Formalization and Quantification of the Workflow in the Catheterization Laboratory

Challenge the Future

Master Thesis K.M. van der Graaf

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Healthcare

Formalization and Quantification of the workflow in the Catheterization Laboratory

First steps towards workflow optimization and efficiency enhancement in the Catheterization Laboratory

By

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PREFACE

This report marks the end of a my 7.5 month journey to finish my master thesis for the Biomedical Engineering programme at Delft University of Technology I am proud of the result. This report also marks the end of my time as a student. It has been an amazing 6.5 years. I have learned more than I can comprehend and thought I would even make sense of, I made friends for life and I have experienced countless of inspiring and joyous moments.
I would like to use this preface to thank several people without whom this thesis could not have taken shape.

Firstly, I want the thank my supervisors Benno and John for giving me opportunity and the responsibility to execute this project independently. You have challenged me to investigate literature, implement my own methods and theories and draw my own conclusions. This experience has made me a better, more confident and relaxed researcher. I want to sincerely thank you for all the feedback, valuable time and help. I also want to thank you for your kind and positive attitude. I hope that my work can be a strong contribution to your work and the field in general. And of course, I want to thank Teddy and Maarten for providing me with additional feedback and help.

Secondly, I would like to express my gratitude for the team of the catheterization laboratory for welcoming me in the lab during procedures and also for guiding me through the procedures. Special thanks to dr Jan Constandse for introducing me to the cath lab team and to dr Bech for showing me the ins and outs of the catheterization laboratory at Haga hospital.

I want to thank all the people who took the time to review my work and provided me with valuable tips to improve my thesis. Rochelle, Meike, Nathalie and Loes your input is very much appreciated. When it is your time to graduate, I will definitely return the favour. Then, a really big shout-out to my lovely sister, a.k.a. the wizard with words, without you feedback and tips I would be lost.

And of course, I want to thank friends for the necessary distractions, laughter, encouragements and support. I cherish all the adventures we went through together.

Last but not least, I want to thank my family for being absolutely amazing. My parents for always being available and the unconditional support throughout the years. My sister for your wise words and contagious energy.
It has been a hell of a ride. I look forward to what is to come.

Kristien van der Graaf
Delft, March 2020

Executive Summary

Introduction

Cardiovascular disease is the number one cause of death in the USA and number two in the Netherlands(1, 2). In addition, it is expected that in 2030 40.5% of the population in America will be inflicted with a form of cardiovascular disease(2). The growing volumes and thereby health care costs will put a strain on hospitals and health care providers, as more individuals need to be treated with the same resources. Workflow and efficiency optimization are topics that are gaining momentum over the last years in the field of medicine (3-6). Health care providers see this as a viable solution to treat more patients and reduce the costs, i.e. increasing efficiency. This research group intend to automatically evaluate the workflow efficiency in the cath lab with use of two sensors: the X-ray imaging system and video cameras. In order to facilitate automatic workflow monitoring and optimization, prior research should be conducted, as “the initial step for improving the process is to acquire knowledge of how things are done”(7). To continue in this line of reasoning, in this research the current peri-operative workflow of the CAG procedure is formalized and quantified.

Method

We used the SPM (surgical process model) methodology to formalize the peri-operative workflow of the CAG. The role activity diagram (RAD) was chosen as the model representation. The model approach was top-down. The metrics were determined and designed based on a previous conducted literature study, the formalization of the workflow and the design criteria. The metrics were divided in two groups: 1) the high-level metrics and 2) the procedure and CAG specific metrics. To evaluate metrics two datasets were used: 1) the manually acquired dataset through observations and 2) the dataset retrieved from the X-ray imaging system. To validate the methodology, the outcomes of the metrics were compared with the experience of the cath lab team. The generalizability was tested by utilizing the phases and metrics in different endovascular procedures and in a different hospital.

Results

In total 19 metrics were created of which 11 evaluated the high-level workflow, three the procedure specific process and five the CAG specific steps. Prior the first procedure in the morning, the LA waiting time showed an average of 37 minutes and on average seven minutes are used for lab preparation. In the afternoon similar results are found: the LAs waiting time is longer than the actual lab preparation. The average percentage on-time start cases was 43%. A significant mean difference of 3.3 minutes ($p=0.041$) regarding the turn-over time was found between the two LA and three LA group. Delivery time showed a mean difference of 3.7 minutes ($p=0.004$), comparing inpatients ($M = 8.1 \pm 5.43$ minutes) to outpatients ($M = 4.4 \pm 4.4$ minutes). There was significant positive correlation between delivery times and turn-over times, $r=0.66$ ($p<0.001$). Longer delivery times resulted in longer turn-over times. The procedure time presented the highest mean and variance, $M=38.0 \pm 21.1$ minutes. The patient preparation time and post-care duration presented low variances, respectively $M=11.8 \pm 3.8$ minutes and $M=4.6 \pm 3.3$ minutes. The variability in the procedural time could be attributed to the operative phase, $M=22.4 \pm 18.8$ minutes. Within the operative phase, the duration of P1 and P2 accounted for 70% of the variability in the operative length. The X-ray imaging system was able to correctly measure consolidation of metrics describing P2, P3 and P4. The non-procedure specific metrics have the potential to be generalized to any type of procedure. Only P1 and P5 showed potential to be utilized in other endovascular procedures. The analysis in Haga hospital suggests that phases and the metrics could be generalized and therefore used in more cath labs throughout the Netherlands.

Discussion

This research has paved the way for in-depth efficiency assessment and workflow optimization in the cath lab. The cost of delay in an OR is $25 /minute(8). In the event that turnover time can be shortened by five minutes, 20 minutes of scarce lab time would be saved each day. Assuming the cost of delay in the cath lab is similar to the cost of delay in the OR, 500 $/day can be saved by optimizing the turn-over times. Moreover, the LAs wait in the morning for 20 minutes and in the afternoon for 15 minutes. In case the waiting time could be reduced with 50%, 18 minutes of wasted time would be utilized and 450 $/day would be saved. Enhancing starting time and the turn-overtime can result in saving 38 minutes that account for 950 $/day, which is approximately the scheduled time of one CAG procedure. As a result of optimization, an extra patient could be treated every day and money could be saved.

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LIST OF ABBREVIATIONS

Medical

CAG	Coronary Angiogram
HCP	Health Care Professionals
LA	Lab Assistant
Cath Lab	Catheterization Laboratory
LCA	Left Coronary Artery
RCA	Right Coronary Artery
IR	Interventional Radiology
OR	Operation Room
EHR	Electronic Health Record
CAD	Coronary artery disease
IHD	Ischemic heart disease

Technical

SPM	Surgical Process Modelling
RAD	Role Activity Diagram
CT	Computed Tomography
DES	Discrete event simulation
MRI	Magnetic Resonance Imaging
SD	Standard Deviation
SWA	Surgical Workflow Analysis
LAO	Left Anterior Obtuse
RAO	Right Anterior Obtuse
M	Mean
VBA	Virtual Basic for Applications

1 INTRODUCTION

1.1 This research: problem statement and relevance

This section will provide a background relevant to the research presented in this thesis. Firstly, the relevance of the study is discussed. Secondly, the research questions are formulated and thirdly, the structure of this thesis is presented.

1.1.1 Relevance

A fact most people are aware of is that health care costs are rising. Ultimately causing individuals to be unable to afford and access health care. To illustrate, over the last 5 years total health care costs have increased by €9 billion in the Netherlands. Logically, this undesirable phenomenon is not restricted to the Netherlands; all around the world health care costs are rising. For example, in the US the health care costs increased with $1 trillion in a period of 5 years. The increased cost can be explained in view of different developments, to be divided in three main causes: 1) The continued growth of the population with concurrent increase in life; 2) The increase in disease incidence and prevalence; and 3) the development of new and advanced technologies in health care.

The latter includes specialist medical care. Specialist medical care is the care provided in the hospital. This type of health care is the largest contributor to the total health care costs, accounting for roughly 30%, as visualized in Figure 1. When examining costs within hospitals, it has been found that operation rooms (OR) and cardiac catheterization laboratories (cath labs) are two of the most costly and resource demanding units within the hospital(9, 10).

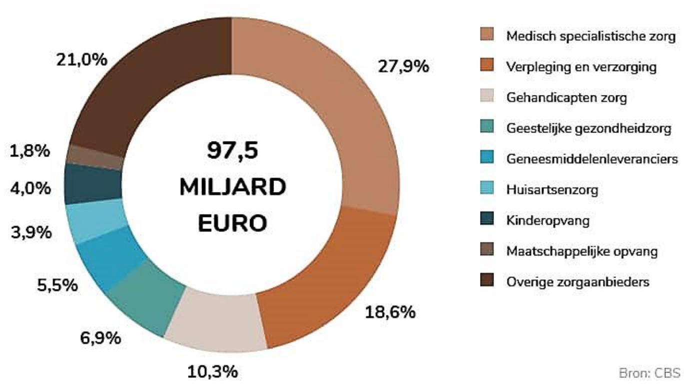

Figure 1: The health care cost divided per sector. The biggest contributor is specialist medical care with 27. 9%

It is expected that the demand for cardiac catheterization procedures will rise. The rising demand can be explained by the growing interest in minimally invasive interventions and the increased prevalence of cardiovascular diseases. The number of IR (interventional radiology) procedures has increased by 21% from 2010 to 2012 (11). To further proclaim its relevance, the range of IR procedures is extensive and still growing, as it is expected that new types of complex procedures and devices will continue to be invented.

Cardiovascular disease is the number one cause of death in the USA and number two in the Netherlands(1, 2). In addition, it is expected that in 2030 40.5% of the population in America will be inflicted with a form of cardiovascular disease(2). With this knowledge, it is likely that the cath lab volumes will exponentially increase in the near future. This most likely will tax health care providers and increase health care costs, possibly limiting health care access. The growing volumes and health care costs will put a strain on hospitals and health care providers, as more individuals need to be treated with the same resources. We aim to focus on the efficiency of cath labs. We reason that it is necessary to increase the efficiency in the cath lab to facilitate the growth in cath lab volumes and to control the costs.

1.1.2 Knowledge gap and problem description

Workflow and efficiency optimization are topics that are gaining momentum over the last years in the field of medicine (3-6). Health care providers see this as a viable solution to treat more patients and reduce the costs, i.e. increasing efficiency. The surgical workflow describes a sequence of actions and tasks that are executed to perform a procedure(9). The peri-operative workflow involves multiple actors, locations and encompasses many consequential steps, making it a complex and dependent system (12, 13). As a result, the workflow in and around the cath lab is prone to inefficiency and difficult to quantify.

Previous research has shown that optimizing the workflow is key to increasing efficiency in the operating room (9, 11, 14-16). Ang et al. (2016) have shown a yearly loss of $347,327 and 241 hours per OR, due to inefficient use of the turnover times. In recognition of the fact that the traditional OR as well as the cath lab are both labour and capital intensive departments, we can assume that they have several operational inefficiencies in common. Examples are: incorrect estimating surgical end time, inadequate scheduling and inefficient turnover times(10).

In response to the rising health care costs and growing demand for surgical procedures, the government tries to control the costs with restrictions. For example, the government aims to control the major contributor, the hospitals and the OR, by placing a limit on the expenses in the OR. As a result, less patients can be treated and queues are becoming longer. We believe that restrictions are only fighting symptoms and that they do not tackle the problem at the root cause. Therefore, hospitals and researchers should enhance the efficiency and decrease costs by optimizing the peri-operative workflow of the cath lab.

Recent studies have investigated the workflow and the efficiency in the cath lab (4, 5, 10, 12, 14, 17-19). These endeavours are commendable, but the efficiency assessments were confined to the cath lab. Efficiency in the cath lab is constrained by the events before (pre-operative) and after (post-operative) intervention in the cath lab(20, 21). Therefore, the peri-operative (pre-, post- and intra-operative) process should be reviewed in future efficiency assessment.

A research group consisting of the Technical University of Delft, Reinier de Graaf Gasthuis and Philips Health Care intend to automatically evaluate the workflow efficiency in the cath lab with use of two sensors. Through extensive programming and deep learning methods, we are able to automatically analyse the procedure and automatically identify the surgical phases and the inefficiencies. The two sensors are the X-ray imaging system and video cameras. We presume that the sensors produce interesting data on efficiency and process variations. In the event our assumptions are confirmed, these data should be gathered and analysed in a structured transparent manner.

However, the step from the collected raw data to the deliverables is too big. Because the question that needs to be answered first is: "How can one translate the data to meaningful information?" In order to achieve this, quantitative metrics are needed that describe the efficiency of the cath cab. Unfortunately, the existing metrics of efficiency are poorly defined and not standardized in the peri-operative workflow of the cath lab (14). Furthermore, based on a recent literature study, no adequate metrics are available that describe the complete workflow of the cath lab and evaluate the procedure in steps or phases.

Thus, in order to facilitate automatic workflow monitoring and optimization, prior research should be conducted, as "the initial step for improving the process is to acquire knowledge of how things are done"(7). To continue in this line of reasoning, in this research the current workflow of the cath lab is formalized and quantified

1.2 Research scope and research questions

SCOPE

This research investigates the workflow in and around the cath lab. In order to execute an in-depth research, the peri-operative workflow of one procedure is extensively researched, namely the elective coronary angiogram (CAG). As there are multiple methods to analyse the workflow in the operative environment, this research will look at it from the perspective of the cath lab.

MAIN RESEARCH QUESTION

The main research question that this thesis will answer is as follows:

How can the peri-operative workflow of the elective CAG procedure in the Cath Lab be assessed by quantitative metrics in order to evaluate its efficiency and what are the identifiers of these metrics to realize automatic (camera) detection?

To be able to answer this main research question, some other questions also need to be answered. The sub-questions in this research are:

1. What is the current situation of the OR management and in what manner is the high-level workflow of the catheterization laboratory defined?
2. What are the roles and activities of the involved health care professionals during workflow of a CAG?
3. How can we divide the peri-operative workflow of the CAG into phases?
4. Which metrics can be used or designed to quantify the peri-operative the workflow and how can the operational inefficiencies be registered?
5. What are the results of the quantification of the CAG procedure and how are they connected to the operational inefficiencies?
6. To what extent is the X-ray imaging system able to evaluate the procedural and operative metrics?
7. What are the cameras able to register and what is the consequence of the missing information?
8. What are the identifiers for real-time video-based phase recognition in order to evaluate the metrics?
9. Are the observations in line with the experience of the HCP?
10. Can this research be generalized and applied in other institutions and catheterization procedures?
11. What is the implication of this research for future endeavours?

1.3 Structure of this report: a reading guide

RQ	Activity	Method and tools	Chapter
NA	Provide back ground information about cath lab, the heart, efficiency and the surgical workflow	Literature review	Chapter 2
SQ 1	Create a general overview of the current situation of the OR management and the high-level workflow in the cath lab	Expert interview and observations	Chapter 3
SQ 2 SQ 3	Formalize the peri-operative workflow of the CAG	Literature review, expert interviews and observations	Chapter 4
SQ 4	Design quantitative metrics that evaluate the peri-operative workflow of the CAG to collect data	Literature review, expert interviews and observations	Chapter 5
SQ 5 SQ 6	Collect the manual and X-ray imaging data, analyse the results, illustrate how they are related to operational inefficiencies	VBA Excel and Matlab	Chapter 6
SQ 7 SQ 8	Identify the capabilities of the camera's and assign the identifiers to extract data points for the metrics	Observations, dosimeter data log, Matlab	Chapter 7
SQ 9	Validate the metrics by comparing the experience of the HCP with the outcomes in chapter 7	Questionnaire	Chapter 8
SQ 10	Validate the metrics by apply the methodology in the cath lab in the Haga hospital	Observation and interviews	Chapter 9
SQ 11	Discuss the results. Draw conclusions and formulate recommendations		Chapter 10

2 Background

2.1 Catheterization laboratory, the heart and coronary angiogram

The development of advanced surgical tools and new imaging systems resulted in a transformation of invasive surgical procedures and the traditional operating theatre(22). Surgical procedures and operating theatres have become increasingly technologically advanced over the course of years and therefore becoming more complex. Due to these advances and the evident trend towards minimally invasive surgery, a relatively new medical specialisation and accessory operation room emerged, namely interventional radiology (IR) and the catheterization laboratory (cath lab). IR originated from the medical field of cardiology, but nowadays a wide range of specialisations can benefit from this technique, including urology, nephrology, neurology and oncology(23). IR "refers to a range of techniques which rely on the use radiological image guidance (X-ray fluoroscopy, ultrasound, computed tomography [CT] or magnetic resonance imaging [MRI]) in order to precisely target therapy" by accessing the vessel like structures(23). Even though IR serves many specialisations, the bulk of the interventions is related to diagnosing and treating diseases of the heart.

The heart consist of four chambers: two atria and two ventricles. The heart pumps oxygen rich blood to your organs and tissues, providing with oxygen and nutrients. The oxygen rich blood leaves the heart through the aorta. The heart also need oxygen supply to execute its pumping function. The two coronary arteries, left and right coronary artery, supply the heart with oxygen rich blood. The coronary arteries arise from the aorta, branch out over the heart, supplying the heart with oxygen.

When the arteries are narrowed or occluded, the blood flow to heart muscle is reduced. Coronary artery disease (CAD) and ischemic heart disease (IHD) are used to describe the narrowing of the coronary arteries. Due to the reduced oxygen supply the heart is not able the function properly, resulting in a set of symptoms and complaints. When untreated, this can be life threatening. In order to diagnose or assess the coronary circulation, a visualisation is the LCA and the RCA is needed. This intervention is called the coronary angiogram.

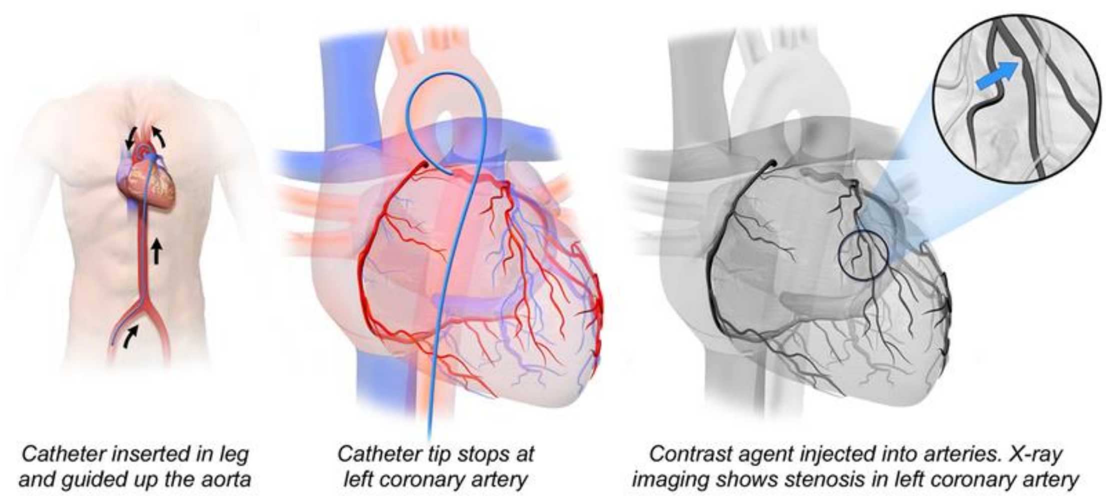

Figure 2: Visualization of the execution of the coronary angiography

2.2 Efficiency in the peri-operative workflow

Efficiency is one of six the key performance indicators (KPI) of quality in health care developed and acknowledged by the WHO(24). Indicators give hospital management and clinicians the opportunity to monitor and evaluate the quality of care. As a consequence, it is possible to make comparisons between surgeries, departments and even between hospitals, resulting in benchmarking treatments and processes(25). The scientific level of evidence and reliability of the metrics varies from evidence-based to consensus among health care professionals. According the WHO efficiency is defined as "a hospital's optimal use of inputs to yield maximal outputs, given its available resources"(24). A more recent article described efficiency in the cath lab as "the ratio of cath lab productivity(volume of cases in a period of time) to costs (e.g. time, money, nursing resources)"(14). It is known that researchers do not abide by one strict definition of efficiency, resulting in varied interpretation and use efficiency metrics. As a consequence, it is difficult to extrapolate and compare these constructs with other hospitals and departments.

