijd +
        neuro_disfunctie + postinfarct_VSR + thorac_aortachir +
        BMI + lengte + multiv + CVA_eerder +
```

```
        ven_anast + ven_graft + art_graft + conversie +
        (1 | eersteOperateur) +
        (1 | XXXpat),
      family = skew_normal,
      cores = 4,
      inits = 0,
      data = .)
L_M_bp72 <- loo(M_bp72)
M_bp73 <- d15 %>%
  filter(ECC == F) %>%
  brm(laagste_druk_syst ~ 1 + CABGexp04 + specialisatie +
        eurolog + cardiochir_eerder + geslacht + leeftijd +
        neuro_disfunctie + postinfarct_VSR + thorac_aortachir +
        BMI + lengte + multiv + CVA_eerder +
        ven_anast + ven_graft + art_graft + conversie +
        (1 | eersteOperateur) +
        (1 + CABGexp04 + specialisatie +
        eurolog + cardiochir_eerder + geslacht + leeftijd +
          neuro_disfunctie + postinfarct_VSR + thorac_aortachir +
        BMI + lengte + multiv + CVA_eerder +
        ven_anast + ven_graft + art_graft + conversie | XXXpat),
      family = skew_normal,
      cores = 4,
      inits = 0,
      data = .)
L_M_bp73 <- loo(M_bp73)
list(L_M_bp0,
     L_M_bp68,
     L_M_bp70,
     L_M_bp72,
     L_M_bp73) %>%
  compare_IC() #order: 73, 72, 70, 68, 0

M_bp74 <- d15 %>%
  filter(ECC == F) %>%
  brm(laagste_druk_syst ~ 1 + CABGexp04 + specialisatie +
        eurolog + cardiochir_eerder + geslacht + leeftijd +
        neuro_disfunctie + postinfarct_VSR + thorac_aortachir +
        BMI + lengte + multiv + CVA_eerder +
        ven_anast + ven_graft + art_graft + conversie +
        (1 | eersteOperateur) +
        (1 + CABGexp04 + specialisatie +
        eurolog + cardiochir_eerder + geslacht + leeftijd +
          neuro_disfunctie + postinfarct_VSR + thorac_aortachir +
        BMI + lengte + multiv + CVA_eerder +
        ven_anast + ven_graft + art_graft + conversie | XXXpat) +
        (1 | tweedeOperateur),
      family = skew_normal,
      cores = 4,
      inits = 0,
      data = .)
L_M_bp74 <- loo(M_bp74)
M_bp75 <- d15 %>%
  filter(ECC == F) %>%
```

```
  brm(laagste_druk_syst ~ 1 + CABGexp04 + specialisatie +
        eurolog + cardiochir_eerder + geslacht + leeftijd +
        neuro_disfunctie + postinfarct_VSR + thorac_aortachir +
        BMI + lengte + multiv + CVA_eerder +
        ven_anast + ven_graft + art_graft + conversie +
        (1 | eersteOperateur) +
        (1 + CABGexp04 + specialisatie +
        eurolog + cardiochir_eerder + geslacht + leeftijd +
          neuro_disfunctie + postinfarct_VSR + thorac_aortachir +
        BMI + lengte + multiv + CVA_eerder +
        ven_anast + ven_graft + art_graft + conversie | XXXpat) +
        (1 + CABGexp04 + specialisatie +
        eurolog + cardiochir_eerder + geslacht + leeftijd +
          neuro_disfunctie + postinfarct_VSR + thorac_aortachir +
        BMI + lengte + multiv + CVA_eerder +
        ven_anast + ven_graft + art_graft + conversie | tweedeOperateur),
      family = skew_normal,
      cores = 4,
      inits = 0,
      data = .)
L_M_bp75 <- loo(M_bp75)
list(L_M_bp0,
     L_M_bp73,
     L_M_bp74,
     L_M_bp75) %>%
  compare_IC() #order: 73, 74, 75, 0

M_bp76 <- d15 %>%
  filter(ECC == F) %>%
  brm(laagste_druk_syst ~ 1 + CABGexp04 + specialisatie +
        eurolog + cardiochir_eerder + geslacht + leeftijd +
        neuro_disfunctie + postinfarct_VSR + thorac_aortachir +
        BMI + lengte + multiv + CVA_eerder +
        ven_anast + ven_graft + art_graft + conversie +
        (1 | eersteOperateur) +
        (1 | XXXpat) +
        (1 | anesthesist),
      family = skew_normal,
      cores = 4,
      inits = 0,
      data = .)
L_M_bp76 <- loo(M_bp76)
M_bp77 <- d15 %>%
  filter(ECC == F) %>%
  brm(laagste_druk_syst ~ 1 + CABGexp04 + specialisatie +
        eurolog + cardiochir_eerder + geslacht + leeftijd +
        neuro_disfunctie + postinfarct_VSR + thorac_aortachir +
        BMI + lengte + multiv + CVA_eerder +
        ven_anast + ven_graft + art_graft + conversie +
        (1 | eersteOperateur) +
        (1 + CABGexp04 + specialisatie +
        eurolog + cardiochir_eerder + geslacht + leeftijd +
          neuro_disfunctie + postinfarct_VSR + thorac_aortachir +
        BMI + lengte + multiv + CVA_eerder +
```

```
        ven_anast + ven_graft + art_graft + conversie | XXXpat) +
        (1 + CABGexp04 + specialisatie +
        eurolog + cardiochir_eerder + geslacht + leeftijd +
          neuro_disfunctie + postinfarct_VSR + thorac_aortachir +
        BMI + lengte + multiv + CVA_eerder +
        ven_anast + ven_graft + art_graft + conversie | anesthesist),
      family = skew_normal,
      cores = 4,
      inits = 0,
      data = .)
L_M_bp77 <- loo(M_bp77)
list(L_M_bp0,
     L_M_bp73,
     L_M_bp76,
     L_M_bp77) %>%
  compare_IC() #order: 77, 73, 76, 0

fixef_ml(M_bp77)
fixef(M_bp77)
ranef(M_bp77)
grpef(M_bp77)
fixef(M_bp0)
```

operation duration

```
# a GMM is estimated as reference. Any model that fits worse than that is
useless
M_od0 <- d15 %>%
  filter(ECC == F) %>%
  brm(operatieduur ~ 1,
      family = exgaussian,
      data = .)
L_M_od0 <- loo(M_od0)