KPIs used for the efficiency assessment of the entire hospital (a high-level structure) are different than the ones used for measuring efficiency in the operating room (a low level structure). However, it is important to realize that the low level structure is an element of the high-level structure, thus these KPI's are connected: the low level structure influences the outcome of the high-level outcome.

2.3 Pre-existing efficiency metrics

A recent literature study about existing metrics concerning procedures in the cath lab identified 50 different metrics to measure efficiency in the cath lab. The overview of the used metrics for efficiency is presented in appendix 12.6 . The majority of the metrics were generic constructs that were also used in other operative environments. The metrics that were utilized the most were procedure time, lab utilization, turn-over time, % of first on-time start.

2.4 Surgical process modelling

Workflow is a becoming a popular buzz word and is being analysed in many different disciplines. But what is and what does the workflow describe? The workflow describes the involved process in a "sequence of steps and actions with their temporal relation" that are conducted in to perform a medical intervention in a hospital(15).

Surgical Process Modelling[1] (SPM) presents the opportunity to gain insight in the peri-operative workflow, with "the potential to improve OR efficiency, efficacy and quality and surgical care(26)." SPM can either be descriptive or numeric(13). Numeric models can be divided based on the distinction between graphic flow charts/diagrams and the computer/quantitative models. SPM consists of 5 components with their corresponding aspects. The five components are: 1) granularity level, 2) data acquisition method, 3) model representation, 4) modelling approach or analysis, 5) generalization. The purpose and goal of the study dictates the combination and completion of the above components. In the following sections a brief explanation is provided of the six components and their elements. Nevertheless, in case a higher level of detailed information is desired, including advantages and disadvantages for each option, the articles of Gholinejad et al. (2019) and Lalys et al. (2014) are able to clarify these topics(2, 16).

2.4.1 Granularity level

The description of the workflow in the operating room can be constructed at different granularity levels. Granularity level specifies the level of detail and abstraction at which the workflow is described. For the description of SPM Lalys et al.(27) distinguished six levels of granularity, from low to high: 1) the procedure, 2) phase, 3) step, 4) activity, 5) motion and 6) low-level information.

2.4.2 Data acquisition

The data acquisition is determined by the granularity level of the process you desire to model. Data is either manual or computer based acquired. Manual acquisition is performed by a human observer. The human observer collects the data via documentation, interviews, literature studies or by observing the process online (being physically present in the OR) or offline (analysing video recordings of the process in the OR)(13, 27). Computer based acquisition is realized through the use of sensors. Ultimately leading to automated data acquisition and real-time sensing(9).

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[1] *"SPM has been defined a simplified pattern of the surgical process, SP, (sequence of consecutive steps in the workflow) that reflects a predefined subset of interest of the SP in a formal or semi-formal representation"(9)*

2.4.3 Model representation

The range of model representation in SPM is wide and involves many concepts. The models can either be described as numeric or descriptive(13). Descriptive models simply includes plain text description of the workflow. In contrary to descriptive models, a wide variety of concepts fall under the scope of numeric models, ranging from workflow block schemes and flow diagrams to (automated) computer models(13). Due to the ambiguity of the concept of a numeric model, I propose another distinction among numeric models, namely qualitative and quantitative models. Qualitative models are models that visualize the workflow by means of block schemes, flow diagrams and use methods such as value stream mapping. The striking distinction between the qualitative and quantitative models is that the quantitative models are subject to input data and by means of an algorithm or other techniques generate an (numeric) output. The purpose of the study determines the model representation.

2.4.4 Modelling approach or analysis

There are multiple techniques available to make the step from data to model, including machine learning, pattern recognition and statistical approaches. But the granularity of the workflow you desire to model, limits your options. In the study of van Luyn et al. (2017) the techniques applicable for analysis are discussed in detail(28).

2.4.5 Generalization

Generalization explains to what extend the model can be used in different situations and in this case medical procedures(13). In the event that the model has in high-level granularity and represent a unique and specific procedure, the possibility that we are able to generalize the model to any other situation is highly unlikely. However, even if the model is generalizable, one must take into account the heterogeneity of the data, as it directly affects the generalizability of the model (13, 29).

3 THE CURRENT SITUATION OF THE PLANNING, THE SCHEDULE AND THE SET-UP IN THE CATH LAB

Reinier the Graaf Group(RDGG) is a hospital situated in Delft the Netherlands. RDGG is equipped with 2 cath labs, albeit only one in use. In the cath lab a number of image-guided interventions are performed using Allura Clarity of Philips. Last year, from 01/02/2019 to 21/02/2020, a total of 1093 procedures were performed in the cath lab, of which 909 cases were coronary angiograms. In this section the current situation with respect to the planning, schedule and the set-up in the cath lab is explained.

3.1 The planning and the schedule of the cath lab

3.1.1 Approach and planning in general

In the RDGG the HIX software is used for electronic health record. In HIX the schedule of the cath lab can be created. Despite this feature, the planners make use a paper calendar for their own administration. The schedule in HIX is visible for all the health care professionals (HCP). The schedule in HIX prevails over the paper calendar. The cardiologists request the procedures and the patient is added on the to do list of the planners. The patients are scheduled on a first come first serve basis, meaning that the patient name highest on the to do list is scheduled in first. The schedule of the cath lab is planned week by week, every Friday the schedule is sent to the HCP for the next week. The schedule is static. Static schedules do not update the scheduled times in case of delays or adjustments. Before the summer of 2019 there was a waiting list of 100 patients, which corresponds with a waiting time of 10 weeks. The morning sessions last from 08:30 to 12:30. The afternoon sessions last from 13:30 to 17:00.

3.1.2 The timeframes used for the planning of the interventions

Every procedure in the cath lab has standardized scheduled duration. The scheduled time for a CAG is 45 minutes. The scheduled duration is based on the input of the cath lab team. The interpretation and definition of the starting and end time of the procedure varies among the health care professionals and planners. An overview of the wielded interpretation and definition is shown in Table 1.

Table 1: Interpretation and definition of the starting and endpoint for the endovascular procedures by different disciplines

	LA	Planners	Cardiologists
Starting time of procedure	- Entry patient cath lab - Injection anaesthetics in the wrist	- Entry patient cath lab - Injection anaesthetics in the wrist	- Entry patient cath lab - Injection anaesthetics in the wrist
Ending time of procedure	- Compression band	- Exit patient cath lab	- Compression band - Exit patient cath lab

3.1.3 The set-up and other rooms

The cath lab consist of the control room and the 'procedure room'. In the control room two software systems are used to monitor and log details of the procedure. The two software systems are DoseWise and Xper information system. DoseWise is a software that is created to gain insight in the radiation dose by registering every X-ray acquisition in a database. In addition, DoseWise collects the acquired videos and the imaging details of the X-ray imaging system. Xper information systems facilitates manual logging of the utilized instruments and procedure details, such as patient entry/exit and realizing accessing the endovascular in the arteria radialis. In addition, in Xper information system the monitoring LA is able to take snapshots of heart function (i.e. frequency blood pressure, O2 saturation) and include it in the heart function report. The details from both systems are processed in the EHR. The acquired procedure details together with cardiologists' evaluation about the CAG form the basis for the heart function report. In Figure 3 the set-up in the control room is shown. The cath lab is connected to the ward and the lounge. The lounge is reserved for outpatients. The ward is reserved for inpatients. However, in the event of shortage of personnel, outpatients can also be admitted to ward (as there is not enough personnel to staff the lounge). The nurses prepare the patient in the ward or lounge prior to the intervention. Once the procedure is completed, the patient is returned to the ward and observed and cared for. After four hours the patients is discharged.

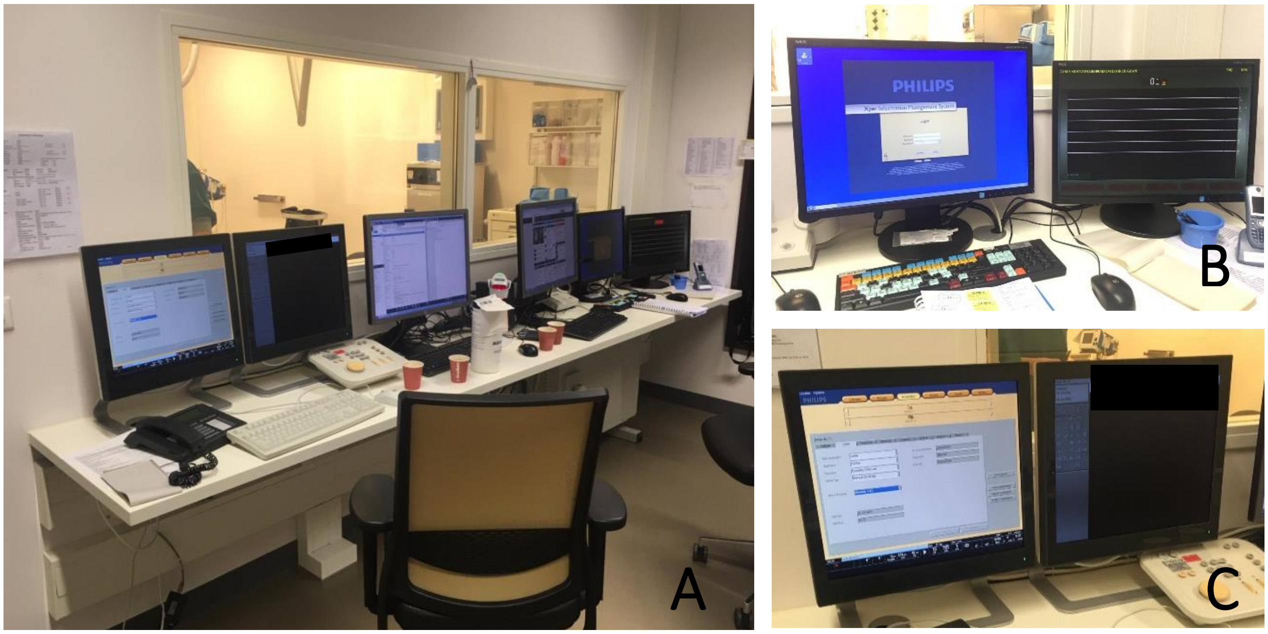


Figure 3: A) Visualisation of the control room of the Cath lab. The first 2 computers on the left run the DoseWise software and save the imaging of the X-ray imaging system(B). The 2 computer on the right are equipped with Xper information system (C)

3.1.4 Conditions the planners use

1. According to the planner two places every week are reserved for the emergency cases, but in practice it is more
2. Breaks of 15 minutes are scheduled after two scheduled procedures
3. In the morning (08:30 - 12:30) maximum five CAG cases and in the afternoon (13:00 – 17:30) maximum four CAG cases
4. In case of a busy morning room (for delay) is left in the afternoon
5. Outpatients are scheduled first, then the inpatients, as it is easier to cancel inpatient than outpatient
6. The number of daily scheduled outpatient are constrained by the number of available bed in the ward and the lounge
7. The number of available beds is constrained by the number of nurses available for the pre and after care of the patients

3.1.5 Team composition and communication between the HCP

The team in the cath lab consists of one cardiologists and two or three laboratory assistants. The team can be either present in the cath lab or in the control room. The LAs are assigned with different tasks during the procedure. Depending on availability of the LAs and the schedule in the cath lab either two or three are assigned to the cath lab. In Figure 4 an overview is provided of the team composition with their main tasks. LA 3 has the main function that is otherwise known as the roulating. The roulating LA provides the sterile LA and cardiologist with extra assistance. In the event that the cath lab team is composed of two LAs, the roles and tasks of the second LA and third LA are merged.

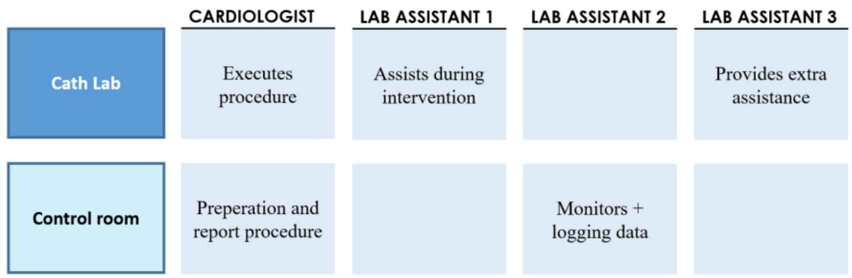


Figure 4: The team composition in the cath lab and their main tasks

The cath lab team does not adhere to the schedule. The planning in HIX serves as a guideline and check list with patients for the cath lab team.

3.2 Conclusion and the key take-away

There is mismatch in the comprehension of the starting and ending time or the scheduled procedure time. As a result different time stamps are logged. These administrative tasks have a lower priority than patient care. As a consequence the logged time stamps that coincide with readying the patient, are not accurate representations of reality. The logged time stamps that coincide with readying the patient are patient entry, patient on table, and inserting lidocaine in the wrist. There is no specific reason for the planning of two or three LA.

Comparing the available time is to the scheduled time, shows that the schedule has only 15 minutes left for delays in the morning and 25 minutes in the afternoon. The calculations are shown in the section below and based on the hours available for the procedure and the maximum number of procedures that can be scheduled. The morning session ranges from 08:30 to 12:30 and having a maximum five scheduled CAG. The afternoon session ranges from 13:00 to 17:00, having a maximum four scheduled CAG cases.

- 5 * 45 = 225 minutes procedure time morning
- 4 * 4 = 180 minutes procedure time in the afternoon
- 4 * 60 = 240 minutes time in the morning
- 3 * 60 = 190 minutes time in the afternoon
- 15 minutes of slack in the morning and 25 minutes in the afternoon

4 THE FORMALIZATION OF THE PERI – OPERATIVE WORKFLOW OF THE CAG PROCEDURE

In order to create a SPM of the peri-operative workflow of the CAG, the theoretical framework described in section 2.4 was used. The granularity level was set at activity level. The data acquisition was conducted manually. Multiple procedures were observed to extract their sequence of steps and tasks with their temporal relation. The role activity diagram (RAD) was chosen as the model representation. The model approach was top-down, meaning that we started with analysing the high-level structures and worked our day down to the activity level.

4.1 High-level overview of the workflow of the cath lab

In Figure 5 a visualisation is provided to illustrate the high-level workflow and the phases of the cath lab. The main phases are the lab preparation, the procedure, the turnaround and the clean-up. The day in the cath lab starts around 08:15. The nurses prepare the room for the first patient. The procedure commences as the patient enters the cath lab and procedure concludes the moment the patient exits the lab. Subsequently patient exit, the LAs convert the cath lab for the next patients. This phase is otherwise known as the turnaround. The procedure and the turnaround, together defined as the cycle time, iterate until the break. Prior to the break the LAs need to clean up the remainders of the previous procedure. The room is prepared for the next patient after the break. The lab preparation that is succeeding the break consists of less tasks than the lab preparation for the first case of the day. To conclude the day, the LAs clean up and finish the day with restocking the equipment.

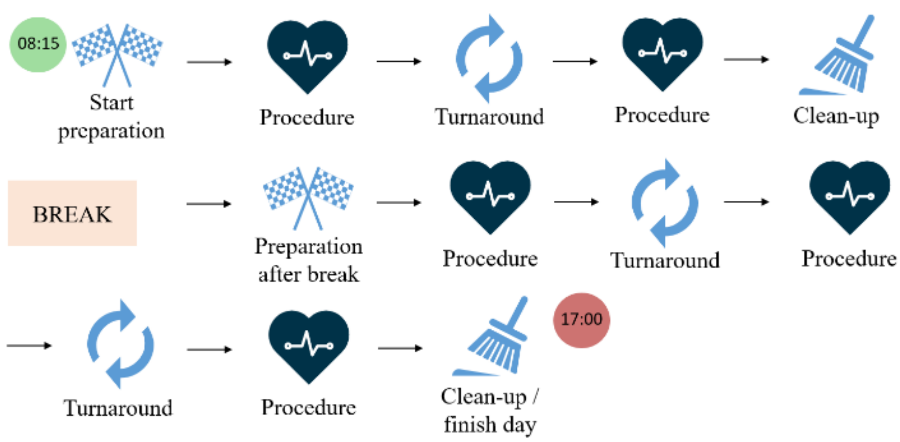


Figure 5: High-level overview of the workflow in the cath lab

4.2 Phases of the peri-operative workflow of the CAG procedure

In order to evaluate the workflow an analysis was conducted based on the activities of cath lab team. The workflow was structured in a role activity table. The workflow was disassembled in consecutive and parallel activities. In appendix 12.1 the complete role activity table is presented.

The role activity table was used as the guideline to allocate the phases in the workflow. The phases were created in agreement with the cardiologists of the RDGG hospital. The high-level workflow was divided in the four phases:

1. *Lab preparation*
   In this phase the lab is prepared for the patient
2. *The procedure*
   The time the patient is in the cath lab

3. *The turnaround*
   The phase to in which the lab is readied for the next patient. The resources of the previous patients and the lab are cleaned up and the lab is prepared for the next patient
4. *The clean-up*
   The resources and the supplies of the procedure and the lab are cleaned.

The procedure can be divided in three phases:
1. *The patient preparation phase*
   In this phase the patient has entered the room and is being prepared for the CAG
2. *The operative phase*
   In this phase the coronary angiogram is executed
3. *The post-care phase*
   In this phase the patient the procedure is finalized and patient prepared to leave the cath lab

The operative phase was divided in five phases:

Phase 1. Realizing endovascular access
Phase 2. Insert the catheter and leading it to the upper aorta arch
Phase 3. Entering and recording the first coronary artery
Phase 4. Entering and recording the second coronary artery
Phase 5. Removing the catheter and closing the entry wound

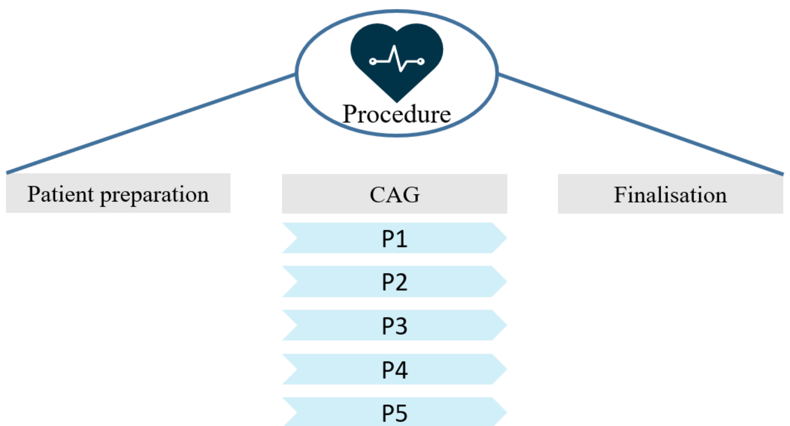


Figure 6: Visualization of the phases inside the CAG procedure. The letter P denotes the phase.

4.3 Role activity diagram (RAD) of the CAG procedure

4.3.1 The RAD methodology

Multiple exist methods to formalize the workflow. The methodology is chosen, based on the desired level of understanding of the workflow. An overview of the modelling methods is presented in Table 2. Currently the state of the art methodology used in literature are process based flowcharts(7). Despite flowcharts are insightful, they lack the ability to evaluate parallel and collaborative processes.

Table 2: Classification of process modelling methods for process redesign in healthcare. Courtesy of Shukla et al. (2014)

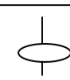
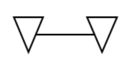
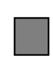
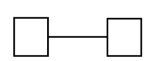
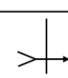
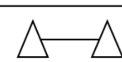
Capability / Methods	Information Flow	Sequential Processes	Parallel Processes	Collaborative Processes
DFDs	Yes	No	No	No
Flowchart	Yes	Sequential flow of actions	No	No
IDEF0	Yes	Yes	Not easy to visualize	No
IDEF3	Yes	Yes	Yes	No
VSM	Yes	Yes	Yes	No
RAD	Yes	Yes	Yes	Represents collaboration among roles

In contrast to flowcharts, role activity diagrams (RAD) provide greater understanding of the workflow in the hospitals. RAD is able to "represent complex process relations and interactions between clinicians and staff"(7) and the model is easy to understand. For these reasons the proposed RAD methodology in the article of Shukla et al. (2014) is used to formalize the workflow. However, due to monetary reasons, this author was not able to use Microsoft Visio and therefore manually created the RAD. In

the graphical representations of the RAD concepts are illustrated.

In order to create a RAD of the workflow, an analysis was conducted based on the activities of cath lab team. The workflow was structured in a role activity table. A subset of role activity table in appendix 12.1 is used for the creation of the RAD.

Table 3: Description of the RAD concepts and its graphical notation. A subset of the concepts used in the article of Shukla et al. (2014)

RAD concept	***Capability type***	***General description***	***Graphical notation***
Role	Collaboration	A role performs a set of actions in order to fulfil a particular responsibility within a process. Roles are usually performed by an individual, group of people, IT system, and machine or equipment	
State	State transitions	A state describes what is true either before or after some actions (actions can encompass activities, interactions, and encapsulated processes).	
Case refinement	Sequential Process	The case refinement is used to represent decision question and possible outcomes.	
Activity	Sequential or Parallel process	An activity is a unit of work performed by a particular role	
Interaction	Information flow or Collaboration	People collaborate in order to achieve the service delivery process objective.	
Trigger	Sequential Process	Trigger is an event that starts the activity thread	
Encapsulated process	Hierarchy	The encapsulated process allows us to represent complex sub-processes as a separate diagram and indicating it as a symbol in the main diagram	
Part refinement	Parallel Process	The part refinement symbol refers to the work done simultaneously by a role. This is graphically represented by single thread of activity dividing into parallel threads within a role.	

4.3.2 RAD of the elective CAG procedures

The complete RAD model of the workflow consist of four separate RAD models: cath lab preparation, the procedure, the CAG and the turnaround. Figure 7 shows the flow between these RADs.

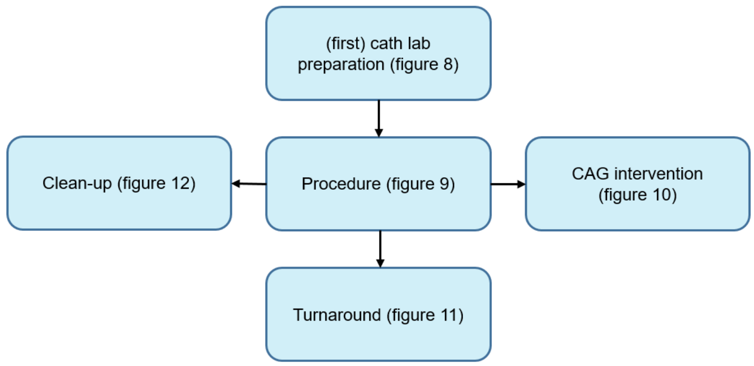


Figure 7: RAD model for the workflow of the CAG intervention, divided into the cath lab preparation, procedure, CAG intervention and the turnaround.

The cath lab preparation starts with the arrival of the LAs in the cath lab, illustrated Figure 8. The LAs assess if the lab is clean, turn on the devices and continue with preparing the lab and the equipment for the first patient. Meanwhile, the nursing staff allocates the patient and prepares him/her for the procedure. The cardiologist arrives after the morning meeting is finished and starts to prepare herself for the procedure. The LA request the patient if the lab is prepared and the cardiologist is (almost) present. The procedures starts the moment the patients enters the cath lab.

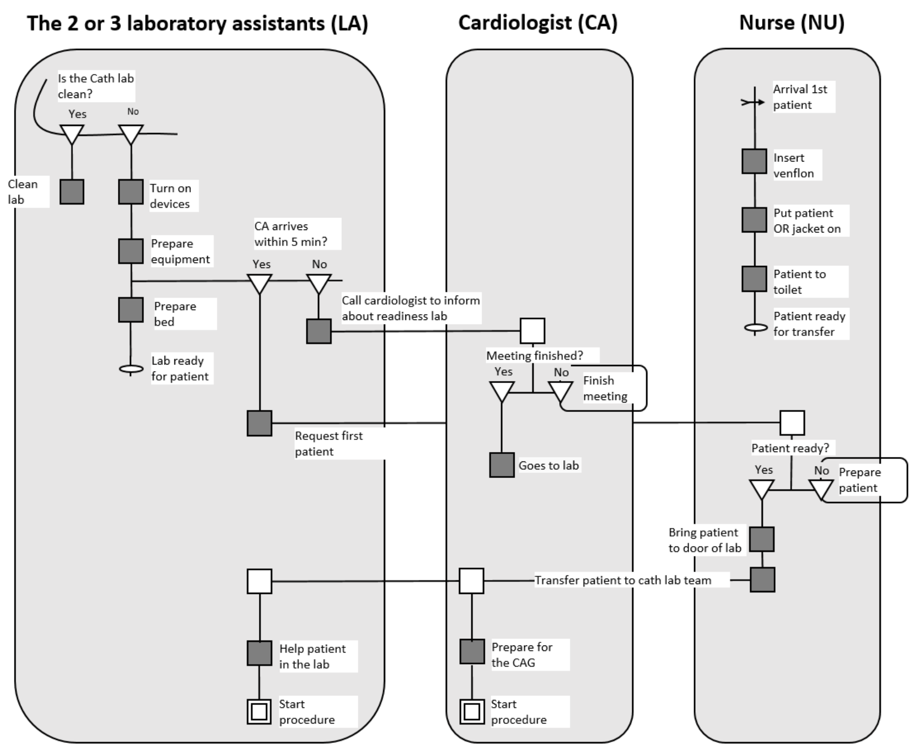


Figure 8: The RAD model of the cath lab preparation for the procedure, involving 2 or 3 laboratory assistants, a cardiologists and the nursing staff on the ward

Figure 9 succeeds Figure 8, Figure 9 is a visualization of the process steps of the CAG procedure. The procedure is divided in 3 phases: 1) the patient preparation, 2) the CAG intervention and 3) the finalization of the procedure. The RAD model of the CAG intervention is shown in Figure 10.

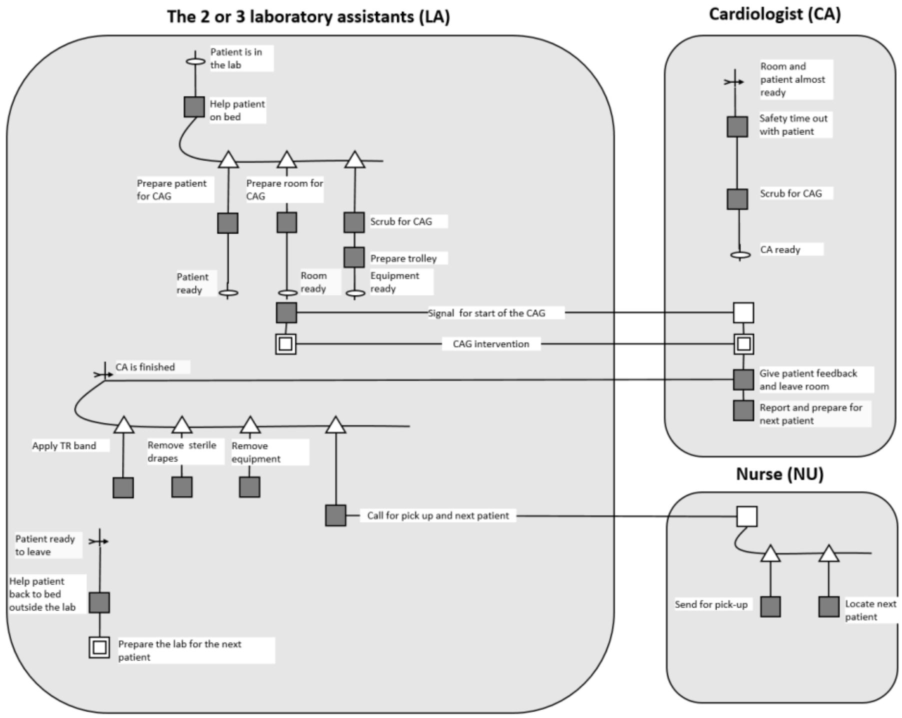


Figure 9: The RAD model of the CAG procedure, involving the 2 or 3 laboratory assistants, a cardiologists and the nursing staff on the ward.

The first step of the CAG intervention is the needle incision. During the CAG intervention the LAs are divided in 3 roles: the assisting LA, the roulating LA and the monitoring LA. The assisting LA is in the cath lab with the cardiologist and assists the cardiologist. The roulating LA provides extra assistance for the cardiologist and assisting LA. The roulating LA is allocated in the control room. The monitoring LA monitors the cardiac performance of the patients. The monitoring and roulating LA can be merged to one role.

The CAG intervention is divided in five phases, but it is possible to have a repetition of the first two phases. Repetition is due to the fact that the possibility exists cardiologists are not able realize endovascular access or guide the catheter up to the aorta arch. The endovascular access route can be realized through the wrist (the radialis) or the groin (the femoralis). The favourable route is the arteria radialis due to lower complication rate, procedure time and recovery time. However, in the event the access route cannot be realized through the wrist (phase 1) or the catheter cannot reach the aorta arch (phase 2), the cardiologist has the option to use the left arteria radialis and/or the arteria femoralis as an access route. Once the catheter has reached the aorta arch, the cardiologist has to execute sequential steps to image and record the RCA and the LCA. The last step of the intervention is to realize wound closure. The wound is closed by means of a compression band, also referred to as the TR band. The process steps of the procedure continue in Figure 9.

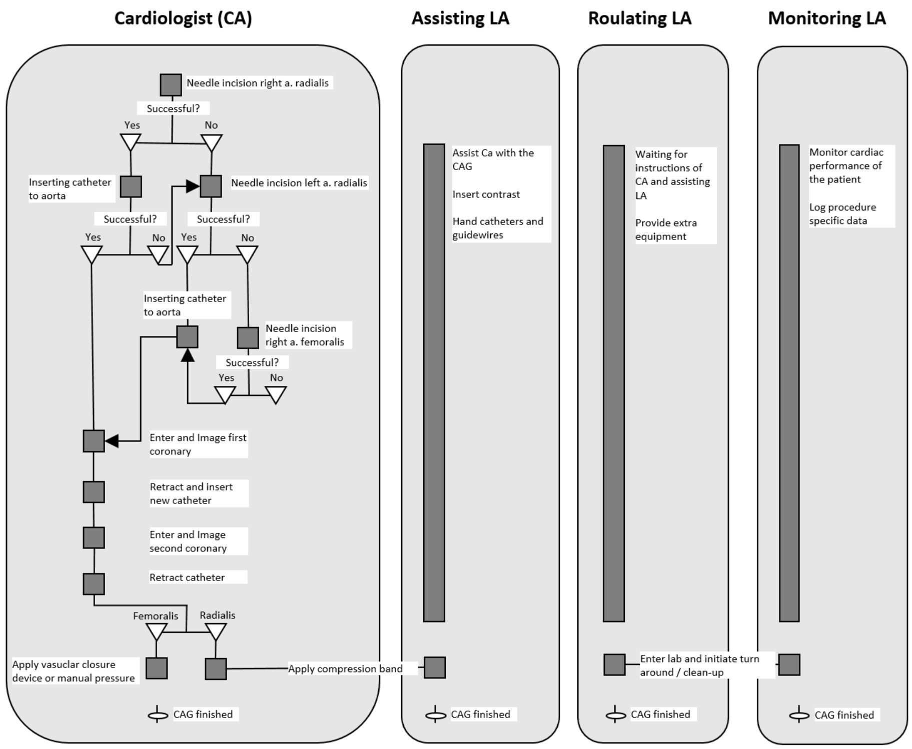


Figure 10: The RAD model of the CAG intervention, involving a cardiologists and the assisting, roulating and monitoring LA. In case of 2 LAs the roulating and monitoring LA is converged to one role.

The turnaround is shown in Figure 11. During this phase the LA convert the lab for the next patient. This consists of cleaning up after the previous patient and preparing cath lab room ready for the next patient.

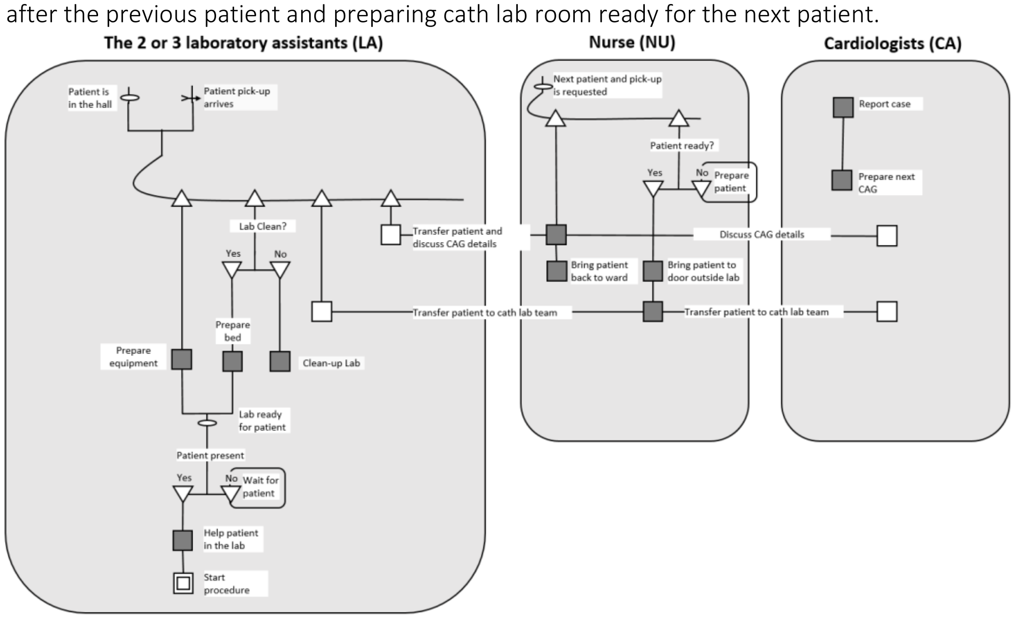


Figure 11: The RAD model of the turnaround, involving the 2 or 3 laboratory assistants, a cardiologists and the nursing staff on the ward

4.3.3 Deviations in process steps in the RAD of the workflow of the CAG procedure

The RAD models present the standardized process steps of the workflow. Even though, one should realize that the process steps are subjected to variation, as working in a surgical environment is unpredictable and requires flexibility from the health care personnel. Due to the fact that the workflow consists of parallel and collaborative steps and is situated in a fast-paced environment, it can occur that steps that belong to the next phase have already been executed in the prior phase. To gain insight in the deviations from the standardized RAD, the deviations are outlined in the section below.

CATH LAB PREPARATION

- The steps that are required to prepare the cath lab after the break consist of less tasks than the preparation of the first case of the day. On the first session of the day the equipment and software has to be turned on.
- Room set-up can be changed if the cardiologists wishes to use the left arteria radialis to realize endovascular access
- The LA can choose to pick-up the patient themselves
- The tasks that are listed for the LAs in the appendix 12.1 can be shuffled in order of execution and by role

THE PROCEDURE

- The safety check is done prior to the first step of the operative phase
- There is no exact temporal relation for the request of the next patient
- In general the RCA is filmed first followed by the LCA, but reversal is possible

THE CAG INTERVENTION

- The cardiologist executes the CAG intervention without the assistance of the LA
- In case the arterial access in the right wrist was unsuccessful, some cardiologist chose to directly convert to a CAG femoralis, instead of trying to achieve arterial access through the left wrist.

THE TURN AROUND

- The LA can choose to pick-up and patient to the ward/lounge by themselves
- The LA can choose to bring back the patient to the ward/lounge by themselves
- After several (generally two or three) sequential procedures, the cath lab team can choose to have a small coffee break

4.4 Conclusions and key take-away

The peri-operative workflow consists of many sequential, parallel and collaborative steps. Long sequential tasks and repetitions of activities can be sensitive to inefficiencies and delays, as the previous task must be completed in order to execute the next. In general can be stated that the content of the phase is constrained to a specific set of activities. Nonetheless, it occurs that tasks and activities are shuffled in order of execution and by role, with the exception of the operative phase. For the reason that the patient preparation, turnover and lab preparation consist of parallel activities, they can be executed in a different sequence. Resulting in a large variation in the sequence of the process steps. On the contrary, the activities in the operative phase have to be executed in a specific order of sequence to complete the intervention.

5 METRICS FOR THE QUANTIFICATION OF THE PERI-OPERATIVE WORKFLOW

In this chapter the metrics to quantify the workflow are introduced. The metrics were determined and designed based on a previous conducted literature study, the formalization of the workflow and design criteria. The metrics were divided in two groups: 1) the high-level metrics and 2) the procedure and CAG specific metrics. The metrics were approved by the cardiologists of the RDGG hospital.