# first round of fittings, the various experience variables are compared,
then specialization is added to the best fitting
M_od1 <- d15 %>%
  filter(ECC == F) %>%
  brm(operatieduur ~ 1 + CABGexp04,
      family = exgaussian,
      data = .)
L_M_od1 <- loo(M_od1)
M_od2 <- d15 %>%
  filter(ECC == F) %>%
  brm(operatieduur ~ 1 + CABGexp15,
      family = exgaussian,
      data = .)
L_M_od2 <- loo(M_od2)
M_od3 <- d15 %>%
  filter(ECC == F) %>%
  brm(operatieduur ~ 1 + expECC,
      family = exgaussian,
      data = .)
L_M_od3 <- loo(M_od3)
```

```
M_od4 <- d15 %>%
  filter(ECC == F) %>%
  brm(operatieduur ~ 1 + expECC + specialisatie,
      family = exgaussian,
      data = .)
L_M_od4 <- loo(M_od4)
list(L_M_od0,
     L_M_od1,
     L_M_od2,
     L_M_od3,
     L_M_od4) %>%
  compare_IC() #order: 4, 3, 2, 0, 1

# add euroscores
M_od5 <- d15 %>%
  filter(ECC == F) %>%
  brm(operatieduur ~ 1 + expECC + specialisatie +
        euroI,
      family = exgaussian,
      cores = 4,
      inits = 0,
      data = .)
L_M_od5 <- loo(M_od5)
M_od6 <- d15 %>%
  filter(ECC == F) %>%
  brm(operatieduur ~ 1 + expECC + specialisatie +
        eurolog,
      family = exgaussian,
      cores = 4,
      inits = 0,
      data = .)
L_M_od6 <- loo(M_od6)
M_od7 <- d15 %>%
  filter(ECC == F) %>%
  brm(operatieduur ~ 1 + expECC + specialisatie +
        euroII,
      family = exgaussian,
      cores = 4,
      inits = 0,
      data = .)
L_M_od7 <- loo(M_od7)
list(L_M_od0,
     L_M_od4,
     L_M_od5,
     L_M_od6,
     L_M_od7) %>%
  compare_IC() #order: 6, 5, 7, 4, 0

# add individual euroscore variables
M_od8 <- d15 %>%
  filter(ECC == F) %>%
  brm(operatieduur ~ 1 + expECC + specialisatie +
        eurolog + leeftijd,
      family = exgaussian,
```

```
      cores = 4,
      inits = 0,
      data = .)
L_M_od8 <- loo(M_od8)
M_od9 <- d15 %>%
  filter(ECC == F) %>%
  brm(operatieduur ~ 1 + expECC + specialisatie +
        eurolog + geslacht,
      family = exgaussian,
      cores = 4,
      inits = 0,
      data = .)
L_M_od9 <- loo(M_od9)
M_od10 <- d15 %>%
  filter(ECC == F) %>%
  brm(operatieduur ~ 1 + expECC + specialisatie +
        eurolog + chron_longziekte,
      family = exgaussian,
      cores = 4,
      inits = 0,
      data = .)
L_M_od10 <- loo(M_od10)
M_od11 <- d15 %>%
  filter(ECC == F) %>%
  brm(operatieduur ~ 1 + expECC + specialisatie +
        eurolog + art_vaatpathologie,
      family = exgaussian,
      cores = 4,
      inits = 0,
      data = .)
L_M_od11 <- loo(M_od11)
M_od12 <- d15 %>%
  filter(ECC == F) %>%
  brm(operatieduur ~ 1 + expECC + specialisatie +
        eurolog + neuro_disfunctie,
      family = exgaussian,
      cores = 4,
      inits = 0,
      data = .)
L_M_od12 <- loo(M_od12)
M_od13 <- d15 %>%
  filter(ECC == F) %>%
  brm(operatieduur ~ 1 + expECC + specialisatie +
        eurolog + cardiochir_eerder,
      family = exgaussian,
      cores = 4,
      inits = 0,
      data = .)
L_M_od13 <- loo(M_od13)
M_od14 <- d15 %>%
  filter(ECC == F) %>%
  brm(operatieduur ~ 1 + expECC + specialisatie +
        eurolog + kreatinine_gehalte,
      family = exgaussian,
```

```
      cores = 4,
      inits = 0,
      data = .)
L_M_od14 <- loo(M_od14)
M_od15 <- d15 %>%
  filter(ECC == F) %>%
  brm(operatieduur ~ 1 + expECC + specialisatie +
        eurolog + endocarditis,
      family = exgaussian,
      cores = 4,
      inits = 0,
      data = .)
L_M_od15 <- loo(M_od15)
M_od16 <- d15 %>%
  filter(ECC == F) %>%
  brm(operatieduur ~ 1 + expECC + specialisatie +
        eurolog + krit_preop_toestand,
      family = exgaussian,
      cores = 4,
      inits = 0,
      data = .)
L_M_od16 <- loo(M_od16)
M_od17 <- d15 %>%
  filter(ECC == F) %>%
  brm(operatieduur ~ 1 + expECC + specialisatie +
        eurolog + instabiele_AP,
      family = exgaussian,
      cores = 4,
      inits = 0,
      data = .)
L_M_od17 <- loo(M_od17)
M_od18 <- d15 %>%
  filter(ECC == F) %>%
  brm(operatieduur ~ 1 + expECC + specialisatie +
        eurolog + LVEF,
      family = exgaussian,
      cores = 4,
      inits = 0,
      data = .)
L_M_od18 <- loo(M_od18)
M_od19 <- d15 %>%
  filter(ECC == F) %>%
  brm(operatieduur ~ 1 + expECC + specialisatie +
        eurolog + recent_MI,
      family = exgaussian,
      cores = 4,
      inits = 0,
      data = .)
L_M_od19 <- loo(M_od19)
M_od20 <- d15 %>%
  filter(ECC == F) %>%
  brm(operatieduur ~ 1 + expECC + specialisatie +
        eurolog + PA_druk,
      family = exgaussian,
```

```
      cores = 4,
      inits = 0,
      data = .)
L_M_od20 <- loo(M_od20)
M_od21 <- d15 %>%
  filter(ECC == F) %>%
  brm(operatieduur ~ 1 + expECC + specialisatie +
        eurolog + thorac_aortachir,
      family = exgaussian,
      cores = 4,
      inits = 0,
      data = .)
L_M_od21 <- loo(M_od21)
M_od22 <- d15 %>%
  filter(ECC == F) %>%
  brm(operatieduur ~ 1 + expECC + specialisatie +
        eurolog + postinfarct_VSR,
      family = exgaussian,
      cores = 4,
      inits = 0,
      data = .)
L_M_od22 <- loo(M_od22)
M_od23 <- d15 %>%
  filter(ECC == F) %>%
  brm(operatieduur ~ 1 + expECC + specialisatie +
        eurolog + NYHA,
      family = exgaussian,
      cores = 4,
      inits = 0,
      data = .)
L_M_od23 <- loo(M_od23)
M_od24 <- d15 %>%
  filter(ECC == F) %>%
  brm(operatieduur ~ 1 + expECC + specialisatie +
        eurolog + CCS_IV,
      family = exgaussian,
      cores = 4,
      inits = 0,
      data = .)
L_M_od24 <- loo(M_od24)
M_od25 <- d15 %>%
  filter(ECC == F) %>%
  brm(operatieduur ~ 1 + expECC + specialisatie +
        eurolog + diabetes,
      family = exgaussian,
      cores = 4,
      inits = 0,
      data = .)
L_M_od25 <- loo(M_od25)
M_od26 <- d15 %>%
  filter(ECC == F) %>%
  brm(operatieduur ~ 1 + expECC + specialisatie +
        eurolog + slechte_mob,
      family = exgaussian,
```