5.1 Design criteria

The design criteria for the quantitative metrics are as follows:

- Explanatory and in correspondence with the phases of the peri-operative workflow of the CAG procedure
- Linked to fixed step or activity in the workflow
- Mutually exclusive and collectively exhaustive
- Defined variables for quantification
- Intuitively for health care professionals
- In agreement with expert opinions

5.2 High-level metrics

The high-level metrics quantify the processes of the workflow that are not related to a specific procedure. The high-level metrics explain how the processes of the peri-operative workflow are aligned. The metrics and its definition are illustrated in Table 4. Percentage first case on-time start, turn-over time, room utilization, cycle time and average imprecision (overtime and under time) were found in studies which were utilized to evaluate the efficiency in the cath lab.

Table 4: The high-level metrics of efficiency and the corresponding definition of the created variables for quantification

Metric	Definition and/or variables for quantification
First case on-time start (%)	The duration between the designated cath lab start time and patient arrival was ≤10 min and the physician was present within 10 min of the designated cath lab start time or within 10 min of the patient arrival to the cath lab (17)
Patient waiting time	Start: Patient transfer from nurses to the cath lab team End: Patient entry in the cath Lab
Patient delivery time	Start: LA request new patient End: Patient transfer from nurses to the cath lab team
Cath lab preparation time	Σ(duration of the fragmented steps needed to prepare the cath lab for the patient by the LAs)
LA waiting time	(Patient entry cath lab – Arrival cath lab LAs) – cath lab preparation time
Clean – up time	Start: Patients exit out the End: LAs finish with the with finalizing the cath lab
Turn-over time	$entry\_patient(x+1) - exit\_patient(x)$ (5, 12, 14, 17, 30)
Procedure time	Start: Patient entry in the cath Lab End: Patient exit in the cath lab
Cycle time	Procedure time + Turnaround time
Lab utilization	Hours lab used / hours lab staffed (5)
Average imprecision	The difference between the planned time and the observed time of the procedure(31)

cath lab = Catheterization laboratory – LA = laboratory assistant

5.3 Procedure and CAG specific metrics

The procedure specific metrics quantify the processes that occur in the cath lab while the patient is present, without the specification of the intervention. These metrics can explain how the processes of the intra-operative workflow are aligned and evaluate how efficient the procedure and the interventions are. The metrics procedure time can be decomposed in three metrics: 1) the patient preparation time, 2) the operative length and 3) the post-care duration. These three metrics explain the workflow and efficiency of the procedure. To evaluate the intervention, operative specific metrics have to be created. For the aim of this research the metrics were created for the CAG procedure. Five metrics describe the CAG intervention, denoted as P1, P2, P3, P3 and P5. The procedure and CAG specific metrics and its definitions are illustrated in Table 5

Table 5: The procedure and CAG specific metrics of efficiency and the corresponding definition of the created variables for quantification

Metric	Definition and/or variables for calculation
Patient preparation time	Start: Patient entry in the cath Lab End: Start needle incision
Operative length	Start: Start needle incision End: Application of the compression band
Duration P1	Start: Start needle incision End: Insert medication through the transducer
Duration P2	Start: Insert medication through the transducer End: Catheter arrives in the upper aorta arch
Duration P3	Start: Catheter arrives in the upper aorta arch End: First guide wire and catheter are removed from the artery
Duration P4	Start: The second guidewire and catheter is inserted in the artery End: Second guide wire and catheter are removed from the artery
Duration P5	Start: Second guide wire and catheter are removed from the artery End: Application of the compression band
Post-op care duration	Start: Application of the compression band End: Patient exit in the cath lab

5.4 Listing the inefficient events, deviations and complications in the workflow

In order to the gain insight into efficiency of the workflow every abnormality, deviation from the standard or disarranged process steps were documented. These events deteriorate the workflow and the efficiency in the cath lab environment. By eliminating these the inefficiencies in the process, it is possible to streamline the process and increase the efficiency. Based on previous literature research and observations in the cath lab of most frequent events that impair the workflow were listed.

1. Cath lab team and cath lab ready for patient, but the patient is not present
    - Patient is lost
    - Cath lab team not ready
    - Doctor arrives too late at the cath lab room
2. Little awareness of health care professionals about the schedule and starting times of the procedures
3. Difficulties finding arteries to execute the needle incision to ensure endovascular access
4. Difficulties inserting guidewire and catheter through the arteria radialis to the aorta arch
5. Patient not properly prepared
    - The intravenous was access not realized
6. Schedule was incorrect or not up to date
7. Supplies not available
8. Transformation to CAG femoralis
    - Arterial spasm or tortuosity

5.5 Conclusions and key take-away

In total 19 metrics were created of which 11 evaluate the high-level workflow, three the procedure specific process and 5 the CAG specific steps. Starting from high-level to more detail information about the procedure. All the metrics were time related. The list of metrics consist of pre-existing constructs and newly designed metrics. The majority of pre-existing metrics are in the high-level segment, namely turnover time, lab utilization, procedure time and % on-time starts. These metrics are well-known concepts and frequently used to describe the efficiency in the OR. Even though the cath lab has many things in common with the OR, several metrics were customized for the cath lab setting. The newly designed metrics were established based on the formalization of the CAG and verified by the cardiologist in the RDGG.

6 IDENTIFIERS FOR THE CAMERA-BASED EVALUATION

In this chapter the camera-based evaluation is discussed. First the capabilities and the constraints are discussed. Followed by the evaluation of the features that can be filmed by the cameras and used to identify and extract the variables for evaluation efficiency metrics.

6.1 The capabilities and constraints of the camera system: assessment of the missing information

It is of utmost importance to investigate what is needed and required to create a complete holistic functioning system. What information and context cannot be analysed by the sensor, but are essential to ensure correct analysis? The cameras are not able to register the events which occur outside the cath lab. The locations were other workflow related activities take place are the hall and the control room. The camera system is not able to measure following variables:

- The duration between the designated Cath Lab start time and patient arrival
- On-time arrival of the cardiologist
- Patient transfer to the cath lab team
- Patient request
- LA waiting time for the start of the procedure

As a consequence the metrics first on-time case, patient delivery and patient waiting time cannot be measured. Beside the metrics, other concepts exist that the camera system cannot correctly register and analyse. Due to the fact that the schedule is static, changes are verbally communicated among the staff and are not updated in the schedule. Concepts such as (sub sequential) delays, cancellations and changes in the schedule cannot be assessed.

6.2 Possible features for the extraction of variables

Identifiers can be divided 3 groups: 1) the equipment, X-ray imaging system, 2) the movement, activities and presence of the actors and 3) the instruments. In Table 6 the variables of the metrics with their corresponding identifiers are demonstrated.

The X-Ray imaging system consists roughly of the patient bed and the CT arch. The cardiologists control the movement of the bed and the CT-arch with a panel that is connected to the bed. With the use of two pedals the cardiologist initiate fluoroscopy or a stationary acquisition. Fluoroscopy is used for navigation through the arteries and has lower dose and resolution. The stationary acquisition denotes the recording of the films of the LCA and the RCA and has a higher dose and resolution. In DoseWise database detailed information of the imaging acquisition are registered. The detailed information ranges from position and angulation of the image intensifier to the time, type and duration of every acquisition. Additionally, the DoseWise database includes the corresponding procedure, operator and generalized information about the patient. This database can be used as a second input for analysing the workflow and the progression of procedures in the cath Lab. The position and angulation of the CT-arch can be used for determining the CAG specific phases. The recordings of the coronary arteries are standardized with respect to positioning of the CT arch and the sequence of recordings. The CT-arch can make a left-right and caudal-cranial angulation. The RCA requires two or three recordings and the LCA four or five recordings. Every recording has a specific range regarding left-right and caudal-cranial angulation.

At the beginning of the intervention the arm is in rest position, corresponding with 0° left-right and 0° cranial-caudal angulation. In general the cardiologists start with the recordings of the RCA. The first acquisition (fluoroscopy) is realized as the catheter has arrived in the aorta arch corresponding with a 0° left-right and 0° cranial-caudal angulation. The possibility exists that prior to the first acquisition the arm is already moved in the position for the first recording corresponding with a LAO 30° – 40 ° and caudal 0° angulation. In the event that the cardiologist experiences resistance in the arteria radialis manipulating the catheter to the aorta arch, the first acquisition can be acquired of the right arm and/or elbow. While recording the LCA and the RCA, it is preferred to keep the angulation as small as possible to minimize the scatter radiation.

The standardized angulations of image intensifier for the recording of the RCA and the LCA are described in the next sections. These are standardized angulations of the image intensifier based on the input of the cardiologists and the protocol of the CAG intervention.

Figure 12: The position and angulation of the CT-arch and the image intensifier

Figure 13: Rest position of the X-ray Imaging system. Both the angulations are 0°

The 3 recordings in standard order of sequence of the RCA are: 1) LAO 30° – 40 ° & Caudal 0°, 2) RAO 30° – 40° & Caudal 30 - 40° , 3) LAO 30 – 40 ° & Cranial 30 – 40 °. The angulation of the first recording is shown in . The ostium of the RCA. This recording is not obligatory and can be left out.

The 5 recordings of the LCA are: 1) LAO 30° – 40 ° & Caudal 0°, 2) LAO 30° – 40° & Caudal 30° - 40° , 3) LAO 30 ° & Cranial 30 °, 4) RAO 0° – 20° & Cranial 30° - 40° , 5a) RAO 20° & Caudal 20° and 5b) RAO 20° & Caudal 40°. Recording 1 is not obligatory is and can be left out. Recording 5b is done when 5a does not provide an appropriate recording.

The present actors in the workflow are the cardiologists, LAs, patients and nursing staff. Distinguishing between sterile assistant and cardiologist can be done based on position at the table and tasks. The movements of the hands of the cardiologists and the LA are characteristic for the activities and tasks in each phase.

The instruments that are used in each phase are unique and only used in that specific phase. A list of the most frequent used is demonstrated in appendix 12.3.

Table 6: The identifiers of the variables of the high-level specific metrics for automatic detection by the camera system

Definition and/or variables for calculation	Identifier or marker for camera system and machine learning
The duration between the designated cath Lab start time and patient arrival was ≤10 min and the Physician was present within 10 min of the designated cath lab start time or within 10 min of the patient arrival to the cath lab	Cannot be identified – cannot determine the start time of the procedure
	Cannot be identified – low resolution camera in the hall
Patient transfer from nurses to the cath lab team	Cannot be identified – low resolution camera in the hall
Patient entry in the cath Lab	Presence involved actors
Patient exit in the cath lab	Cannot be identified
Patient transfer from nurses to the cath lab team	Cannot be identified – low resolution camera in the hall
Fragmented steps needed to prepare the cath lab for the patient by the LAs	Presence involved actors and the corresponding activities
LAs request new patient	Presence involved actors
LAs arrive at the cath lab for the first case	Presence involved actors
LAs finish with the with finalizing the cath lab	Presence involved actors
The planned time and the observed time of the procedure	Consist of previous defined variable. For the planned time predetermined values are set (see appendix 12.3 for complete list of all the procedure times)
Hours room used	Presence involved actors and the corresponding activities
Hours room staffed	The schedule of the cath lab team
Start needle incision	CA palpates wrist – inserts lidocaine in skin - inserts needle syringe in the wrist – surgical blade – insert small guidewire then transducer – remove guidewire
Application of the compression band	Compression band is montaged on the wrist connected with a syringe to inflate it with air – done by CA, LA or together
Insert medication	With a syringe the CA inserts Cocktail radialis: nitro glycerine 0,2 mg + Verapamil HCL 2,5 mg/10ml and Heparin 5000 IE/ml through the transducer
Catheter arrives in the upper aorta arch	First acquisition of the position CT arch, positioned in rest 0° – 0° or for first acquisition LAO 30° – 40°, LA injects contrast
First guide wire and catheter are removed from the artery	The guidewire is inserted and the JR 5 or 6 Fr.[1] Catheter is retracted then the guidewire, the LA hands over the equipment
The second guidewire and catheter is inserted in the artery	The guidewire is inserted and the JL 3,5 or 6 Fr.[2] Catheter is inserted and the guidewire is removed, the LA hands over the equipment
Second guide wire and catheter are removed from the artery	The guidewire is inserted and the JL 3,5 or 6 Fr.[2] Catheter is extracted and the guidewire is removed, the LA hands over the equipment
Application of the compression band	Compression band is montaged on the wrist connected with a syringe to inflate it with air – done by CA, LA or together

[1] this is the standard catheter for the RCA - [2] this is the standard catheter for the LCA. The most common used catheters are listed in the appendix 12.2

6.3 Conclusions and key take-away

The position and angulation of the CT-arch are characteristic for every specific recoding of the coronary arteries. The movement of the X-ray imaging system is standardized for visualizing the LCA and RCA in the CAG procedure. Even though, the sequence and the angulation for the recordings is standardized, deviations from the standard are often observed. The cardiologists have their own preference for the sequence of recordings, resulting in different sequences of recordings. However, the personal preference of the cardiologist can be used as an input for automatic analysis. Based on the angulation of the imaging intensifier, the use of fluoroscopy and/or stationary acquisition and the cardiologists' personal preferences for the sequence of recordings, the possibility exists to automatically detect P2, P3 and P4.

Multiple variables cannot be identified by the cameras inside the cath lab, as these activities take place outside the cath lab. To resolve these issues a low resolution camera can be placed on the hall to identify patient transfer, patient delivery and patient waiting time. The camera does not need the technological advanced properties to identify hand movements or high-level details, as it only needs to assess the presence of certain actors in the hall.

7 THE QUANTIFICATION AND EVALUATION PERI-OPERATIVE WORKFLOW OF CAG

The previous chapters have defined the peri-operative workflow of the CAG and the metrics. Consequentially, the evaluation of the workflow of the CAG can commence. This chapter will present the main results of the data acquisition, data analysis, the quantification and evaluation of the efficiency metrics. The methods used to acquire the data and analyse the data are discussed first.

7.1 Method

To evaluate the procedure 2 databases were used: 1) manually required dataset through observations and 2) dataset retrieved from the DoseWise database.

7.1.1 Data acquisition

Manual data acquisition

By means of the VBA (virtual basic for applications) and Macro extension in excel a program was created to accurately measure the timestamps of the variables of the metrics. The endpoints were automatically collected in the correct column and row. The code can be found in appendix 12.4.2. In order to provide context for measured procedures, case specifications were collected:

- Composition cath lab team
    - 2 or 3 lab assistants
- Inpatient or outpatient
- Scheduled date and time
- Events that deviated from the norm
- Case reference

These endpoints were collected in one sheet and formed the raw data of the peri-operative workflow of the CAG. The data was acquired through observations of this author.

Automatic data acquisition

DoseWise dataset was retrieved from the server of RDGG by the clinical physic and merged in one excel sheet, procedures were included from 01/02/2019 to 21/02/2020. Only the details of the procedures were extracted which had been observed and included in the manual dataset.

7.1.2 Data processing

The raw data was processed through Matlab. The Matlab code can be found in appendix 12.4.2.

Statistical analysis

Parametric statistical tests require a normal distribution, such as two-sampled t-test and Pearson's correlation test. In this research we only aim to use the sampled t-test and the Pearson's correlation test. Before we commence parametric testing, we have to verify whether the data is normally distributed. In the event this not the case, it is possible to transform to a lognormal distribution. By taking the log of our every entry in raw data, we can transform the data to a distribution that is nearly normal. To verify the transformation a histogram is plotted. After confirmation of the nearly normal distribution, the data can be submitted to parametric statistical tests in order to confirm or reject or hypothesis(32).

However, it is possible that after transformation that the data still does not satisfy the underlying assumptions of the proposed analysis, i.e. normal distributed data. If the transformation was unsuccessful the choice can be made to make use of non-parametric tests, namely the Mann-Whitney U-test and Spearman's correlations test. Non-parametric tests are useful when the sample size is small and the standard deviation is not visible. It is important to be cautious interpreting the non-parametric tests, as the tests have less power than the parametric tests(32).

The two-sampled t-test is used to compare the groups based on the number of lab-assistant and the patient type (outpatients or inpatients). The two-sampled assumes unequal populations with a significance level of P=0.05. P=0.05 suggests there is sufficient evidence to reject the null hypothesis. If P>0.05 we can conclude that there is insufficient evidence to reject the null hypothesis. The choice of P is arbitrary. In case P=0.05, in 5% of the cases we wrongfully reject the null hypothesis. The transformed data are back-transformed to the original scale to draw conclusions from the hypothesis test on the transformed data. The back transformation is called the antilog, also referred to as the exponential, *e*.

7.2 Results

Over the course of 2 months, 40 CAG procedures were observed. This author was present during the procedures to acquire the data to analyse the predetermined metrics. In the event the notation of an entry was missed or did not occur, the entry number was denoted as NaN (not any number) and not included in the analysis. In the following section the descriptive and statistical outcomes of the metrics are illustrated. Thereafter, the outcomes of the manually acquired data set and data set from X-ray imaging system are compared. Lastly, the events that distorted the workflow are displayed.

7.2.1 Outcomes of high-level metric

The descriptive outcomes of the metrics of the high-level metrics are demonstrated in Table 7. The procedure time presented the highest mean and high variance, M =38.0 ± 21.1 minutes. The procedure time showed a wide range, 21.6 – 123.3 minutes. Only 43% of the cases facilitated an on-time start of the procedure. LAs waited an average of 30.1 ± 14.3 minutes in the morning shift and 20.1 ± 6.9 minutes afternoon prior to patient entry. The lab preparation was small compared to the LA waiting time, namely M= 7.1 ± 3.4 minutes in the morning and M =4.3 ± 2.1 minutes in the afternoon. The clean-up time was considerably smaller compared the clean-up time before the break, M = 4.1 ± 2.8 minutes, than at the end of the day M= 16.8 ± 9.9 minutes. The mean lab utilization was 58% with a variance of 18%. The lab utilization was not calculated for the entire day, but separately for the morning and the afternoon. In the event the observer could not be present for the entire part of the day, the entry was not included in the analysis for the lab utilization.

Table 7: Descriptive outcomes of the high-level metrics of the peri-operative workflow of the CAG procedure, units are in minutes

Metric		N	Mean	Median	SD	Min	Max
First case on-time start (%)		6 (14)	43%	N/A	N/A	N/A	N/A
Patient waiting time		40	2.5	2.3	1.4	0.7	6.7
Patient delivery		34	6.6	5.8	5.5	0.7	23.9
Turnaround time		26	9.8	8.3	4.7	2.3	18.8
Procedure time		40	38.0	30.4	21.1	21.6	123.3
Cycle time		25	50.6	43.5	24.1	27.5	138.0
LA waiting time	*Morning*	6	30.1	25.3	14.3	17.2	44.7
	Afternoon	5	20.1	18.1	6.9	14.4	27.7
Lab preparation time	*Morning*	6	7.1	8.0	3.4	5.5	14.5
	Afternoon	5	4.3	3.8	2.1	3.1	6.7
Clean – up time	*Before break*	5	4.1	4.1	2.8	2.1	6.1
	Last case	4	16.8	15.9	9.9	5.9	28.0
Lab utilization		8	58%	63%	18%	31%	89%
Average imprecision	Overtime	12	23.1	14.5	25.5	6.3	78.3
	Under time	27	16.2	18.9	6.3	0.6	23.4

N = the total number of metrics, SD = standard deviation – all units are denoted in [minutes]

In 27 cases the procedure time was overestimated and in 12 cases underestimated. The turnaround coincided three times with a coffee break, the corresponding metrics that evaluated an aspect of that phase were excluded from analysis.