```
      cores = 4,
      inits = 0,
      data = .)
L_M_od26 <- loo(M_od26)
M_od27 <- d15 %>%
  filter(ECC == F) %>%
  brm(operatieduur ~ 1 + expECC + specialisatie +
        eurolog + dialyse,
      family = exgaussian,
      cores = 4,
      inits = 0,
      data = .)
L_M_od27 <- loo(M_od27)
M_od28 <- d15 %>%
  filter(ECC == F) %>%
  brm(operatieduur ~ 1 + expECC + specialisatie +
        eurolog + urgentie,
      family = exgaussian,
      cores = 4,
      inits = 0,
      data = .)
L_M_od28 <- loo(M_od28)
list(L_M_od0,
     L_M_od6,
     L_M_od8,
     L_M_od9,
     L_M_od10,
     L_M_od11,
     L_M_od12,
     L_M_od13,
     L_M_od14,
     L_M_od15,
     L_M_od16,
     L_M_od17,
     L_M_od18,
     L_M_od19,
     L_M_od20,
     L_M_od21,
     L_M_od22,
     L_M_od23,
     L_M_od24,
     L_M_od25,
     L_M_od26,
     L_M_od27,
     L_M_od28) %>%
  compare_IC() #order: 9, 28, 6, 20, 21, 15, 22, 24, 11, 18, 12, 10, 14, 1
7, 26, 27, 19, 8, 16, 13, 23, 25, 0

M_od29 <- d15 %>%
  filter(ECC == F) %>%
  brm(operatieduur ~ 1 + expECC + specialisatie +
        eurolog + geslacht + urgentie,
      family = exgaussian,
      cores = 4,
```

```
      inits = 0,
      data = .)
L_M_od29 <- loo(M_od29)
list(L_M_od0,
     L_M_od6,
     L_M_od9,
     L_M_od28,
     L_M_od29) %>%
  compare_IC() #order: 29, 9, 28, 6, 0


M_od30 <- d15 %>%
  filter(ECC == F) %>%
  brm(operatieduur ~ 1 + expECC + specialisatie +
        eurolog + geslacht + urgentie +
        lengte,
      family = exgaussian,
      cores = 4,
      inits = 0,
      data = .)
L_M_od30 <- loo(M_od30)
M_od31 <- d15 %>%
  filter(ECC == F) %>%
  brm(operatieduur ~ 1 + expECC + specialisatie +
        eurolog + geslacht + urgentie +
        gewicht,
      family = exgaussian,
      cores = 4,
      inits = 0,
      data = .)
L_M_od31 <- loo(M_od31)
M_od32 <- d15 %>%
  filter(ECC == F) %>%
  brm(operatieduur ~ 1 + expECC + specialisatie +
        eurolog + geslacht + urgentie +
        BMI,
      family = exgaussian,
      cores = 4,
      inits = 0,
      data = .)
L_M_od32 <- loo(M_od32)
M_od33 <- d15 %>%
  filter(ECC == F) %>%
  brm(operatieduur ~ 1 + expECC + specialisatie +
        eurolog + geslacht + urgentie +
        CVA_eerder,
      family = exgaussian,
      cores = 4,
      inits = 0,
      data = .)
L_M_od33 <- loo(M_od33)
M_od34 <- d15 %>%
  filter(ECC == F) %>%
  brm(operatieduur ~ 1 + expECC + specialisatie +
```

```
        eurolog + geslacht + urgentie +
        multiv,
      family = exgaussian,
      cores = 4,
      inits = 0,
      data = .)
L_M_od34 <- loo(M_od34)
M_od35 <- d15 %>%
  filter(ECC == F) %>%
  brm(operatieduur ~ 1 + expECC + specialisatie +
        eurolog + geslacht + urgentie +
        AF,
      family = exgaussian,
      cores = 4,
      inits = 0,
      data = .)
L_M_od35 <- loo(M_od35)
M_od36 <- d15 %>%
  filter(ECC == F) %>%
  brm(operatieduur ~ 1 + expECC + specialisatie +
        eurolog + geslacht + urgentie +
        coronairchir_overig,
      family = exgaussian,
      cores = 4,
      inits = 0,
      data = .)
L_M_od36 <- loo(M_od36)
M_od37 <- d15 %>%
  filter(ECC == F) %>%
  brm(operatieduur ~ 1 + expECC + specialisatie +
        eurolog + geslacht + urgentie +
        roker,
      family = exgaussian,
      cores = 4,
      inits = 0,
      data = .)
L_M_od37 <- loo(M_od37)
M_od38 <- d15 %>%
  filter(ECC == F) %>%
  brm(operatieduur ~ 1 + expECC + specialisatie +
        eurolog + geslacht + urgentie +
        rooktnu,
      family = exgaussian,
      cores = 4,
      inits = 0,
      data = .)
L_M_od38 <- loo(M_od38)
M_od39 <- d15 %>%
  filter(ECC == F) %>%
  brm(operatieduur ~ 1 + expECC + specialisatie +
        eurolog + geslacht + urgentie +
        nierfalen,
      family = exgaussian,
      cores = 4,
```

```
      inits = 0,
      data = .)
L_M_od39 <- loo(M_od39)
list(L_M_od0,
     L_M_od6,
     L_M_od29,
     L_M_od30, #lengte
     L_M_od31, #gewicht
     L_M_od32, # BMI
     L_M_od33, #CVA_eerder
     L_M_od34, #multiv
     L_M_od35,
     L_M_od36,
     L_M_od37,
     L_M_od38,
     L_M_od39) %>%
  compare_IC() #order: 34, 32, 31, 30, 33, 29, 38, 39, 35, 37, 36, 6, 0



M_od40 <- d15 %>%
  filter(ECC == F) %>%
  brm(operatieduur ~ 1 + expECC + specialisatie +
        eurolog + geslacht + urgentie +
        BMI + lengte,
      family = exgaussian,
      cores = 4,
      inits = 0,
      data = .)
L_M_od40 <- loo(M_od40)
M_od41 <- d15 %>%
  filter(ECC == F) %>%
  brm(operatieduur ~ 1 + expECC + specialisatie +
        eurolog + geslacht + urgentie +
        gewicht + lengte,
      family = exgaussian,
      cores = 4,
      inits = 0,
      data = .)
L_M_od41 <- loo(M_od41)
M_od42 <- d15 %>%
  filter(ECC == F) %>%
  brm(operatieduur ~ 1 + expECC + specialisatie +
        eurolog + geslacht + urgentie +
        BMI + gewicht + lengte,
      family = exgaussian,
      cores = 4,
      inits = 0,
      data = .)
L_M_od42 <- loo(M_od42)
M_od43 <- d15 %>%
  filter(ECC == F) %>%
  brm(operatieduur ~ 1 + expECC + specialisatie +
        eurolog + + geslacht + urgentie +
```

```
        BMI + gewicht,
      family = exgaussian,
      cores = 4,
      inits = 0,
      data = .)
L_M_od43 <- loo(M_od43)
list(L_M_od0,
     L_M_od29,
     L_M_od31,
     L_M_od32,
     L_M_od33,
     L_M_od40,
     L_M_od41,
     L_M_od42,
     L_M_od43) %>%
  compare_IC() #order: 43, 41, 40, 32, 42, 31, 33, 29, 0

M_od44 <- d15 %>%
  filter(ECC == F) %>%
  brm(operatieduur ~ 1 + expECC + specialisatie +
        eurolog + geslacht + urgentie +
        BMI + gewicht + multiv,
      family = exgaussian,
      cores = 4,
      inits = 0,
      data = .)
L_M_od44 <- loo(M_od44)
list(L_M_od0,
     L_M_od43,
     L_M_od44) %>%
  compare_IC()  #order: 44, 43, 0


M_od45 <- d15 %>%
  filter(ECC == F) %>%
  brm(operatieduur ~ 1 + expECC + specialisatie +
        eurolog + geslacht + urgentie +
        BMI + gewicht + multiv +
        start_operatie,
      family = exgaussian,
      cores = 4,
      inits = 0,
      data = .)
L_M_od45 <- loo(M_od45)
M_od46 <- d15 %>%
  filter(ECC == F) %>%
  brm(operatieduur ~ 1 + expECC + specialisatie +
        eurolog + geslacht + urgentie +
        BMI + gewicht + multiv +
        art_graft,
      family = exgaussian,
      cores = 4,
      inits = 0,
      data = .)
```

```
L_M_od46 <- loo(M_od46)
M_od47 <- d15 %>%
  filter(ECC == F) %>%
  brm(operatieduur ~ 1 + expECC + specialisatie +
        eurolog + geslacht + urgentie +
        BMI + gewicht + multiv +
        art_anast,
      family = exgaussian,
      cores = 4,
      inits = 0,
      data = .)
L_M_od47 <- loo(M_od47)
M_od48 <- d15 %>%
  filter(ECC == F) %>%
  brm(operatieduur ~ 1 + expECC + specialisatie +
        eurolog + geslacht + urgentie +
        BMI + gewicht + multiv +
        ven_graft,
      family = exgaussian,
      cores = 4,
      inits = 0,
      data = .)
L_M_od48 <- loo(M_od48)
M_od49 <- d15 %>%
  filter(ECC == F) %>%
  brm(operatieduur ~ 1 + expECC + specialisatie +
        eurolog + geslacht + urgentie +
        BMI + gewicht + multiv +
        ven_anast,
      family = exgaussian,
      cores = 4,
      inits = 0,
      data = .)
L_M_od49 <- loo(M_od49)
M_od50 <- d15 %>%
  filter(ECC == F) %>%
  brm(operatieduur ~ 1 + expECC + specialisatie +
        eurolog + geslacht + urgentie +
        BMI + gewicht + multiv +
        conversie,
      family = exgaussian,
      cores = 4,
      inits = 0,
      data = .)
L_M_od50 <- loo(M_od50)
M_od51 <- d15 %>%
  filter(ECC == F) %>%
  brm(operatieduur ~ 1 + expECC + specialisatie +
        eurolog + geslacht + urgentie +
        BMI + gewicht + multiv +
        totalgrafts,
      family = exgaussian,
      cores = 4,
      inits = 0,
```

```
      data = .)
L_M_od51 <- loo(M_od51)
M_od52 <- d15 %>%
  filter(ECC == F) %>%
  brm(operatieduur ~ 1 + expECC + specialisatie +
        eurolog + geslacht + urgentie +
        BMI + gewicht + multiv +
        voorstellen,
      family = exgaussian,
      cores = 4,
      inits = 0,
      data = .)
L_M_od52 <- loo(M_od52)
M_od53 <- d15 %>%
  filter(ECC == F) %>%
  brm(operatieduur ~ 1 + expECC + specialisatie +
        eurolog + geslacht + urgentie +
        BMI + gewicht + multiv +
        planvsuitg,
      family = exgaussian,
      cores = 4,
      inits = 0,
      data = .)
L_M_od53 <- loo(M_od53)
M_od54 <- d15 %>%
  filter(ECC == F) %>%
  brm(operatieduur ~ 1 + expECC + specialisatie +
        eurolog + geslacht + urgentie +
        BMI + gewicht + multiv +
        artgrdiff,
      family = exgaussian,
      cores = 4,
      inits = 0,
      data = .)
L_M_od54 <- loo(M_od54)
M_od55 <- d15 %>%
  filter(ECC == F) %>%
  brm(operatieduur ~ 1 + expECC + specialisatie +
        eurolog + geslacht + urgentie +
        BMI + gewicht + multiv +
        vengrdiff,
      family = exgaussian,
      cores = 4,
      inits = 0,
      data = .)
L_M_od55 <- loo(M_od55)
M_od56 <- d15 %>%
  filter(ECC == F) %>%
  brm(operatieduur ~ 1 + expECC + specialisatie +
        eurolog + geslacht + urgentie +
        BMI + gewicht + multiv +
        interv_datum,
      family = exgaussian,
      cores = 4,
```

```
      inits = 0,
      data = .)
L_M_od56 <- loo(M_od56)
list(L_M_od0,    #GMM
     L_M_od44,   #best previous model
     L_M_od45,   #start_operatie
     L_M_od46,   #art_graft
     L_M_od47,   #art_anast
     L_M_od48,   #ven_graft
     L_M_od49,   #ven_anast
     L_M_od50,   #conversie
     L_M_od51,   #totalgrafts
     L_M_od52,   #voorstellen
     L_M_od53,   #planvsuitg
     L_M_od54,   #artgrdiff
     L_M_od55,   #vengrdiff
     L_M_od56) %>%    #interv_datum
  compare_IC()  #order: 49, 50, 51, 47, 53, 52, 45, 48, 55, 44, 54, 56, 46
, 0