After log transformation of the turn-over times, the histogram presented a nearly normal distribution. Consequentially, the two-sampled t-test was used to analyse the data. The turnaround of the cath lab realized by 3 LAs showed a duration of M=8.1 ± 3.3 minutes. The turnaround of the cath lab realized by two LAs presented a duration of M=11.5 ± 3.9 minutes. Resulting in a significant mean difference of 3.3 minutes (p=0.041). The turn-over time appeared to be unaffected by the patient type, inpatient vs outpatient. No significant differences were found in these two groups (p=0.33). The log transformation of the delivery time did not result in a normal distribution. Therefore, the Mann-Whitney U-test was used to evaluate the delivery time. Delivery time presented a significant mean difference of 3.7 minutes (p=0.004) comparing inpatients (M=8.1 ± 5.43minutes) to outpatients (M=4.4 ± 4.4 minutes). There was significant positive correlation found between delivery times and turn-over times, r=0.69 (p<0.001). Longer delivery times result in longer turn-over times.

The sample size of the lab preparation, the LA waiting time and the clean-up time are too small to allow for parametric testing. As a consequence, the Mann-Whitney U-test was used to evaluate the differences between the morning and afternoon sessions of the outcomes. None of these differences were statistically significant.

7.2.2 Outcomes of the CAG specific metrics

The descriptive outcomes of the metrics of the procedure and CAG specific metrics are demonstrated in Table . The patient preparation time and post-care duration showed low standard deviation, respectively M=11.8 ± 3.8 minutes and M=4.6 ± 3.3 minutes. The patient preparation time and post-care duration did not contribute to the variability in the procedure time. Among the three metrics that evaluated phases of the procedure, the operative length showed the highest average and variation, M=22.4 ± 18.8 minutes. The operative length showed a range of 10.0 to 101.4 minutes. P1 up to and including P5 evaluate the duration within the operative length. The highest variation was seen in metrics P1 and P2, respectively SD=4.2 and SD=7.1 minutes. P2 presented the highest range of the 5 intra-operative metrics [0.4 – 39.8 minutes], followed by P1 [1.0 – 18.3 minutes]. The variability in the procedure time was explained by the operative phase. To be explicit, P1 and P2 were the major contributors of the high variability. P1 and P2 together accounted for 70% (p<0.001) of the variability in the operative length time.

Table 8: Descriptive outcomes of the CAG specific metrics of the workflow of the CAG procedure, units are in minutes.

Metric	N	Mean	Median	SD	Min	Max
Patient preparation time	39	11.8	11.1	3.8	6.5	22.0
Operative length	39	22.4	15.0	18.8	10.0	101.4
Duration P1	46	4.8	2.8	4.2	1.0	18.3
Duration P2	41	3.4	1.4	7.1	0.4	39.8
Duration P3	39	4.1	3.2	2.8	1.7	14.9
Duration P4	39	5.2	4.1	3.2	2.1	16.0
Duration P5	39	1.8	1.3	1.4	0.6	8.4
Post-care duration	39	4.6	3.4	3.3	0.9	16.2

N = the total number of measured procedures, SD = standard deviation – all units are denoted in [minutes]

7.2.3 Comparison with the automatic data set from the X-ray imaging system

The records from the X-ray imaging system were obtained from the DoseWise software. The database registers the specifications of every X-ray image acquisition. The first logged data entry is study time. The study time reflects the moment when the patient file is uploaded in DoseWise. The last logged data entry is the last image acquisition, either acquired during the last video recording or during the removal of the catheter. DS-M denotes the use of the manual acquired dataset and DS-A denotes the dataset acquired by DoseWise. As DS-A did not contain all the variables to calculate the pre-determined metrics, proxies were used to represent the variables. To provide an example, the variable study time is a proxy for patient entry. The comparison of the two datasets are presented in Table 9. There is a discrepancy between the outcomes procedural time and patient preparation time. The outcome procedural time retrieved from DS-M is higher than DS-A. The outcome patient preparation time based on the DS-M was lower than based on the DS-A. The standard variation was also lower for DS-M. The outcome of P2 up to and including P4 was approximately the same for DS-M and DS-A.

Table 9: Comparison of the outcomes of the metrics describing the procedural times of the CAG procedure

Metric	Method	Definition	N	Mean	Median	SD	Min	Max
Procedural time	DS-M	S: Patient entry E: Patient exit	40	38.1	30.5	21.5	21.7	123.1
	DS-A	S: Start DoseWise E: Last x-ray acquisition	40	30	25	19	7	103
Patient preparation time	DS-M	S: Patient entry E: Start needle incision	39	11.8	11.1	3.8	6.5	22
	DS-A	S: Start DoseWise E: First x-ray acquisition	40	20	18	12.4	1	82
P2 up to and including P4	DS-M	S: Insert medication E: 2nd catheter retracted	39	12.3	9.4	12.3	6.1	74.7
	DS-A	S: First x-ray acquisition E: Last x-ray acquisition	40	11	7	13	4	72

N = the total procedures, SD = standard deviation –units are denoted minutes. DS-M = manual data acquisitions – DS-A= automatic data acquisition

7.2.4 Observed events in the cath lab that influence the workflow

The observed events were denoted in an excel file and connected to the case reference. The causes of the events were reported. In Table 10 an overview of the observed events is shown.

Table 10: Overview of the observed events in that deteriorated the peri-operative workflow of the CAG procedure

Observed events	N	n
Cath lab team and cath lab ready for patient, but the patient is not present:	12	
Patient was lost		3
Patient was not prepared on the ward		3
Schedule was not updated; therefore the next patient was not prepared on-time		2
Undefined		5
Cardiologist arrived too late at the first casus of the day:	8	
Cardiologist is in the morning meeting		5
Undefined		3
Difficulties finding arteries to execute the needle incision to ensure endovascular access (P1)	6	
Difficulties inserting guidewire and catheter through the arteria radialis to the aorta arch (P2)	6	
Difficulties entering the LCA and/or RCA due to a dilated aorta – (P3 and P4)	3	
Inefficient communication about readiness patient, cath lab and changes in the schedule	8	
Patient not properly prepared when he/she has entered the cath lab:	2	
No intravenous access realized		1
Patient needed to go to the restroom		1
Transformation to CAG femoralis:	6	
Not able to ensure endovascular access in the wrist(s) (P1)		2
Not able to manipulate the catheter through the a. radialis to the upper aorta arch (P2)		4
Cancellations:	3	
Due to delays, there was no room left on the planning to execute the last CAG		1
Patient was not able to lie down		1
Patient was transferred to Haga hospital		1
Other events:	2	
Allergic reaction to contrast		1
Oesophageal reaction to needle incision		1

N = number of observed events. The small n presents the breakdown of the above events.

7.3 Conclusion and key take away

In Figure 14 and Figure 15 the outcomes of the high-level, procedure and CAG specific phases of workflow are presented.

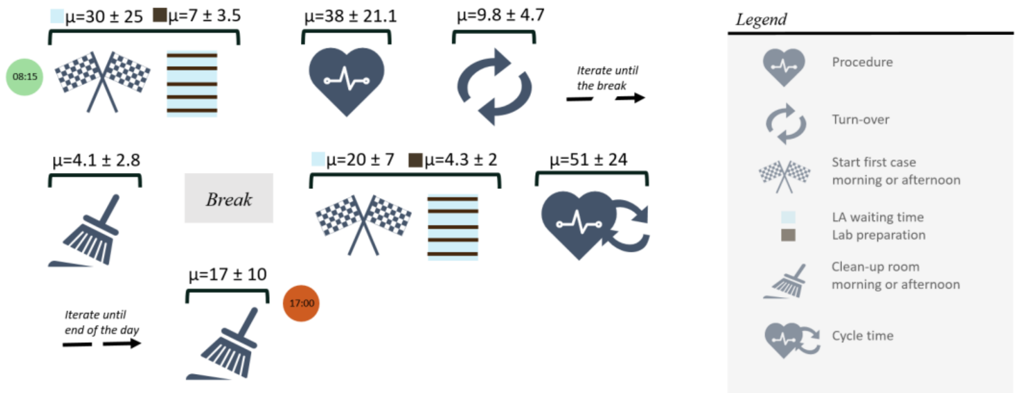


Figure 14: Visualization of the outcomes of the phases of the high-level workflow. The units are denoted in minutes.

From arrival to entry of the first patient the LAs have to wait a long period, namely 37 minutes. Prior the first procedure in the morning, seven minutes are used for lab preparation, resulting 30 minutes in which a patient could have been treated. In the afternoon similar results are found: the LAs waiting time is longer than the actual lab preparation. Based on this result, it is to be expected that the percentage on-time start cases is 43%. A significant mean difference of 3.3 minutes ($p=0.041$) regarding the turn-over time was found between the two LA and three LA group. Delivery time showed a mean difference of 3.7 minutes ($p=0.004$) comparing inpatients ($M = 8.1 \pm 5.4$ minutes) to outpatients ($M = 4.4 \pm 4.4$ minutes). There was significant positive correlation between delivery times and turn-over times, $r=0.66$ ($p<0.001$). Longer delivery times result in longer turn-over times.

The procedure time has a high variance, meaning the duration is very variable. The variability in the procedure is explained by the operative phase. The variance of the operative phase is approximately the same as the average. In this study the highest variances were found in the phases P1 and P2, having a high influence on the total procedure time, accounting for 70% of the variability. The patient preparation and post-care have a low mean and standard variation compared to the operative phase of the CAG. The X-ray imaging system was able to correctly measure the consolidation of metrics describing P2, P3 and P4.

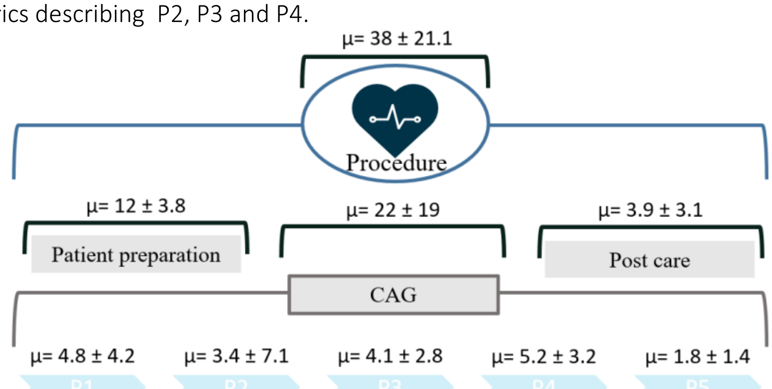


Figure 15: Visualization of the outcomes of the procedure and CAG specific metrics. The units are denoted in minutes.

8 Experience and opinion of the health care professionals in the cath lab

8.1 Method

A short questionnaire was designed to ascertain the experience and opinion of the HCP about the workflow of the cath lab. The aim of the questionnaire was to evaluate whether the 'experience' of the cath lab team is in agreement with the results, presented in chapter 7. Cardiologists and lab assistants were asked to fill in the questionnaire. The survey contained 28 question. All survey questions utilized a 5-point Likert scale, '1' presented '*strongly agree* 'and '5' presented *'strongly disagree*'. The questionnaire ended with one open-ended question that presented the possibility to pinpoint additional challenging issues in the workflow. To ensure that the responses cannot be connect to the individuals or professions, the results of the questionnaire were generalized.

8.2 Results

Ten individuals have responded on the survey, data has been collected from five lab-assistants and five cardiologists. Table 12 in appendix 12.5 presents an overview of the questions and the summary statistics of the outcomes of the survey. The most striking results are discussed below.

Almost 70% of the participants indicated that the patient delivery to the cath lab could be executed faster. The response to the statement *"outpatients have a shorter delivery time than inpatients"* varied. Half of the interviewees did not have an opinion, 20% disagreed with the statement and 30% were in agreement with the statement. Over half of the cath lab team agreed with the statement that *"the biggest efficiency loss can be attributed to the patient delivery"*. The response to statement *"the first procedure starts on-time"* varied: 1/3 believed the first case started on-time, while 2/3 strongly disagreed.

The cath lab team is consensus about the statement "*it is normal that patients' procedures are moved or postponed to the next day*", 90% (strongly) agrees with this statement. The majority of the cath lab (90%) team believe that a team composed three lab assistants resulted in shorter turnaround times. Just over half of those who answered the question about the accuracy of the schedule, were of the opinion that the schedule is inaccurate. 30% were of the opinion that a more accurate schedule would be beneficial to streamlining the workflow.

When asked whether peak pressure leads to stress, 80% of the responses ranged from agree to strongly agree. All the participant were of the opinion that there is room for workflow optimization in the cath lab, 30 % strongly agreed and 70% agreed with the statement.

Opinions differed whether the administrative burden was too high, the responses were equally distributed over the 5-point scale. However, in response to the statement *"the administrative tasks contribute to the workload*", 50% of responses varied from strongly agree to agree. In addition, roughly the same 50% indicate that they would like to be relieved from the administrative tasks. To continue in the questions about workload, the participants were asked about whether delays and overtime influence the workload, 50% agreed, 20% did not experience an effect and 30% disagreed. In response to the statement *"The preparation of the procedure is longer than the intervention, the CAG"*, most of the interviewees, 90%, reported answers ranging from *strongly agree* to *agree*. Asked whether *"slow computer systems contribute to inefficiency"*, half of those surveyed were in agreement with the statement.

Commenting on the open question to pinpoint challenging issues, one cardiologist explained that they have to report similar events and outcomes in different databases. He hopes that these redundant administrative tasks can be resolved. One interviewee stated that *"waiting for patients is the biggest inefficiency"*. Another response to this question was *"patient that are not prepared on the ward at the time of patient request for patient delivery"*. One comment concerned the lead aprons. The mandatory protective garment can result in beginning neck and shoulder complaints, if they are worn for a longer period.

8.3 Conclusion and key take-away

The cath lab team was of the opinion that the patients could be faster delivered to the cath lab and consider delayed patient transfer (i.e. waiting for the patient to arrive) the main distortion in the system. In addition, only 30% of the cath lab team is aware that the patient type (inpatient vs outpatient) has an influence on the delivery time. This outcome is in line with the results in chapter 7, as patient delivery time is tainted by relative high variability and wide range. However, it is of utmost importance to realize that inefficient patient delivery is not the only flaw in the system.

The response with regard to the procedure cancellations is in contrast with the observed events. Two procedures were cancelled, one due to delays and one due to the patients' physical inability to lie down on the table. 30% were of the opinion that a more accurate schedule would be beneficial to streamlining the workflow. The cath lab teams' opinion on the effect of the number of LAs on the turn-over time was affirmed by the result. Turn-over times with three LAs was 3.3 minutes shorter than turn-over times with two LAs ($p=0.041$).

The perception of the cath lab team is in conflict with the outcomes of the procedure specific metrics. Patient preparation reported 11.8 ± 3.8 minutes and the operative length reported 22.4 ± 18.8 minutes. The conflicting outcomes can be attributed to the fact that the perception of the cath lab team based on procedures that went 'smoothly'. Procedures that are executed without any disruptions and completed without any difficulty, can have similar durations in the operative and patient preparation phase. In-depth and individual analysis of the procedures show that it is possible that the patient preparation of the procedure is longer than the operative phase.

9 GENERALIZATION OF THE PHASES AND EFFICIENCY METRICS

To In order to validate and evaluate the level of generalization of the methodology, we used in a different context. We verified whether the metrics could be utilized in a different hospital and could be used to measure aspects of the workflow of different endovascular procedures. Generalization explains to what extend the model can be used in different situations and in this case medical procedures(13).

9.1 Using the metrics for different endovascular procedures

Three procedures were used to validate the metrics and evaluate the level generalization to other procedures. The high-level metrics are applicable in every procedure. Every procedure consists of a patient preparation, operative phase and post-care phase. These concepts can be generalized to all (endovascular) procedures. The first and last phase of the operative specific metrics have the potential to be utilized in procedures, all endovascular procedures start with realising endovascular access and ends with closing the artery. The type of intervention determines the activities and tasks in operative phase, consequentially influencing the demarcation of the phases in the workflow and the design of the metrics. We hypothesize that P2, P3 and P4 cannot be used in different intervention in order to capture a relevant meaningful outcome. In the next section we discuss to what extent the operative metrics (P1 t/m P5) can be used for three different procedures. The three procedures are: 1) CAG with bypasses, 2) CAG femoralis and 3) PCI.

CAG PATIENTS WITH BYPASSES

In a CAG with bypasses, an extra coronary has to be visualized. The workflow of the procedure of the CAG bypass is approximately the same as the CAG radialis. The biggest difference is the extra visualization of the bypass(es), resulting in more recordings of the coronary arteries. The angulations of the image intensifier for the video recordings of the graft are presented in the section below.

For the graft which branches from the internal mammary artery:

- LAO 0 – 10˚ & cranial 25 – 40˚
- RAO 0 – 10˚ & caudal 15 – 20˚

For the venous graft:

- LAO 45 – 60˚
- RAO 0 – 10˚ & caudal 15 – 20˚
- RAO 0 – 30˚

In order to provide a holistic overview, one or two phases and metrics must be added to incorporate the recordings of the bypass.

CAG FEMORALIS

The workflow of the procedure is has the same phases the CAG radialis. The CAG femoralis differs from the CAG radialis regarding the following aspects:

- Different catheters and transducer are used in the intervention
- Location endovascular access is the arteria femoralis, which is located in the groin
- An angioseal or manual compression is used to close the femoral artery

PERCUTANEOUS CORONARY INTERVENTION AND STENTING

P1 and P5 can be utilized in the PCI procedure. In order to provide a holistic overview, the methodology introduced in this research must be applied to identify the phases in the PCI intervention to create adequate metrics for the surgical phases.

9.2 Using the methodology in Haga Hospital the Hague

The Haga hospital has five catheterization laboratories and performs a wide range of endovascular procedures. One cath lab is always reserved for emergency patients. The high-level workflow of Haga is similar to RDGG hospital. In Haga hospital the cath lab team has made efficiency a priority. The cath lab team utilizes a different logging system than the team in RDGG. The system in Haga hospitals enables the cath lab team to monitor the high-level workflow throughout the day and procedure.