M_od57 <- d15 %>%
  filter(ECC == F) %>%
  brm(operatieduur ~ 1 + expECC + specialisatie +
        eurolog + geslacht + urgentie +
        BMI + gewicht + multiv +
        ven_anast + ven_graft,
      family = exgaussian,
      cores = 4,
      inits = 0,
      data = .)
L_M_od57 <- loo(M_od57)
M_od58 <- d15 %>%
  filter(ECC == F) %>%
  brm(operatieduur ~ 1 + expECC + specialisatie +
        eurolog + geslacht + urgentie +
        BMI + gewicht + multiv +
        ven_anast + vengrdiff,
      family = exgaussian,
      cores = 4,
      inits = 0,
      data = .)
L_M_od58 <- loo(M_od58)
M_od59 <- d15 %>%
  filter(ECC == F) %>%
  brm(operatieduur ~ 1 + expECC + specialisatie +
        eurolog + geslacht + urgentie +
        BMI + gewicht + multiv +
        vengrdiff + ven_graft,
      family = exgaussian,
      cores = 4,
      inits = 0,
      data = .)
L_M_od59 <- loo(M_od59)
```

```
M_od60 <- d15 %>%
  filter(ECC == F) %>%
  brm(operatieduur ~ 1 + expECC + specialisatie +
        eurolog + geslacht + urgentie +
        BMI + gewicht + multiv +
        ven_anast + ven_graft + vengrdiff,
      family = exgaussian,
      cores = 4,
      inits = 0,
      data = .)
L_M_od60 <- loo(M_od60)
list(L_M_od0,
     L_M_od43,
     L_M_od48,
     L_M_od49,
     L_M_od55,
     L_M_od57,
     L_M_od58,
     L_M_od59,
     L_M_od60) %>%
  compare_IC()  #order: 60, 58, 57, 49, 59, 48, 55, 43, 0

#art anast, conversie, total grafts, planvsuitg, voorstellen, start operat
ie
M_od61 <- d15 %>%
  filter(ECC == F) %>%
  brm(operatieduur ~ 1 + expECC + specialisatie +
        eurolog + geslacht + urgentie +
        BMI + gewicht + multiv +
        ven_anast + ven_graft + vengrdiff +
        art_anast,
      family = exgaussian,
      cores = 4,
      inits = 0,
      data = .)
L_M_od61 <- loo(M_od61)
M_od62 <- d15 %>%
  filter(ECC == F) %>%
  brm(operatieduur ~ 1 + expECC + specialisatie +
        eurolog + geslacht + urgentie +
        BMI + gewicht + multiv +
        ven_anast + ven_graft + vengrdiff +
        art_anast + conversie,
      family = exgaussian,
      cores = 4,
      inits = 0,
      data = .)
L_M_od62 <- loo(M_od62)
M_od63 <- d15 %>%
  filter(ECC == F) %>%
  brm(operatieduur ~ 1 + expECC + specialisatie +
        eurolog + geslacht + urgentie +
        BMI + gewicht + multiv +
        ven_anast + ven_graft + vengrdiff +
```

```
        art_anast + conversie + totalgrafts,
      family = exgaussian,
      cores = 4,
      inits = 0,
      data = .)
L_M_od63 <- loo(M_od63)
M_od64 <- d15 %>%
  filter(ECC == F) %>%
  brm(operatieduur ~ 1 + expECC + specialisatie +
        eurolog + geslacht + urgentie +
        BMI + gewicht + multiv +
        ven_anast + ven_graft + vengrdiff +
        art_anast + conversie + totalgrafts + planvsuitg,
      family = exgaussian,
      cores = 4,
      inits = 0,
      data = .)
L_M_od64 <- loo(M_od64)
M_od65 <- d15 %>%
  filter(ECC == F) %>%
  brm(operatieduur ~ 1 + expECC + specialisatie +
        eurolog + geslacht + urgentie +
        BMI + gewicht + multiv +
        ven_anast + ven_graft + vengrdiff +
        art_anast + conversie + totalgrafts + planvsuitg +
        voorstellen,
      family = exgaussian,
      cores = 4,
      inits = 0,
      data = .)
L_M_od65 <- loo(M_od65)
M_od65 <- d15 %>%
  filter(ECC == F) %>%
  brm(operatieduur ~ 1 + expECC + specialisatie +
        eurolog + geslacht + urgentie +
        BMI + gewicht + multiv +
        ven_anast + ven_graft + vengrdiff +
        art_anast + conversie + totalgrafts + planvsuitg +
        voorstellen + start_operatie,
      family = exgaussian,
      cores = 4,
      inits = 0,
      data = .)
L_M_od65 <- loo(M_od65)
list(L_M_od0,
     L_M_od60,
     L_M_od61,
     L_M_od62,
     L_M_od63,
     L_M_od64,
     L_M_od65) %>%
  compare_IC()  #order:60, 59, 58, 57, 49, 56, 43, 0

M_od66 <- d15 %>%
```

```
  filter(ECC == F) %>%
  brm(operatieduur ~ 1 + expECC + specialisatie +
        eurolog + geslacht + urgentie +
        BMI + gewicht + multiv +
        ven_anast + ven_graft + vengrdiff +
        (1 | eersteOperateur),
      family = exgaussian,
      cores = 4,
      inits = 0,
      data = .)
L_M_od66 <- loo(M_od66)
M_od67 <- d15 %>%
  filter(ECC == F) %>%
  brm(operatieduur ~ 1 + expECC + specialisatie +
        eurolog + geslacht + urgentie +
        BMI + gewicht + multiv +
        ven_anast + ven_graft + vengrdiff +
        (1 + expECC + specialisatie +
        eurolog + geslacht + urgentie +
        BMI + gewicht + multiv +
        ven_anast + ven_graft + vengrdiff | eersteOperateur),
      family = exgaussian,
      cores = 4,
      inits = 0,
      data = .)
L_M_od67 <- loo(M_od67)
list(L_M_od0,
     L_M_od60,
     L_M_od66,
     L_M_od67) %>%
  compare_IC()  #order: 66, 67, 60, 0

M_od68 <- d15 %>%
  filter(ECC == F) %>%
  brm(operatieduur ~ 1 + expECC + specialisatie +
        eurolog + geslacht + urgentie +
        BMI + gewicht + multiv +
        ven_anast + ven_graft + vengrdiff +
        (1 | eersteOperateur) +
        (1 | XXXpat),
      family = exgaussian,
      cores = 4,
      inits = 0,
      data = .)
L_M_od68 <- loo(M_od68)
M_od69 <- d15 %>%
  filter(ECC == F) %>%
  brm(operatieduur ~ 1 + expECC + specialisatie +
        eurolog + geslacht + urgentie +
        BMI + gewicht + multiv +
        ven_anast + ven_graft + vengrdiff +
        (1 | eersteOperateur) +
        (1 + expECC + specialisatie + eurolog + geslacht +
           urgentie + BMI + gewicht + multiv + ven_anast +
```