The monitoring LA logs the following workflow related endpoints in the EHR with a corresponding timestamp:

1. Reason for delayed start
2. Patient requested
3. Patient arrival / entry
4. First incision
5. Patient exit
6. Used instruments

Generally speaking, the peri-operative workflow of Haga hospital and RDGG hospital are the similar. Therefore, it is like that the metrics can be utilized in the Haga hospital.

The workflow in the cath lab of Haga hospital differs from the RDGG hospital regarding the fowling aspects:

- One full time employee is responsible for ordering and stocking the instruments in the cath labs
- In case there are three LA, one LA has the responsibility to prepare the sterile trolley with the instruments for the intervention in advance of the procedure
- Haga executes wide range of endovascular procedures, such as electrophysiology, implants and PCI.
- The personnel have a more proactive mind-set towards workflow optimization and efficiency
- Some cardiologists do not have an assisting LA during the intervention

9.3 Conclusion and key take-away

Every surgical procedure is composed the patient preparation, the operative and the post-care phase. Therefore, non-procedure specific metrics can be generalized to any type of procedure. The demarcation within the operative phase is standardized with respect to the start and end of every endovascular procedure. In every endovascular procedure arterial access must be realized and to conclude the intervention the catheter, guidewire, sheet have to be removed from the artery to realize wound closure with a compression band. Therefore, the beginning and ending of the endovascular procedures could be described with P1 and P5. The hypothesis that P2, P3 and P4 cannot be used in different to capture a relevant and meaningful outcomes in other endovascular procedures is true to some extent. The CAG with bypasses is composed of the same phases as the CAG radialis, but the CAG with bypasses involves more steps than the CAG radialis. For this reason, extra phases and metrics should be incorporated to correctly describe the CAG with bypasses. The CAG femoralis is similar to the CAG radialis, with the exception of the location of the arterial access and the required instruments. The PCI is composed of different steps and activities in the operative phase. As a result, the CAG specific metrics (P2, P3 and P4) can only be utilized in CAG like interventions. We aim to evaluate more cath lab interventions, firstly formalizing these interventions and secondly designing corresponding metrics, using methods shown in this research.

10 Discussion and Recommendations

10.1 Short summary of the main results

In total 19 metrics were created of which 11 evaluated the high-level workflow, three the procedure specific process and five the CAG specific steps. Prior the first procedure in the morning, the LA waiting time showed an average of 37 minutes and on average seven minutes are used for lab preparation. In the afternoon similar results were found: the LAs waiting time is longer than the actual lab preparation. The average percentage on-time start cases was 43%. A significant mean difference of 3.3 minutes ($p=0.041$) regarding the turn-over time was found between the two LA and three LA group. Delivery time showed a mean difference of 3.7 minutes ($p=0.004$), comparing inpatients ($M = 8.1 \pm 5.43$ minutes) to outpatients ($M = 4.4 \pm 4.4$ minutes). There was significant positive correlation between delivery times and turn-over times, $r=0.66$ ($p<0.001$). Longer delivery times result in longer turn-over times. The procedure time presented the highest mean and variance, $M=38.0 \pm 21.1$ minutes. The patient preparation time and post-care duration presented low variances, respectively $M=11.8 \pm 3.8$ minutes and $M=4.6 \pm 3.3$ minutes. The variability in the procedural time can be attributed to the operative phase, $M=22.4 \pm 18.8$ minutes. Within the operative phase, the duration of P1 and P2 accounted for 70% of the variability in the operative length. The X-ray imaging system was able to correctly measure consolidation of metrics describing P2, P3 and P4. The non-procedure specific metrics have the potential to be generalized to any type of procedure. Only P1 and P5 showed potential to be utilized in other endovascular procedures. The analysis in Haga hospital suggests that phases and the metrics could be generalized and therefore used in more cath labs throughout the Netherlands

10.2 Discussions of the results and the implications to the efficiency in RDGG

10.2.1 The role activity diagrams and the quantitative metrics

Four role activity diagrams of the phases were created to formalize the peri-operative workflow. The peri-operative workflow consists of many sequential, parallel and collaborative steps and long sequential tasks. In addition the workflow contains repetitions of activities, which can be sensitive to inefficiencies and delays, as the previous task must be completed in order to execute the next. In general, it can be stated that the content of the phase is constrained to a specific set of activities. According to observation, activities and tasks are shuffled at times in order of sequence. Since the patient preparation, the turnaround and lab preparation consist of parallel activities, they can be executed in a different sequence. As a consequence, the sequence of process steps is subjected to large variation and has no consistent flow. This does not apply to the operative phase, in which the activities are executed in a specific order of sequence to complete the intervention. Furthermore, based on the analysis there is no independent phase in the peri-operative workflow of the CAG. To specify, we found that phases influence each other, a new phase could only commence after a previous one has been completed, and co-exist at the same time frame.

The activities of lab preparation consist of a few straightforward and standardized steps and are therefore completed without difficulty. To continue to the next phase, the (so-called) patient preparation phase, the presence of a cardiologist is required. Accordingly, the LAs wait with requesting the patient until they know the arrival time of the cardiologists. The arrival time of the cardiologist is dependent on the transfer meeting (with the other physicians and cardiologist). Therefore, these phases do not connect seamlessly and during that period the LAs wait for the start of the procedure, which can be interpreted as wasted and lost time.

The list of metrics consists of pre-existing constructs and newly designed metrics. The majority of pre-existing metrics are in the high-level segment, namely turnover time, lab utilization, procedure time and percentage of on-time starts. These metrics are well-known concepts and frequently used to describe the efficiency in the OR. Even though the cath lab has many things in common with the OR, several metrics were customized for the cath lab setting. The newly designed metrics were established based on the formalization of the CAG and verified by the cardiologist in the RDGG.

10.2.2 Evaluation of the efficiency metrics

To ensure an adequate interpretation of the outcome, one must compare outcomes to a standard (or benchmark). Alternatively, one can also assess the outcome by a value or scale (low/medium/high). Unfortunately, current benchmarks or scales with the purpose of assigning a level of efficiency to peri-operative workflow do not exist. In an effort to evaluate the outcomes, a literature research was conducted to identify other outcomes of already-existing metrics. The adjective 'already-existing' is used to refer to metrics that are not invented in this study.

10.2.2.1 Evaluation of the metrics with other published outcomes

In literature, 3 metrics were found that measure workflow in and around the cath lab. These metrics are related to on-time start, turn-over time, lab utilization and average imprecision.

ON-TIME START

The percentage of first case on-time start of this study was 31%. The reported first cases on-time starts (%) in literature were:

- M= 63,9% on-time start including ten cath labs (N=7310 cases) (14)
- M= 41.7% in 2009 and M= 62.8% in 2012 on-time start (N=25579 cases) (17)
- M= 29% on-time start (N=91) (4)

In order to evaluate the outcomes 2 studies wielded a self-established standard to evaluate the outcomes. This threshold was established based on the expert opinion of the clinicians and the historical means of the institution. The standards were defined as >75% and >85% of the cases should start on-time, respectively set by Agarwal et al (2015) and Reed et al (2019). The outcome underperformed compared to other outcomes and set standards. The LAs are present at 08:00 and the first patient is scheduled at 08:30. The cardiologist is in the transfer meeting and makes his way to the cath lab when the meeting is finished. In general, the cardiologist arrives arrive 15 to 20 minutes too late for the first case. Meanwhile the LA's wait for the arrival of the cardiologists and the cath lab is staffed but not used for approximately 40 minutes (LA waiting time + Lab preparation). The low percentage of the first case on-time start can mostly be attributed to the tardiness of the cardiologists in the RDGG.

In literature, the reasons for first case delays were also discussed and are in agreement with the observed events of this study demonstrated in Table 10. The delays in starting time of the procedure were associated with the unavailability of the physicians (4, 18, 20) or patient(4), lingering between process steps (17, 20), lack of nursing resources (4, 5) and inefficient communication between the preparation area and the cath lab team (5). One study reported an increase of 13.1 minutes in the preparation time due to unavailability of the physician (10). Another study identified physician unavailability as the biggest contributor of the delays with 13% (N=80)(4).

TURN-OVER TIME

The turn-over time of this study showed a mean of 9.8 minutes with a standard deviation of 8.3 minutes. In literature 2 studies were found which evaluated the turnover time in the Cath Lab. In the first study 43.6% of the cases had an optimal turn time (<20 minutes) based on 25579 cases(17). This data was retrieved from one cath lab, all elective and urgent cardiac catheterization procedures[2] were included. The second study reported M=20.6 min (SD = 0.8 min) based on 7310 cases including 10 cardiac cath labs, including all procedures[2]. The self-established goal was set at M<17 minutes (5). The turnover in this study illustrates a shorter duration than the outcomes reported in literature. This can be explained by the fact only CAG procedures were included in this study. Therefore, the cath lab did not have to be converted to facilitate a different type of intervention, resulting in a shorter turn-over time. Reasons for extended turnover times are partly explained by longer delivery time. Delays in patient transfer results are in literature attributed to inefficient peri-procedural communication between departments and health care professionals (5, 8, 14, 20).

[2] diagnostic coronary angiography, percutaneous coronary interventions, structural interventions and peripheral interventions

CATH LAB UTILIZATION

The lab utilization measured in this study was M=66%. In literature 3 studies investigated the lab utilization (5, 14, 20, 21).

- Reed et al. (2018) reported a utilization M= 91.1 % (SD= 9.1%) with N=7310 cases including 10 ten labs, the self-established goal was set at 100% (5)
- The article of Zhang et al. (2015) reported 95% utilization for one IR suite (N=488 cases) (20)
- The study of Staereling et al. (2014) reported 64.5%, 69.3%, and 70.5 % lab utilization for their three rooms. Room 1 was used for implants and ablations and room 2 and 3 for CAG and PCIs (21)

Compared to the first 2 studies the utilization is low. The outcomes of the third study are approximately the same as in this study. In addition, the low utilization at RDGG hospital can be explained by the scarcity of available beds on the ward. The throughput and therewith the lab utilization are limited by the available capacity at the ward. If all the beds are occupied or there are not enough nurses to manage the patients, outpatients cannot be admitted for the CAG. As a consequence, the lab utilization is low, because the cath lab is staffed with personnel, but no procedures are executed. The study of Staereling et al. was conducted in a Dutch hospital where the utilization time of two rooms were exclusively dedicated for CAG and PCI. Therefore, this setting is most similar to the context wherein this research was conducted. Based on the Staerelings' outcomes, it can be concluded that lab utilization is adequate. Nevertheless, literature shows that a higher utilization is possible. One of the main causes of relatively low lab utilization in this study could be attributed to the late starts of the first case in the morning of afternoon.

It seems that the goal of multiple research groups is to achieve 100% utilization of the cath lab (4, 5, 12, 14). But aiming to realize 100% utilization can lead to negative effects elsewhere in the workflow. Zhang et el (2015) showed that optimizing on IR utilization alone will increase the total costs (20). This research demonstrated the trade-off between total costs and IR utilization. The delay costs increase exponentially when the capacity utilization reaches 100%, resulting in a high total cost. According to this model the optimal daily costs (i.e. the lowest cost) corresponds with a capacity utilization of 73%(20). However, the efficiency is likely limited by the characteristics of the context and the environment of the cath lab. Acknowledging that each hospital arranges its cath lab differently, the highest achievable efficiency can vary among hospitals and cath labs. An example is the capacity constraint in relation to the beds on the wards. The low utilization can be explained by the scarcity of available beds on the ward. Thus, when optimizing efficiency, one should look at the bigger picture.

AVERAGE IMPRECISION

The average imprecision visualizes the inaccuracy of the scheduled procedure duration. The estimate of the procedure is based on what would consist of a meaningful approximation of the duration of the CAG. The poor results of the procedure estimation are also found in literature(31). The poor results are explained by stochastic behaviour of the procedure times, characterized by low means and high variances(10). Experience of the physician, patient characteristics and complexity of the procedure influence the duration of the procedure (10, 21, 33, 34). These aspects are neglected in estimates based on the historical means. Two studies were found that created quantitative models to provide a better estimation of the procedure duration (10, 31).

In order to achieve a more accurate estimate, procedure times were correlated with patient characteristics and/or the surgeon experience level. Two studies tested their model in clinical setting and quantified their results. Kougias et al (2012) illustrated that the average imprecision in minutes of a carotid endarterectomy procedure in comparison with HM estimations were reduced by using a predictive model with linear regression. The average imprecision for surgeons with different levels of expertise was reduced. The imprecision for the least experienced surgeon was reduced by M=44 minutes, for the surgeon of average experience M=8 minutes and for the most experienced compared M=20 minutes compared to HM estimate(31). Stepaniak et al. (2014) created a customized procedural estimate. The estimate was correlated to patient and surgeon characteristics. Decrease in overtime and the number of cancelled procedures was observed(10).

10.2.2.2 Comparison with the automatic data set from Philips and RDGG

DS-A cannot be used to describe the procedural time and the patient preparation, as the outcomes are not similar to the outcomes in DS-A. According to DS-A, the variability in the procedure time is explained by the patient preparation.

The inconsistency in the data can be attributed to the variable 'study time'. DS-M and DS-A have similar outcomes for P2 up to and including P4. This finding has important implications for real-time sensing and automatic phase detection of P2, P3 and P4.

10.2.2.3 High-level metrics

The length of the turn-over time is influenced by more than one factor, namely the number of LAs and the delivery time. The delivery time is influenced by the readiness of the patient, demonstrated in Table 10 in section 0. The turn-over times appear somewhat higher when a request for the new patient is executed at a later time than usual. The likely cause for late requests is that it is up to the intuition of the LA and his/her attentiveness to request the next patient. To achieve optimal turn-over time, all the elements must be aligned and executed seamlessly.
The effect of the team composition showed a mean difference of 3.3 minutes (p=0.041) regarding the turn-over time. Although this result is significant, one could question its actual relevance considering net profit, in terms of economic benefits. However, taking into account that the turn-over time is highly influenced by the patient delivery and acknowledging that there is room for improvement regarding the patient delivery and request, the effect of the number of LAs is slightly bigger.

The average delivery time was 6.6 minutes. Outpatients were brought to the cath lab with an average of 4.4 and inpatients approximately double, namely 8.1 minutes. Nevertheless, in practice the inpatients and outpatients can also be divided in groups. Inpatients can reside either on the cardiology ward or on a completely different ward or floor. Outpatients are residing either on the cardiology ward or at the lounge, which is a room right next to the cath lab. If the patient is at the lounge, then the LAs often retrieve the patients themselves, resulting in a delivery time of almost one minute. Hence even though we find a significant difference in the delivery time (p=0.004), this does not provide us with enough details of patient location effect. To gain more in-depth information concerning the delivery process, these four groups should be investigated in further detail.

10.2.2.4 Procedure and CAG specific metrics

The patient preparation duration and the patient post-op care duration have a low variance compared to operative time. This can be explained by the fact that these two phases were not subjected to stochastic events that cause extreme variability in the duration. Therefore, it can be expected with some certainty that the duration of the patient preparation is approximately 11.8 minutes and the post-care 4.6 minutes.
The variability in the procedure time is explained by the operative phase and is mainly induced by variations in the P1 and P2, namely 70%. The metrics evaluating P1 and P2 have the highest standard deviation, respectively 4.1 and 7.1 minutes. The high variabilities can be explained by the observed events described in Table 10: Overview of the observed events in that deteriorated the peri-operative workflow of the CAG procedure. The events that could have attributed to the high variabilities are difficulties with completing the needle incision to ensure endovascular access and inserting the guidewire up to aorta arch. These events cause delays, reflected in both P1 and P2. The quality of the arteries influence whether these two stages are easily completed.

10.2.3 Areas for improvement within the peri-operative workflow of the CAG

Based on the results and the experience of this author in the RDGG hospital, a few recommendations are made to improve the peri-operative workflow. Recommendations are provided for the high-level workflow and the CAG specific workflow.

1. *Increase % on-time start*

It should be made a priority among cath lab team to start the first case on-time. LAs are hesitant to request the first patient when the cardiologist is not present in the lab. As a result, the patient is requested when the cardiologist is present or arrives within several minutes. If the first case starts on-time 30 minutes of wasted time can be saved on a daily basis.

2. *Time to request the next patient*

The exact time the next patient is requested. The time from wound closure to readying the cath lab for the next patient is close to 6 minutes. Based on the results, outpatients should be requested after application of the compression band to ensure on-time arrival of the patient. Inpatients should be requested after finishing the last recordings. In the event a patient is on a completely different ward, he or she should be requested after completion of P3. Moreover, if a patient is in the lounge, it is recommended that the LA collect him or her themselves. It could be of added value to set a timeframe during which the patient should be requested to ensure on-time arrival.

3. *Preventing conversion to femoralis*

In 3 (of 6) cases cardiologists start with a CAG radialis and converted CAG femoralis, while a previous CAG was also executed through the groin, as access could not be realized through the wrist. This knowledge is available in the EPD (and for the patient) prior to intervention, but not utilized. Unnecessary conversion can be prevented by asking the patient about his/her previous CAG or reading the patients' EHR. As a consequence, scarce cath lab is saved and surplus surgical actions are prevented.

4. *Customized scheduled procedure times*

The results of the study show discrepancy with the observed procedure duration. Research has shown that both patient and operator characteristics affect procedure time. Moreover, customizing procedure time for each patient results in decreased overtime and less cancelled procedures(10). Furthermore, lab preparation, turn-over time and clean-up are not incorporated in the schedule. To develop a full picture of the schedule these elements need to be included.

10.3 Limitations of this research

Acknowledging that metrics were created based on the expertise of the author, the possibility exists that relevant information and details are not considered. Therefore, it should be noted that there is room for adjustment and improvement regarding the metrics that were developed in this study. The opportunities to improve existing metrics and create new metrics to gain a more comprehensive overview of efficiency should be realized. Bearing in mind the possibilities for improvement, these type of metrics referring to the evaluation of the CAG procedure in high detail, do not exist yet according to the knowledge of the author. We hope that our research will be useful for future researchers who aspire to evaluate efficiency in the cath lab.

A total of 40 procedures were observed to collect the variables used to compute the metrics. As some metrics did not follow a normalized distribution, a non-parametric test was used; the Mann-Whitney U test. Non-parametric tests are not as reliable as parametric tests(32). As a result, the significance of the mean difference in the delivery times for inpatients and outpatients can be questioned. Furthermore, the sample size is in the lab preparation, LA waiting time and clean-up times are really small. This can explain the non-significant result, as the test may have had inadequate power to detect a difference. Based on the aforementioned, we should conduct a sample size test to investigate sample we need to detect a difference between the groups.

According to the conclusions of chapter 9, the formalisation and metrics can (with minor adjustments) be used to evaluate the workflow and the efficiency in a different hospital. This preliminary finding suggests that this methodology could be generalized and used in more cath labs throughout the Netherlands. On the other hand, it should be realized that the Haga Hospital and RDGG are part of the same foundation: Reinier Haga Group. In addition, several cardiologists are employed by both hospitals. Recognizing these facts, it can be explained that the workflow of the 2 cath labs are almost identical. As a result, one can question the extent of generalization. Nevertheless, according to the cardiologist, the set-up and workflow of the cath lab is standardized, meaning that other hospitals probably have a similar workflow. In order to verify this assumption and validate the methodology, a third cath lab should be analysed.