```
           ven_graft + vengrdiff | XXXpat),
      family = exgaussian,
      cores = 4,
      inits = 0,
      data = .)
L_M_od69 <- loo(M_od69)
list(L_M_od0,
     L_M_od66,
     L_M_od68,
     L_M_od69) %>%
  compare_IC()  #order: 69, 68, 66, 0

M_od70 <- d15 %>%
  filter(ECC == F) %>%
  brm(operatieduur ~ 1 + expECC + specialisatie +
        eurolog + geslacht + urgentie +
        BMI + gewicht + multiv +
        ven_anast + ven_graft + vengrdiff +
        (1 | eersteOperateur) +
        (1 + expECC + specialisatie + eurolog + geslacht +
           urgentie + BMI + gewicht + multiv + ven_anast +
           ven_graft + vengrdiff | XXXpat) +
        (1 | tweedeOperateur),
      family = exgaussian,
      cores = 4,
      inits = 0,
      data = .)
L_M_od70 <- loo(M_od70)
M_od71 <- d15 %>%
  filter(ECC == F) %>%
  brm(operatieduur ~ 1 + expECC + specialisatie +
        eurolog + geslacht + urgentie +
        BMI + gewicht + multiv +
        ven_anast + ven_graft + vengrdiff +
        (1 | eersteOperateur) +
        (1 + expECC + specialisatie + eurolog + geslacht +
           urgentie + BMI + gewicht + multiv + ven_anast +
           ven_graft + vengrdiff | XXXpat) +
        (1 + expECC + specialisatie + eurolog + geslacht +
           urgentie + BMI + gewicht + multiv + ven_anast +
           ven_graft + vengrdiff | tweedeOperateur),
      family = exgaussian,
      cores = 4,
      inits = 0,
      data = .)
L_M_od71 <- loo(M_od71)
list(L_M_od0,
     L_M_od69,
     L_M_od70,
     L_M_od71) %>%
  compare_IC()  #order: 71, 69, 70, 0

M_od72 <- d15 %>%
  filter(ECC == F) %>%
```

```
  brm(operatieduur ~ 1 + expECC + specialisatie +
        eurolog + geslacht + urgentie +
        BMI + gewicht + multiv +
        ven_anast + ven_graft + vengrdiff +
        (1 | eersteOperateur) +
        (1 + expECC + specialisatie + eurolog + geslacht +
           urgentie + BMI + gewicht + multiv + ven_anast +
           ven_graft + vengrdiff | XXXpat) +
        (1 + expECC + specialisatie + eurolog + geslacht +
           urgentie + BMI + gewicht + multiv + ven_anast +
           ven_graft + vengrdiff | tweedeOperateur) +
        (1 | anesthesist),
      family = exgaussian,
      cores = 4,
      inits = 0,
      data = .)
L_M_od72 <- loo(M_od72)
M_od73 <- d15 %>%
  filter(ECC == F) %>%
  brm(operatieduur ~ 1 + expECC + specialisatie +
        eurolog + geslacht + urgentie +
        BMI + gewicht + multiv +
        ven_anast + ven_graft + vengrdiff +
        (1 | eersteOperateur) +
        (1 + expECC + specialisatie + eurolog + geslacht +
           urgentie + BMI + gewicht + multiv + ven_anast +
           ven_graft + vengrdiff | XXXpat) +
        (1 + expECC + specialisatie + eurolog + geslacht +
           urgentie + BMI + gewicht + multiv + ven_anast +
           ven_graft + vengrdiff | tweedeOperateur) +
        (1 + expECC + specialisatie + eurolog + geslacht +
           urgentie + BMI + gewicht + multiv + ven_anast +
           ven_graft + vengrdiff | anesthesist),
      family = exgaussian,
      cores = 4,
      inits = 0,
      data = .)
L_M_od73 <- loo(M_od73)
list(L_M_od0,
     L_M_od71,
     L_M_od72,
     L_M_od73) %>%
  compare_IC()  #order: 73, 72, 71, 0

fixef_ml(M_od73) %>% view()
fixef(M_od73)
ranef(M_od73)
grpef(M_od73)
fixef(M_od0)
```

all complications

```
# a GMM is estimated as reference. Any model that fits worse than that is
useless
```

```
M_ac0 <- d15 %>%
  filter(ECC == F) %>%
  brm(allcomps ~ 1,
      family = skew_normal,
      data = .)
L_M_ac0 <- loo(M_ac0)

# first round of fittings, the various experience variables are compared,
then specialization is added to the best fitting
M_ac1 <- d15 %>%
  filter(ECC == F) %>%
  brm(allcomps ~ 1 + CABGexp04,
      family = skew_normal,
      data = .)
L_M_ac1 <- loo(M_ac1)
M_ac2 <- d15 %>%
  filter(ECC == F) %>%
  brm(allcomps ~ 1 + CABGexp15,
      family = skew_normal,
      data = .)
L_M_ac2 <- loo(M_ac2)
M_ac3 <- d15 %>%
  filter(ECC == F) %>%
  brm(allcomps ~ 1 + expECC,
      family = skew_normal,
      data = .)
L_M_ac3 <- loo(M_ac3)
M_ac4 <- d15 %>%
  filter(ECC == F) %>%
  brm(allcomps ~ 1 + specialisatie,
      family = skew_normal,
      data = .)
L_M_ac4 <- loo(M_ac4)
list(L_M_ac0,
     L_M_ac1,
     L_M_ac2,
     L_M_ac3,
     L_M_ac4) %>%
  compare_IC() #order: 0, 3, 4, 2, 1

M_ac5 <- d15 %>%
  filter(ECC == F) %>%
  brm(allcomps ~ 1 +
        euroI,
      family = skew_normal,
      data = .)
L_M_ac5 <- loo(M_ac5)
M_ac6 <- d15 %>%
  filter(ECC == F) %>%
  brm(allcomps ~ 1 +
        eurolog,
      family = skew_normal,
      data = .)
L_M_ac6 <- loo(M_ac6)
```

```
M_ac7 <- d15 %>%
  filter(ECC == F) %>%
  brm(allcomps ~ 1 +
        euroII,
      family = skew_normal,
      data = .)
L_M_ac7 <- loo(M_ac7)
list(L_M_ac0,
     L_M_ac5,
     L_M_ac6,
     L_M_ac7) %>%
  compare_IC() #order: 0, 7, 5, 6