10.4 Recommendations for further research

10.4.1 Investigating the effect of patient details on success rate and duration of P1 and P2

Physicians hypothesize that age, BMI and blood pressure have an effect on the success rate of P1 and that arterial constriction and tortuosity influence the duration or success rate of P2. As patients age, their arteries are becoming smaller and more fragile. In general, the arteries of obese patients lay deep in the wrist. Due to low blood pressure, a weak pulsations in the wrist can be observed. The pulsations in the wrist are used by cardiologists to find the location for the needle incision. High age, high BMI and low blood pressure are factors that could influence the needle incision. However, no scientific research is conducted to support this hypothesis. Further studies, which take these variables into account, will need to be undertaken. Data should be collected of every CAG radialis, CAG femoralis and a converted CAG radialis with the corresponding aforementioned patient details to assess the correlation. Even though this thesis already provided a set of patient details, this does not imply that the set is complete. It is most likely that additional factors influence the success rate or conversion rate of P1 and P2. Therefore, prior to data collection, research is required to evaluate whether this set of patient details is sufficient. This author has identified which patient details could be collected and in what manner the data can be collected. In order to a converted procedure, one has to investigate the evaluation of the CAG in the HER (electronics health record). The patient details cannot automatically be extracted and converted to an excel sheet for analysis, according to the clinic physics. The data must be manually extracted from the EHR. In order to collect the data, access to the EHR is required. This research would be relevant, as predicting in advance which patients are ineligible for CAG radialis, unnecessary resources (e.g. time, supplies, and money) can be saved and patients' distress can be prevented.

10.4.2 Evaluation of the workflow in Haga hospital

With the idea to realize an efficiency benchmark, identical research could be conducted in the Haga hospital. The cath lab team logs more details about the flow of the procedure in the EPD with the corresponding timestamp; examples are the main reasons for a delayed start, patient request and first incision. These data can be used to conduct an in-depth analysis of the workflow. The complete description of their registration system can be found in section 9.3. Bearing in mind that personnel has a more proactive mind-set towards workflow optimization and efficiency, this would imply that logged data points are trustworthy. In addition, Haga Hospital has five cath labs, therefore producing more data. Haga utilizes Siemens' X-ray imaging system and has not implemented a software such as DoseWise. Thus, the data collected by the imaging system cannot be easily extracted. Furthermore, Haga hospital is unacquainted with anything similar to a database generated by the X-ray imaging system. This author is in the process of acquiring the manual logged database and database of the Siemens' imaging system. Contact has been established with the research coordinator of the heart centre. Once the data has been collected, analysis can commence. Nevertheless, the author of this thesis strongly recommends to first get acquainted with the workflow in and around the cath lab.

10.4.3 Automatic evaluation of P2, P3 and P4: using the X-ray imaging system

For every image acquisition, DoseWise registers the dose, position and angulation of the image intensifier, start and duration of acquisition. The first logged data entry is the study time. The study time is the moment the patient file is uploaded in DoseWise to collect the DoseWise endpoints in the correct patient file. The position and angulation of the CT-arch can be used for determining the CAG specific phases. In the event, cardiologists experience resistance in the artery, stationary acquisitions are made of the arm and elbow to navigate through the arteries. The position and the angulation for filming the arm/elbow are unique and can be used to evaluate P2. The recordings of the coronary arteries are standardized with respect to positioning of the CT arch and the sequence of recordings. Every recording has a specific range regarding left-right and caudal-cranial angulation. Based on the angulation of the imaging intensifier, the use of fluoroscopy and/or stationary acquisition and the cardiologists' personal preferences of the sequence of the recordings, the possibility exists to automatically detect P3 and P4. Since P3 is the visualisation of the first coronary artery and P4 the visualisation of the second coronary artery. Nevertheless, the cardiologist customizes the angulation and the sequence to their preference. Moreover, it comes to pass that the cardiologist acquires an extra recording to use as a live navigation tool or because a recordings' resolution was too low. In the event in which this is not considered, false-positive recordings are likely. Now, as we have assessed the probability and possibility to identify the surgical phases P2, P3 and P4. The next step should be to investigate the level of accuracy in which we can identify and extract the operative phases P2, P3 and P4.

10.5 What are the implications of this research for future endeavours

Meaningful metrics and phases that evaluate the peri-operative workflow of the cath lab were invented and assembled in this study. This graduation research is the stepping stone for future studies that are involved in evaluating and improving efficiency in the cath. With the use of sensors and the digital equipment in the cath lab, it is likely that the workflow in the cath lab can be automatically observed. Through extensive programming and deep learning methods we are able to automatically analyse the procedure and automatically identify the surgical phases and the inefficiencies. This can be used for several future applications including context awareness systems, optimization cath lab management, dynamic scheduling and automatic signalling to enhance efficiency.

The CAG intervention is suitable for automatic phase detection, as the variability is high. Real-time progress monitoring can result in an accurate prediction of the surgical end-time(26). SPMs are able to automatically recognize the different phases and predict surgical end-time. The predicted end-times can be used to communicate to the ward to deliver the next patient and to optimize the scheduling system. As the progress of the intervention is visible for every HCP, the peri-operative awareness and thereby communication can be improved. The difficulty with real-time progress monitoring is accuracy, as predictions must be accurate in order to have a relevant effect on efficiency in the workflow. A reasonable approach to tackle this issue is to identify the accuracy of the sensors and investigate implication on the workflow and the efficiency in the event the predictions are false.

Real-time sensing can be used for context awareness systems. As complicated procedures require a lot of mental capacity from a cardiologist, it could be beneficial to support the decision-making process. To be specific; remind them of important tasks and direct the next surgical step. An example of a context support system is reminding to insert the second round of heparin. Heparin is inserted in the patient to prevent blood cloths during a CAG procedure. However, after one hour the effect of the heparin is diminished and a second round of heparin is required. It is up to the cardiologists to remind and initiate these tasks.

Throughout the surgical procedures all the used equipment is logged. These administrative tasks are conducted by the LAs or operation assistants. By using camera sensors, the equipment can be automatically detected and registered. Thereby we can decrease the administrative burden of the assistants.

This research has paved the way for in-depth efficiency assessment and workflow optimization in the cath lab. In the introduction, the yearly loss of $347,327 and 241 hours per OR caused only by inefficient use of the turnover times was mentioned(8). Considering that inefficiencies can also occur inside the procedure, the yearly loss is expected to higher. The cost of delay in an OR is $25 /minute(8). In the event that turnover time can be shortened by five minutes, 20 minutes of scarce lab time would be saved each day. Assuming the cost of delay in the cath lab is similar to the cost of delay in the OR, 500 $/day can be saved by optimizing the turn-over times. Moreover, the LAs wait in the morning for 20 minutes and in the afternoon for 15 minutes. In case the waiting time could be reduced with 50%, 18 minutes of wasted time would be utilized and 450 $/day would be saved. Enhancing starting time and the turn-overtime can result in saving 38 minutes that account for 950 $/day, which is approximately the scheduled time of one CAG procedure. As a result of optimization, an extra patient could be treated every day and money could be saved.

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12 Appendix

12.1 Role Activity of the CAG procedure

Table 11: Role activity table of the CAG procedure including the locations of the actors and activities. Orange denotes a deviation in the process

LA (1)		LA (2)		LA(2)/LA (3)		CA		NU	
Action	Place	Action	Place	Action	Place	Action	Place	Action	Place
Turn on devices[1]	CL	Turn on devices [1]	CL						
Clean the lab[2]	CL	Clean the lab[2]	CL					Prepare patient	WARD
Patient bed preparation	CL								
Place equipment	CL	Place equipment	CL	Call CA if he is not present	CR				
Set-up trolley for CAG [3]	CL	Set-up trolley for CAG [3]	CL	Call to request patient	CR			Bring patient to the door	DOOR
Help patient in the lab	CL	Discuss patient details	CR	Discuss patient details		Discuss patient details	CR		
Help patient on bed	CL	Help patient on bed	CL			Prepare for the intervention	CR	Discuss patient details	CR
Couple ECG on patient	CL	Couple on ECG patient	CL						
Apply drapes on patient	CL	Apply drapes on patient	CL	Administration					
Apply plastics on machines	CL	Arm patient in position	CL						
Scrub for CAG	SR	Set-out catheter equipment on bed	CL			Safety check with patient and LA (1) [4]	CL		
	CL	Couple contrast and IV on syringe	CL			Scrub for CAG	SR		
Put on sterile clothes/gloves	CL	Disinfect wrist [5]	CL	Report begin time	CR				
Set-up tray for CAG [3]	CL	Help LA(1) with sterile clothes	CL	Signal CA for start		Puts on sterile clothes/gloves	CL		
Finalize tray set-up	CL	Helps CA with clothes	CL						
Assist CA during the CAG	CL	Finalize tray set-up	CL			Disinfect wrist [5]	CL		
				Monitor heart function	CR	Sedate skin wrist	CL		
				Administers used equipment	CR	Needle incision in A. Radialis	CL		

						Insert introducer in A. Radialis	CL		
						Insert the sheet in A. Radialis	CL		
						Insert Heparin + vasodilators	CL		
				Logs events of heart	CR	Insert guidewire + catheter	CL		
		Put lights out	CR			Guide catheter A. Radialis to the upper aorta arch	CL		
		Assist LA(1) and CA if needed: supplies + extra tasks				Repeat imaging + contrast until RCA ostium is found	CL		
Repeat contrast till RCA entry is found	CL					Enter the RCA			
				Archiving images		Take 3 video recordings[3]: 1) left anterior obtuse, 2) right anterior obtuse 3) left anterior obtuse cranial	CL		
						Remove guidewire	CL		
						Insert new guide wire for LCA	CL		
						Repeat imaging + contrast until LCA ostium is found	CL		
Repeat contrast till LCA entry is found	CL					Enter LCA	CL		
						Take 4 video recordings[4]: 1) left anterior caudal, 2) left anterior cranial, 3) right anterior cranial, 4) right anterior caudal	CL		
						Remove catheter with guidewire	CL		
				Archiving images	CR	Remove introducer sheet	CL		

[3] This position is from the x-ray image intensifier (receives the radiation)
[4] This position is from the x-ray image intensifier

						Put compression band on[5]	CL		
Put compression band on[5]	CL					Give feedback to patient	CL		
Remove equipment on bed	CL	Remove equipment on bed	CL			Report the casus	CR		
Remove drapes from patient	CL	Throw away used products and sterile drapes		Call holding for pick-up [6]	CR	Brief the NU about the case	CR	Come to CL to pick up patient [6]	WARD
Decouple patient from ECG and IV	CL					Report the casus	CR	Receive details about the case [6]	CR
Help patient back to the bed outside the door	CL	Help patient back to the bed outside the door	CL			Prepare for new casus	CR	Bring patient back to holding[6]	DOOR
Bring back patient to ward[6]	WARD	Bring back patient to ward[6]	WARD						
Finish cleaning	CL	Finish cleaning	CL	Call to request patient	CR				
Prepare lab for next patient[7]	CL	Prepare lab for next patient[7]	CL	Prepare lab for next patient[7]	CL				
Restock supplies	CL								
Close down lab	CL								

N.B.

In case of having 2 LA's instead of 3, the dynamics and tasks change. Then LA (3) takes over the tasks of LA (2).

Variable tasks:

[1]: Only conducted at the first sessions of the day

[2]: Should be done the day before when the final intervention is finalized. However it can occur, that the room is not cleaned. As a result in the morning, the lab must be cleaned.

[3]: These actions can also take place when the patient is already in the room, it changes with the preference of the LA when this task is done

[4]: It can occur that the safety check is done after the CA has scrubbed for the procedure

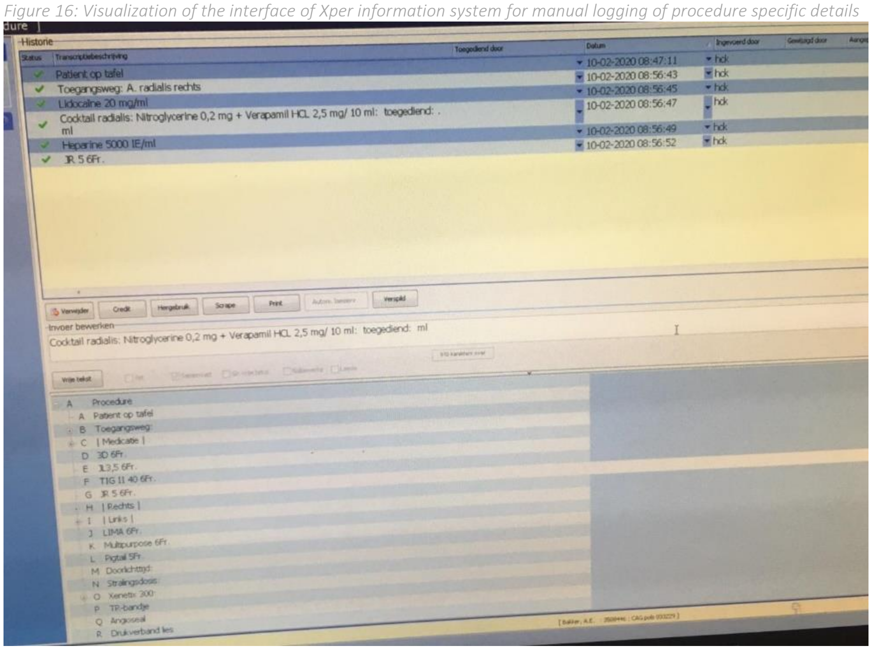
[5]: Either the CA or the LA conducts this action

[6]: Depends on the amount of LA's that are working and 'whether they feel like it'. In case there are 3 present they bring back the patient to the holding. In case of 2, they in general call the nurses to pick up the patients

[7]: This activity is not conducted in the event it is the last intervention of the session or the day

12.2 List for logging the procedure related details

Figure 16: Visualization of the interface of Xper information system for manual logging of procedure specific details



List from the interface:

- Patient on the table
- Access route: radialis/femoralis
    - Left or right
- Medication
    - Lidocaine 20 mg/ml
    - Cocktail radialis: nitroglycerine 0,2 mg + Verapamil HCL 2,5 mg/10ml
    - Heparin 5000 IE/ml
- 3D 6Fr Catheter
- JL3, 5, 6 Fr Catheter
- TIG II 40 6 Fr Catheter
- JR 5 6 Fr
- LIMA 6 Fr Catheter
- Multipurpose 6Fr
- Pigital 5 Fr
- More left and right Catheters
- Duration of radiation
- Radiation dose
- Xenetix 300
- Compression band wrist
- Angioseal
- Compression bandage groin
- Patient of table
- End procedure

12.3 Standard procedure times for all the interventions executed in RDGG

Reinier de Graaf

Verrichtingen cardiokamer:

Omschrijving:	verrichting:	
CAG met bypasses	033229	→ 60min
CAG lies	033229	→ 45min
CAG pols	033229	→ 45 min
Centrale lijn	039829	→ 30min
Doorlichting Riata draad	085000	→ 30 min
Externe pacemaker	033266	→ 60 min
ICM implantatie	039698/190329	alleen nog LinQ impl worden gedaan.
ICM verwijderen	039699/190329	45min
Lead bijplaatsen	039757	→ 60 min
Lead vervangen	039757	→ 60 min
Pericard punctie	039114	→ 60 min
PMI AAIR	033267/190331	→ 60 min
PMI CRT-p	033279/190333	→ 240 min
PMI DDD	033272/190332	→ 90 min
PMI VVI	033267/190331	→ 60 min
PMV AAIR	033283/190331	→ 45 min
PMV CRT-p	033283/190333	→ 45 min
PMV DDD	033283/190332	→ 45 min
PMV VVI	190331	→ 45min
PM verwijderen	033284	→ 30min
PM pocket revisie	033252	→ 150 min
Rechtskatheterisatie	033219	→ 90 min
Repositie lead of upgrading	039757	→ 60 min
Venogram links/rechts	084024	→ 30 min

Alles wat meer of minder gedaan wordt doorgeven aan de planning

tel 3073 of op de mail: planningcardio@rdgg.nl

Figure 17: Procedures that are executed in the RDGG hospital with their corresponding standard procedure duration for the schedule

12.4 Code

12.4.1 Excel

```
Sub Requestpatient()
nr = ThisWorkbook.Sheets("Raw_Data").Cells(Rows.Count, 10).End(xlUp).Row + 1
Cells(nr, 10) = Time
End Sub
Sub Deliverypatient()
nr = ThisWorkbook.Sheets("Raw_Data").Cells(Rows.Count, 11).End(xlUp).Row + 1
Cells(nr, 11) = Time
End Sub
Sub Entrypatient()
nr = ThisWorkbook.Sheets("Raw_Data").Cells(Rows.Count, 12).End(xlUp).Row + 1
Cells(nr, 12) = Time
End Sub
Sub Insertcocktail()
nr = ThisWorkbook.Sheets("Raw_Data").Cells(Rows.Count, 13).End(xlUp).Row + 1
Cells(nr, 13) = Time
End Sub
Sub ArrovilAortaArch()
nr = ThisWorkbook.Sheets("Raw_Data").Cells(Rows.Count, 14).End(xlUp).Row + 1
Cells(nr, 14) = Time
End Sub
Sub Retractfirstcath()
nr = ThisWorkbook.Sheets("Raw_Data").Cells(Rows.Count, 15).End(xlUp).Row + 1
Cells(nr, 15) = Time
End Sub
Sub Insertsecondcath()
nr = ThisWorkbook.Sheets("Raw_Data").Cells(Rows.Count, 16).End(xlUp).Row + 1
Cells(nr, 16) = Time
End Sub
Sub Retractsecondcath()
nr = ThisWorkbook.Sheets("Raw_Data").Cells(Rows.Count, 17).End(xlUp).Row + 1
Cells(nr, 17) = Time
End Sub
Sub TRband()
nr = ThisWorkbook.Sheets("Raw_Data").Cells(Rows.Count, 18).End(xlUp).Row + 1
Cells(nr, 18) = Time
End Sub
Sub Exitpatient()
nr = ThisWorkbook.Sheets("Raw_Data").Cells(Rows.Count, 19).End(xlUp).Row + 1
Cells(nr, 19) = Time
End Sub
```