M_ac8 <- d15 %>%
  filter(ECC == F) %>%
  brm(allcomps ~ 1 + leeftijd,
      family = skew_normal,
      data = .)
L_M_ac8 <- loo(M_ac8)
M_ac9 <- d15 %>%
  filter(ECC == F) %>%
  brm(allcomps ~ 1 + geslacht,
      family = skew_normal,
      data = .)
L_M_ac9 <- loo(M_ac9)
M_ac10 <- d15 %>%
  filter(ECC == F) %>%
  brm(allcomps ~ 1 + chron_longziekte,
      family = skew_normal,
      data = .)
L_M_ac10 <- loo(M_ac10)
M_ac11 <- d15 %>%
  filter(ECC == F) %>%
  brm(allcomps ~ 1 + art_vaatpathologie,
      family = skew_normal,
      data = .)
L_M_ac11 <- loo(M_ac11)
M_ac12 <- d15 %>%
  filter(ECC == F) %>%
  brm(allcomps ~ 1 + neuro_disfunctie,
      family = skew_normal,
      data = .)
L_M_ac12 <- loo(M_ac12)
M_ac13 <- d15 %>%
  filter(ECC == F) %>%
  brm(allcomps ~ 1 + cardiochir_eerder,
      family = skew_normal,
      data = .)
L_M_ac13 <- loo(M_ac13)
M_ac14 <- d15 %>%
  filter(ECC == F) %>%
  brm(allcomps ~ 1 + kreatinine_gehalte,
      family = skew_normal,
      data = .)
```

```
L_M_ac14 <- loo(M_ac14)
M_ac15 <- d15 %>%
  filter(ECC == F) %>%
  brm(allcomps ~ 1 + endocarditis,
      family = skew_normal,
      data = .)
L_M_ac15 <- loo(M_ac15)
M_ac16 <- d15 %>%
  filter(ECC == F) %>%
  brm(allcomps ~ 1 + krit_preop_toestand,
      family = skew_normal,
      data = .)
L_M_ac16 <- loo(M_ac16)
M_ac17 <- d15 %>%
  filter(ECC == F) %>%
  brm(allcomps ~ 1 + instabiele_AP,
      family = skew_normal,
      data = .)
L_M_ac17 <- loo(M_ac17)
M_ac18 <- d15 %>%
  filter(ECC == F) %>%
  brm(allcomps ~ 1 + LVEF,
      family = skew_normal,
      data = .)
L_M_ac18 <- loo(M_ac18)
M_ac19 <- d15 %>%
  filter(ECC == F) %>%
  brm(allcomps ~ 1 + recent_MI,
      family = skew_normal,
      data = .)
L_M_ac19 <- loo(M_ac19)
M_ac20 <- d15 %>%
  filter(ECC == F) %>%
  brm(allcomps ~ 1 + PA_druk,
      family = skew_normal,
      data = .)
L_M_ac20 <- loo(M_ac20)
M_ac21 <- d15 %>%
  filter(ECC == F) %>%
  brm(allcomps ~ 1 + thorac_aortachir,
      family = skew_normal,
      data = .)
L_M_ac21 <- loo(M_ac21)
M_ac22 <- d15 %>%
  filter(ECC == F) %>%
  brm(allcomps ~ 1 + postinfarct_VSR,
      family = skew_normal,
      data = .)
L_M_ac22 <- loo(M_ac22)
M_ac23 <- d15 %>%
  filter(ECC == F) %>%
  brm(allcomps ~ 1 + NYHA,
      family = skew_normal,
      data = .)
```

```
L_M_ac23 <- loo(M_ac23)
M_ac24 <- d15 %>%
  filter(ECC == F) %>%
  brm(allcomps ~ 1 + CCS_IV,
      family = skew_normal,
      data = .)
L_M_ac24 <- loo(M_ac24)
M_ac25 <- d15 %>%
  filter(ECC == F) %>%
  brm(allcomps ~ 1 + diabetes,
      family = skew_normal,
      data = .)
L_M_ac25 <- loo(M_ac25)
M_ac26 <- d15 %>%
  filter(ECC == F) %>%
  brm(allcomps ~ 1 + slechte_mob,
      family = skew_normal,
      data = .)
L_M_ac26 <- loo(M_ac26)
M_ac27 <- d15 %>%
  filter(ECC == F) %>%
  brm(allcomps ~ 1 + dialyse,
      family = skew_normal,
      data = .)
L_M_ac27 <- loo(M_ac27)
M_ac28 <- d15 %>%
  filter(ECC == F) %>%
  brm(allcomps ~ 1 + urgentie,
      family = skew_normal,
      data = .)
L_M_ac28 <- loo(M_ac28)
list(L_M_ac0,
     L_M_ac8,
     L_M_ac9,
     L_M_ac10,
     L_M_ac11,
     L_M_ac12,
     L_M_ac13,
     L_M_ac14,
     L_M_ac15,
     L_M_ac16,
     L_M_ac17,
     L_M_ac18,
     L_M_ac19,
     L_M_ac20,
     L_M_ac21,
     L_M_ac22,
     L_M_ac23,
     L_M_ac24,
     L_M_ac25,
     L_M_ac26,
     L_M_ac27,
     L_M_ac28) %>%
  compare_IC() #order:0, 10, 8, 9, 24, 26, 19, 20, 16, 21, 15, 22, 11, 17,
```

```
 13, 12, 25, 28, 23, 18, 14, 27

M_ac29 <- d15 %>%
  filter(ECC == F) %>%
  brm(allcomps ~ 1 + nierfalen,
      family = skew_normal,
      data = .)
L_M_ac29 <- loo(M_ac29)
M_ac30 <- d15 %>%
  filter(ECC == F) %>%
  brm(allcomps ~ 1 + lengte,
      family = skew_normal,
      data = .)
L_M_ac30 <- loo(M_ac30)
M_ac31 <- d15 %>%
  filter(ECC == F) %>%
  brm(allcomps ~ 1 + gewicht,
      family = skew_normal,
      data = .)
L_M_ac31 <- loo(M_ac31)
M_ac32 <- d15 %>%
  filter(ECC == F) %>%
  brm(allcomps ~ 1 + BMI,
      family = skew_normal,
      data = .)
L_M_ac32 <- loo(M_ac32)
M_ac33 <- d15 %>%
  filter(ECC == F) %>%
  brm(allcomps ~ 1 + CVA_eerder,
      family = skew_normal,
      data = .)
L_M_ac33 <- loo(M_ac33)
M_ac34 <- d15 %>%
  filter(ECC == F) %>%
  brm(allcomps ~ 1 + multiv,
      family = skew_normal,
      data = .)
L_M_ac34 <- loo(M_ac34)
M_ac35 <- d15 %>%
  filter(ECC == F) %>%
  brm(allcomps ~ 1 + AF,
      family = skew_normal,
      data = .)
L_M_ac35 <- loo(M_ac35)
M_ac36 <- d15 %>%
  filter(ECC == F) %>%
  brm(allcomps ~ 1 + coronairchir_overig,
      family = skew_normal,
      data = .)
L_M_ac36 <- loo(M_ac36)
M_ac37 <- d15 %>%
  filter(ECC == F) %>%
  brm(allcomps ~ 1 + roker,
      family = skew_normal,
```