12.4.2 Matlab

```
%% author: K.M. van der Graaf
% code for graduation project
clc
close all
clear all
%% import data from excel spreadsheet from the exam and the event sheet from the Imaging system
% the exam is one specific procedure, the events are when the CT arch is used
% [num, txt, raw] = xlsread("RDGG_Data.xlsx", "Exam");          % num are the numeric variables txt are the
textual variables
% [num2, txt2, raw2] = xlsread("RDGG_Data.xlsx", "Event");
%%  Load data from the collected data
[num, txt, raw] = xlsread("Timing_procedures.xlsm", "Metrics (2)");
%% process the metrics
%converting the time to hours, seconds or minutes. Insert 1 if you want to
%turn if of
H = 24
M = 60
S = 1
% estimated time for preparing the lab on the first day

%%  collect the data from the sheet
% sequence of imported metrics 1)patient waiting time, 2)delivery, 3)procedure,
% 4)imprecision, 5)turnaround, 6/7)prep 1-1.2, 8/9)clean 3-3.2
%10)preop 11)operative 12)postcare 13/14) P1 15)P2 16)p3 17)p4 18)p5
% create empty matrix
t = ones(38,18);
% fill in all the metrics in one array
for i = 1:18
    x = num(:,11+i);
    t(:,i) = x;
end
% convert to desired time units --> [minutes]
t_m = t.*(H*S*M);
prep=7.5
t_m(:,6)=t_m(:,6)-prep
% t_m = t_m_log;
%% extract for mean - median - std - min - max for all metrics
specs = ones(12,5);
for i = 1:12;
    mean    = nanmean(t_m(:,i));
    median  = nanmedian(t_m(:,i));
    std     = nanstd(t_m(:,i));
    min     = nanmin(t_m(:,i));
    max     = nanmax(t_m(:,i));
    specs(i,:) = [mean median std min max];
end

specs2 = ones(4,5);

for i = 15:18;
    mean1   = nanmean(t_m(:,i));
    median  = nanmedian(t_m(:,i));
    std     = nanstd(t_m(:,i));
    min     = nanmin(t_m(:,i));
    max     = nanmax(t_m(:,i));
    specs2(i-14,:) = [mean1 median std min max];
end

P1= [nanmean([t_m(:,13) ; t_m(:,14)]), nanmedian([t_m(:,13) ; t_m(:,14)]), nanstd([t_m(:,13) ; t_m(:,14)]),
nanmin([t_m(:,13) ; t_m(:,14)]), nanmax([t_m(:,13) ; t_m(:,14)]) ];
% merge in one array
metrics = [specs ; P1 ;specs2];
% metrics = exp(metrics);
t_mp1=[t_m(:,13) ; t_m(:,14)]
%% convert to table

% You can assign the specific headings to your table in the following manner
T =array2table(metrics)
T.Properties.VariableNames(1:5) = {'mean'; 'median'; 'std'; 'min' ; 'max' }
% List = { 'Patient_waiting_time'; 'Delivery_time'; 'Procedural_length'
% 'average_imprecision';'turnaround_time';'prep_first_case'; 'prep_after_break';
% 'cleanup_last_case'; 'cleanup_after_break'; 'preop_patient' ; 'operative_length';
% 'post_care'; 'P1'; 'P2'; 'P3'; 'P4';'P5'};

%% boxplot of high-level metrics p = 13-17
grp                                                                                                  =
[zeros(1,length(t_mp1)),ones(1,length(t_m(:,15))),2*ones(1,length(t_m(:,16))),3*ones(1,length(t_m(:,17))),4*o
nes(1,length(t_m(:,18)))];
data= [t_mp1; t_m(:,15); t_m(:,16); t_m(:,17); t_m(:,18)]
figure
```

```
subplot (2,1,1)
boxplot([t_m(:,10), t_m(:,11), t_m(:,12)])           % pre op / operative / post care
set(gca,'XTickLabel',{'Patient Preparation duration)','Operative length', 'Post-care duration'})
title(' Break-out of the metrics inside the procedure (N=40)')
%xlabel({''})
ylabel({'Duration', ' in [min]'})
ylim([0 110])
subplot(2,1,2)
boxplot(data, grp)     % evaluation of P1-P5
set(gca,'XTickLabel',{'P1 (n=46)','P2 (n=43)', 'P3 (n=40)', 'P4 (n=40)', 'P5 (n=40)'})
title(' Break-out of the metrics inside the operative phase (N=40)')
%xlabel({''})
ylabel({'Duration', ' in [min]'})
ylim([0 20])
%% cycle time = procedure + turn time
index_ct = find(t_m(:,5)>1)             % index of turntime
c_t = t_m(index_ct,5)+t_m(index_ct,3)
c_t(end-3)=[]

c_t_s = [nanmean(c_t) nanmedian(c_t) nanstd(c_t) nanmin(c_t) nanmax(c_t)]
%% Create histogram to view distribution
p=2                     % insert here you desired metrics to check the normal distribution
x1=t_m(:,p)
x=t_m_log(:,p)
figure()
subplot(1,2,1)
h=histogram(x1,20);
subplot(1,2,2)
h2=histogram(x,20);
%% transform to logorithm
t_m_log = log(t_m)             % transform data into logarithm data
specs = ones(12,2)
for i = 1:12
    mean    = nanmean(t_m_log(:,i))
    std     = nanstd(t_m_log(:,i))
    log(i,:) = [mean std]
end

log2 = ones(4,2)

for i = 15:18
    mean    = nanmean(t_m_log(:,i))
    std     = nanstd(t_m_log(:,i))
    log2(i-14,:) = [mean std]

end

P1_log= [nanmean([t_m_log(:,13) ; t_m_log(:,14)]), nanstd([t_m_log(:,13) ; t_m_log(:,14)]) ]
% merge in one array
metrics_log = [log ; P1_log ;log2]

%% divide the metrics based on context
lab2 = find(num(:,9)==2);       % index fot the lab assistants who work with 2
lab3 =  find(num(:,9)==3);      % index fot the lab assistants who work with 3
self_PU = [13 24 26 32 35 36]-1'  % index for when the lab assiistants picked up the patient by themselves
st = txt(:,7); outpatient = find(ismember(st, 'policlinial'))-1; inpatient=find(ismember(st, 'clinical'))-1
%index for inpatients and outpatients
coffee = [7 12 17]-1'              % index for when extra time was taken for the during the turnovertime e.g.
coffee break
%% turnover times (with 2 or 3 la patients and patient type)
% turn-times where the coffeebreaks are removed
tt_all=t_m_log(:,5); tt_c=t_m(:,5); % turntimes [log] & minutes
tt_all_c=tt_all;
tt_all_c(coffee)=nan;               % turntimes removed where a coffee break was held [log transform]
tt_c(coffee)=nan;                   % turn times [minutes]

% turntimes for in and outpatients in log & minutes
tt_in_l=tt_all_c(inpatient);        % turntimes removed coffeebreaks for inpatients
tt_out_l=tt_all_c(outpatient);      % turntimes removed coffeebreaks for outpatients
tt_in=tt_c(inpatient);            % turntimes removed coffeebreaks for inpatients
tt_out=tt_c(outpatient);          % turntimes removed coffeebreaks for outpatients

% turn-times in groups a number of lab-assisttans in log and minutes
tt_3_l=tt_all_c(lab3);            % 3 LA - log transform
tt_2_l=tt_all_c(lab2);            % 2 LA - log transform
tt_3=tt_c(lab3);                % 3 LA - minutes
tt_2=tt_c(lab2);                % 2 LA - minutes
% ttest of LAs
% [ h_LA, p_LA, ci_LA, stats_LA ] = ttest2 (tt_3, tt_2 ,'Vartype', 'unequal')
% delta_LA = nanmean(tt_2)-nanmean(tt_3)
% Mann-Whitney U-test
[p,h]=ranksum(tt_in, tt_out)
```

```
% ttest  inpatient and outpatient and effect on the mean by turn time
[ h_IO, p_IO, ci_IO, stats_IO ] = ttest2 (tt_in, tt_out ,'Vartype', 'unequal')
delta = nanmean(tt_in)-nanmean(tt_out)
%% patient delivery with inpatients or outpatients
pd_in_l=t_m_log(inpatient, 2);
pd_in=t_m(inpatient, 2);

pd_out_l=t_m_log(outpatient,2);
pd_out=t_m(outpatient, 2);
pd_out(end)=[]
% ttest  inpatient and outpatient patient delivery
[ h_PD, p_PD, ci_PD, stats_PD ] = ttest2 (pd_in, pd_out ,'Vartype', 'unequal')
delta =    nanmean(pd_in)-nanmean(pd_out)
% Mann-Whitney U-test
[p,h]=ranksum(pd_in, pd_out)
%% preparation first case of the day and after the break
fc_l = t_m_log(:,6);
fb_l = t_m_log(:,7);
fc = t_m(:,6); fb=t_m(:,7)
% ttest of LAs and inpatient and outpatient
[ h_rad, p_rad, ci_rad, stats_rad ] = ttest2 (fc_l, fb_l ,'Vartype', 'unequal')
delta = nanmean(fc)-nanmean(fb)
l1=length(find(fc>1))
l2=length(find(fb>1))
%% clean up end of the day or after break
lc_l = t_m_log(:,8);
bc_l = t_m_log(:,9);
lc = t_m(:,8); bc=t_m(:,9)
% ttest of LAs and inpatient and outpatient
[ h_rad, p_rad, ci_rad, stats_rad ] = ttest2 (lc_l, bc_l ,'Vartype', 'unequal')
delta = nanmean(lc)-nanmean(bc)
l1=length(find(lc>1))
l2=length(find(bc>1))
% transform the logarithmics data back to the normal measures
% use exp
%% Fill here the variable in for the Mann Whittney U test
[p,h]=ranksum(t_m(:,8), t_m(:,9))
delta = nanmean(t_m(:,8)) - nanmean(t_m(:,9))
%% boxplots
figure
subplot (2,1,1)
boxplot([tt_3, tt_2])
set(gca,'XTickLabel',{'3 Lab-Assistants(n=)','3 Lab-Assistants(n=)'})
title(' Comparison of turn-overtime with 2 or 3 Lab-Assistants')
xlabel({'Number or assistants'})
ylabel({'Logtransformed turn-over', 'time[min]'})
ylim([2 3])
subplot(2,1,2)
boxplot([preop_3, preop_2])
set(gca,'XTickLabel',{'3 Lab-Assistants(n=)','3 Lab-Assistants(n=)'})
title(' Comparison of patient-preparation with 2 or 3 Lab-Assistants')
xlabel({'Number or assistants'})
ylabel({'Logtransformed patient', 'preparation time[min]'})
ylim([1 6])
%% sample size calculation
nout = sampsizepwr('t2',[10 4], 7, 0.9)            % type test, expected/prior evidence of the outcome
%% transform units to time units 00:00:00
time = {'00:03:30'};
formatIn = 'HH:MM:SS'
t = datenum(time, formatIn);
```

12.5 Questionnaire

The questions were presented in Dutch to the cath lab team.

Table 12: Set of outcomes from the questionnaire. Outcomes are present as the average ± the standard deviation. The questions and outcomes are removed that could not ensure the privacy of the participants.

Questions	M ± SD
Het brengen van de patiënt naar de cath lab kamer kan sneller	2.2 ± 0.8
We beginnen op tijd aan de eerste casus	3.4 ± 1.1
Uitloop is inherent verbonden aan het werken in de cath lab	2.2 ± 0.8
Het is normaal dat patiënten worden doorgeschoven naar de volgende dag of afgebeld	3.9 ± 0.8
Het brengen van poli klinische patiënten naar de cath lab gaat sneller dan klinische patiënten	2.8 ± 1.0
Patient in tot patient uit duurt bij een CAG langer dan 30 minuten	2.7 ± 1.0
Werken met 3 lab assistenten zorgt ervoor dat de cath lab sneller klaar is voor de volgende patiënt	1.6 ± 1.0
De tijden van het rooster zijn accuraat	3.4 ± 1.3
Een beter rooster zou ons helpen in het stroomlijnen van ons werk	3.1 ± 0.9
Piekdrukte bezorgt mij stress	3.9 ± 1.5
De hoogste werkdruk ervaar ik in de tijdens de ingreep	4.2 ± 0.7
De hoogste werkdruk ervaar ik in de voor de start van ingreep	3.6 ± 1.1
De administratielast is hoog	2.8 ± 1.1
De administratieve taken dragen bij aan de werkdruk	2.5 ± 1.0
Ik heb voldoende rustmomenten gedurende mijn werkdag	2.6 ± 1.2
Ik word graag ontlast in mijn administratieve taken	2.4 ± 1.3
Uitloop van ingrepen beïnvloedt de werkdruk	2.8 ± 1.3
Het grootste tijdverlies zit in het brengen van de patient naar dat cath kamer	2.4 ± 1.3
Er is ruimte voor workflow optimalisatie op de cath kamer	1.7 ± 0.5
De voorbereiding duurt langer dan de ingreep, de CAG, zelf	1.7 ± 0.7
De trage computer systemen dragen bij aan inefficiëntie	2.8 ± 0.8
Scale: [1 = strongly agree and 5 = strongly disagree]	

12.6 Overview of the metrics of efficiency used in literature – results from a systematic review

Metric	Definition of the metrics	Phase	Frequency (study)	
	Time related metrics (n=36)			
	Most frequent used time related metrics (n= 6)			
Procedural time/ Procedure duration/ Operative length	1. Time from the start of the puncture to complete removal of the final guide catheter(35) 2. Time the patient entered the cath lab to the time they left the cath lab(36) 3. Time first incision to completion of wound closure(33)	Intra	8	(10, 19, 31, 33, 35-38)
(First case) on-time start	1. On-time patient and physician arrival to the Cath Lab of first case of the day(17) 2. Patient and physician arrival for the first case of the day in any given lab room(5, 14)	Pre	5	(4, 5, 14, 17, 39)
Door-to-Balloon time for PCI procedure	Door time as the time of registration at the emergency department(34, 40-43) Balloon time was defined as the time the first balloon was inflated in the culprit artery(34, 40-43)	Peri	5	(34, 40-43)
Turnaround / Turn-over time	Duration between the exit of the preceding patient and the arrival of the next scheduled patient in the Cath Lab(5, 12, 14, 17,	Intra	5	(5, 12, 14, 17,
Length of stay	Time from outpatient admission to discharge(36)	Peri	3	(36, 44, 45)
	Other time related metrics (n=30)			
Admission-to-pre procedure time	Time patients were admitted to the inpatient care ward unit until arrival outside to the waiting room of the cath lab	Pre	1	(46)
Average imprecision	The difference between the observed surgery length minus the estimated surgery length	Intra	1	(31)
Cath lab-to-balloon time	-	Intra	1	(34)
Cycle time *1. Cycle time phase 1* *2. Cycle time phase 2* *3. Cycle time phase 3* *4. Cycle time phase 4*	Length of patient stay in the IR suite plus the time for IR suite preparation for the next patient 1. Time from patient entry to radiologist entry 2. Time from radiologist entry to skin incision 3. Time from skin incision to sticking plaster 4. Time from skin suture to patient exit	Intra	1	(19)
Days at full capacity operating potential	Proportion of days in which the entire lab is at full capacity = 100% lab utilization	Intra	1	(14)
Door-to-activation time for PCI procedure	Hospital arrival to ST-segment elevation myocardial infarction diagnosis and activation of the catheterization laboratory for PCI treatment	Pre	1	(43)
Door-to-cath lab time	-	Pre	1	(34)
ECG – to balloon time	ECG time corresponds with the first diagnostic 12-lead ECG recorded in the field to the first therapeutic intervention. Balloon time was defined as the time the first balloon was inflated in the culprit artery	Peri	1	(34)
Expected number of procedures in the	The number of patients that are waiting for their surgery	Pre	1	(20)
Expected length of delay	Date of request from physician for the surgery to the date of the intervention	Pre	1	(20)
(First case) on time completion	End time procedure (= when patient exits room) is in line with the schedule	Intra	1	(39)
(First case) on-time patient arrival	The duration between the designated Cath Lab start time and patient arrival was ≤15 min(17)	Pre	1	(17, 19)
(First case) on-time physician arrival	The physician was present in the Cath Lab within 15 min of the designated Cath Lab start time or within 15 min of the patient arrival to the Cath Lab.	Pre	1	(17)
Fluoroscopy time to cross lesion	Fluoroscopy time (sec) required to advance the wire from the tip of the guide catheter to a point well distal to the target lesion.	Intra	1	(35)
Lead time	The sum of cycle time and waiting times between sub processes	Peri	1	(20)
Overtime	Time the operation duration exceeds the scheduled time(21)	Intra	1	(21)

Metric	Definition of the metric	Phase	Frequency (study)	
Physician downtime	Duration between achievement of hemostasis and the arrival of the next patient.	Intra	1	(17)
Pre procedure-to-procedure time	Time patients arrived at the waiting room to the time the procedure begins	Pre	1	(46)
Registration-to-admission time	Time between arrival at registration and admission to inpatient ward unit	Pre	1	(46)
Recovery duration	Time from the end of the procedure to discharge	Post	1	(36)
Room preparation time	-	Pre	1	(19)
Takt time	The daily room uptime divided by daily procedures requested.	Peri	1	(20)
Throughput	The number of procedures performed per time unit on the basis of data from the radiology information system	Intra	1	(20)
Time to cross lesion	Time required to advance the wire from the tip of the guide catheter to a point well distal to the target lesion.	Intra	1	(35)
Total patient waiting time	From arrival to the beginning the catheterization procedure	Pre	1	(46)
Under time	Time left of the scheduled time of the operation	Intra	1	(21)
Workload related metrics (n=6)				
Case volume	Number of cases in a period of time [cases/month]	Intra	2	(14, 39)
(First case) sheath pulls inside the cath lab	1. Proportion of all manual sheath-pulls performed inside the Cath Lab(17) 2. Proportion of non-radial cases in which the vascular access sheath is pulled in the lab room(46)	Intra	2	(17, 46)
Overtime hours	Proportion of hours paid to FTE's classified as overtime(14)	Peri	2	(14, 39)
After-hours cases (%)	Proportion of scheduled cases that occur after normal operating Hours (i.e., after 5 PM).	Intra	1	(5)
Lab productivity	Number of FTE nurses and techs compared with cath lab volume, and proportion of shifts that were overtime after hours or weekends	Intra	1	(5)
Productivity per FTE	Ratio of case volume per non-physician FTE.	Peri	1	(5)
Cost related metrics (n=5)				
Total costs	1. Total hospital costs(44, 47) 2. Total hospital costs adjusted for comorbidities(45) 3. Index procedure, non-procedural hospital costs and physician fees(37) 4. Capacity, supply and delay costs for running an IR suite(20) 5. Total costs stay; physician charges, equipment charges, all other hospital charges, and total admission charge.(36)	Peri	6	(19, 20, 36, 37, 44, 45, 47)
Capacity costs	Labor, lease and overhead costs (20)	Peri	2	(19, 20)
Delay costs	Extra inpatient costs due to the inpatient delay	Peri	1	(20)
Physician charges	Included both cardiologist and anaesthesiologist charges	Intra	1	(36)
Equipment charges	Consisted of sterile supplies, pacemakers, and all other	Intra	1	(36)
Resource related metrics (n =2)				
Lab/IR suite / Room utilization	Percentage of open cath labs at maximum capacity for any given day(14) Ratio of number of hours each lab room is staffed to the number of hours the lab room is utilized.(5)	Intra	4	(5, 14, 20, 21)
Contrast used to cross a lesion [ml]	Amount of contrast (in ml) required to advance the wire to a point well distal to the lesion.	Intra	1	(35)

FTE = full time employee