```
      data = .)
L_M_ac37 <- loo(M_ac37)
M_ac38 <- d15 %>%
  filter(ECC == F) %>%
  brm(allcomps ~ 1 + rooktnu,
      family = skew_normal,
      data = .)
L_M_ac38 <- loo(M_ac38)
list(L_M_ac0,
     L_M_ac29,
     L_M_ac30,
     L_M_ac31,
     L_M_ac32,
     L_M_ac33,
     L_M_ac34,
     L_M_ac35,
     L_M_ac36,
     L_M_ac37,
     L_M_ac38) %>%
  compare_IC() #order: 0

M_ac39 <- d15 %>%
  filter(ECC == F) %>%
  brm(allcomps ~ 1 + interv_datum,
      family = skew_normal,
      data = .)
L_M_ac39 <- loo(M_ac39)
M_ac40 <- d15 %>%
  filter(ECC == F) %>%
  brm(allcomps ~ 1 + start_operatie,
      family = skew_normal,
      data = .)
L_M_ac40 <- loo(M_ac40)
M_ac41 <- d15 %>%
  filter(ECC == F) %>%
  brm(allcomps ~ 1 + art_graft,
      family = skew_normal,
      data = .)
L_M_ac41 <- loo(M_ac41)
M_ac42 <- d15 %>%
  filter(ECC == F) %>%
  brm(allcomps ~ 1 + art_anast,
      family = skew_normal,
      data = .)
L_M_ac42 <- loo(M_ac42)
M_ac43 <- d15 %>%
  filter(ECC == F) %>%
  brm(allcomps ~ 1 + ven_graft,
      family = skew_normal,
      data = .)
L_M_ac43 <- loo(M_ac43)
M_ac44 <- d15 %>%
  filter(ECC == F) %>%
  brm(allcomps ~ 1 + ven_anast,
```

```
      family = skew_normal,
      data = .)
L_M_ac44 <- loo(M_ac44)
M_ac45 <- d15 %>%
  filter(ECC == F) %>%
  brm(allcomps ~ 1 + conversie,
      family = skew_normal,
      data = .)
L_M_ac45 <- loo(M_ac45)
M_ac46 <- d15 %>%
  filter(ECC == F) %>%
  brm(allcomps ~ 1 + totalgrafts,
      family = skew_normal,
      data = .)
L_M_ac46 <- loo(M_ac46)
M_ac47 <- d15 %>%
  filter(ECC == F) %>%
  brm(allcomps ~ 1 + voorstellen,
      family = skew_normal,
      data = .)
L_M_ac47 <- loo(M_ac47)
M_ac48 <- d15 %>%
  filter(ECC == F) %>%
  brm(allcomps ~ 1 + planvsuitg,
      family = skew_normal,
      data = .)
L_M_ac48 <- loo(M_ac48)
M_ac49 <- d15 %>%
  filter(ECC == F) %>%
  brm(allcomps ~ 1 + artgrdiff,
      family = skew_normal,
      data = .)
L_M_ac49 <- loo(M_ac49)
M_ac50 <- d15 %>%
  filter(ECC == F) %>%
  brm(allcomps ~ 1 + vengrdiff,
      family = skew_normal,
      data = .)
L_M_ac50 <- loo(M_ac50)
list(L_M_ac0,
     L_M_ac39,
     L_M_ac40,
     L_M_ac41,
     L_M_ac42,
     L_M_ac43,
     L_M_ac44,
     L_M_ac45,
     L_M_ac46,
     L_M_ac47,
     L_M_ac48,
     L_M_ac49,
     L_M_ac50) %>%
  compare_IC() #order: 0
```

```
#blood pressure model
M_bp77_ac <- d15 %>%
  filter(ECC == F) %>%
  brm(allcomps ~ 1 + CABGexp04 + specialisatie +
        eurolog + cardiochir_eerder + geslacht + leeftijd +
        neuro_disfunctie + postinfarct_VSR + thorac_aortachir +
        BMI + lengte + multiv + CVA_eerder +
        ven_anast + ven_graft + art_graft + conversie +
        (1 | eersteOperateur) +
        (1 + CABGexp04 + specialisatie +
        eurolog + cardiochir_eerder + geslacht + leeftijd +
          neuro_disfunctie + postinfarct_VSR + thorac_aortachir +
        BMI + lengte + multiv + CVA_eerder +
        ven_anast + ven_graft + art_graft + conversie | XXXpat) +
        (1 + CABGexp04 + specialisatie +
        eurolog + cardiochir_eerder + geslacht + leeftijd +
          neuro_disfunctie + postinfarct_VSR + thorac_aortachir +
        BMI + lengte + multiv + CVA_eerder +
        ven_anast + ven_graft + art_graft + conversie | anesthesist),
      family = exgaussian,
      cores = 4,
      inits = 0,
      data = .)
L_M_bp77_ac <- loo(M_bp77_ac)
#operation duration model
M_od73_ac <- d15 %>%
  filter(ECC == F) %>%
  brm(allcomps ~ 1 + expECC + specialisatie +
        eurolog + geslacht + urgentie +
        BMI + gewicht + multiv +
        ven_anast + ven_graft + vengrdiff +
        (1 | eersteOperateur) +
        (1 + expECC + specialisatie + eurolog + geslacht +
           urgentie + BMI + gewicht + multiv + ven_anast +
           ven_graft + vengrdiff | XXXpat) +
        (1 + expECC + specialisatie + eurolog + geslacht +
           urgentie + BMI + gewicht + multiv + ven_anast +
           ven_graft + vengrdiff | tweedeOperateur) +
        (1 + expECC + specialisatie + eurolog + geslacht +
           urgentie + BMI + gewicht + multiv + ven_anast +
           ven_graft + vengrdiff | anesthesist),
      family = exgaussian,
      cores = 4,
      inits = 0,
      data = .)
L_M_od73_ac <- loo(M_od73_ac)
list(L_M_ac0,
     L_M_bp77_ac,
     L_M_od73_ac) %>%
  compare_IC()  # order: 0, od73, bp77
```