Development of a myocardial perfusion phantom

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Preface

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Contents

1 Introduction

Myocardial Perfusion Imaging (MPI), or, simply put, the imaging of the blood flow in the heart muscle, plays an important role in diagnosing heart failure or detecting Coronary Artery Disease (CAD). Imaging systems like Computed Tomography (CT), Magnetic Resonance Imaging (MRI), Single-Photon Emission Computed Tomography (SPECT), or Positron Emission Tomography (PET) can visualise a (radioactive) contrast bolus in the supplying arteries and in underlying myocardial tissue, whose flow can give an indication of narrowed or blocked blood vessels.

Many variations in the visualisation process of myocardial perfusion, including variations in hard- and software, can (significantly) influence the outcome and in turn have consequences for patient treatment. These variations need to be validated against a well-known baseline.

A myocardial perfusion phantom will be developed that is able to simulate the blood flow in the heart muscle, i.e. the myocardium, and is able to mimic cardiac defects like (significant) stenosis.

Document overview

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Abbreviations

CAD Coronary Artery Disease

CT Computed Tomography

HLA Horizontal Longitudinal Axis

MPI Myocardial Perfusion Imaging

MRI Magnetic Resonance Imaging

PET Positron Emission Tomography

SA Short Axis

SPECT Single-Photon Emission Computed Tomography

VLA Vertical Longitudinal Axis

2 Research methodology

This chapter serves as a summary of the previously answered research questions and gives an overview of the research questions to come.

2.1 Main research question

Can patient treatment reliably depend on the D-SPECT, using dynamic scanning, in myocardial perfusion imaging?

Answer

As of Monday 18th February, 2019, the main research question has not been answered.

Answered in

It will be answered in the final report of the master's thesis.

Based on

The answer will be based on the developed myocardial perfusion phantom and the experiments performed with it at the ZGT Hengelo.

2.2 Concept of Operations

Is the D-SPECT's dynamic scanning, in comparison with other modalities(CT, MRI, PET, or SPECT), suitable for quantitative perfusion imaging?

What must the myocardial perfusion phantom be able to simulate?

Answer

The D-SPECT is relatively new in the Netherlands, but it is more widely employed in Japan, Canada, France, and Great-Britain. The highly specialised nature (for cardiac purposes), the patient friendly design, the ability to scan faster and more accurate at significant dose reductions, make the D-SPECT suitable for quantitative myocardial perfusion.

The myocardial perfusion phantom will have to simulate a patient, with stenotic artery (or arteries), in a physiological way, which is compatible with clinical protocol and software.

Answered in

The answer to this research question can be found in the system requirements document section 2.2.1 and 2.2.2, respectively.

Based on

The answer to this research question is based on the literature review and background investigation performed in the project plan, chapter 2.

2.3 Requirements and Architecture

What are the requirements for a myocardial perfusion phantom that can be used in combination with commonly used clinical software?

Answer

The requirements are specified in tables corresponding in the system requirements document.

Answered in

The answer to this research question can be found int he system requirements document, chapters 2 and 3.

Based on

The answer to this research question is based on interviews with a part of the direct stakeholders, as specified in the project plan section 3.2.

2.4 Detailed Design

How can the myocardial perfusion phantom meet the clinical requirements and mimic the perfusion of a human heart?

Answer

It will be answered in the this detailed design document.

Answered in

The answer can be found in chapter 4.

Based on

The answer to this research question is based on a mind map which results in different concept. The most promising concept, based on the requirements, is developed further into a detailed design.

3 Concept design

This chapter defines the global restraints on the concepts and presents an overview of the different concepts.

3.1 Global restraints

This section describes the global restraints on the concepts, as stated in the system requirements.

3.1.1 Myocardium

To ensure compatibility to the clinical software, *4DM*, the myocardium's cross-sectional shapes must be physiological; i.e. the Horizontal Longitudinal Axis (HLA) and Vertical Longitudinal Axis (VLA) have the shape of a horseshoe and the Short Axis (SA) has the shape of a circle. 4DM requires these shapes to determine the contours and consequently determine the myocardial flow.

3.1.2 Modality

The main research question is based around the, relatively new in the Netherlands, D-SPECT's dynamic scanning. Therefore, the modality is bounded to the D-SPECT. As mentioned in section 2.2, the D-SPECT is a suitable choice for myocardial perfusion imaging but still requires validation, which is the goal of the PhD research of which this project is part of.

3.1.3 Tracer

The tracer and injection method are fixed due to clinical, 4DM, and dynamic scanning requirements. The clinical (and D-SPECT) protocol use ^{99m}Tc (Technetium) Tetrofosmin for myocardial perfusion imaging. To ensure proper dynamic scanning results, the tracer must be injected with a pump. The pump can repeatedly inject tracer with identical volumes and injection speeds.

3.1.4 Flow Type

Based on background information on the 4DM software, a decision has been made to use a non-pulsatile flow. The D-SPECT uses gated measurements such that images are extracted at the same point in time of the cardiac cycle. Furthermore, initial experiments with the D-SPECT, with non-pulsatile flow, have been performed on February 5, 2019. The prototype set-up from the individual project, with a dialysis tube, was placed in the D-SPECT and the TAC was extracted. This curve showed proper similarity to TACs extracted from patients.

3.2 Concept overview

Each concept is based on the mind map shown in appendix A. The following sections describe each aspect of the five main categories, respectively:

- Myocardium,
- Modality,
- Design,
- Tracer, and
- Flow.

3.2.1 Myocardium

The myocardium has two subcategories, the shape and the model. As described in section

Shape

As described in section 3.1.1, the shape of the myocardium is especially important for the 4DM software since it looks for the contours of the left ventricle's walls. Therefore, the shape of the myocardium is fixed (as per system requirements):

- VLA: Horseshoe (figure.
- HLA: Horseshoe.
- SA: circle.

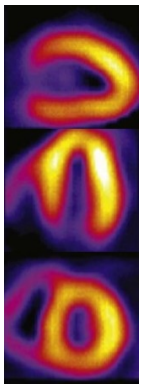

Figure 3.1: Left ventricle's myocardial shapes: VLA, HLA, SA, respectively (Niwaz, 2015)

Model

[todo] this section, depending on 4dm.

The 4DM software offers different segment models in addition to the full 17-segment model, i.e. ..... The goal is to develop a phantom with 17 segments, fully compatible with 4DM. However, 4DM's ability to downscale to a fewer-segment model, provides the opportunity for a more simplified first prototype.

3.2.2 Modality

As described in section 3.1.2, the modality is fixed to the D-SPECT's dynamic scanning.

3.2.3 Design

The phantom can be designed in three different ways: using a 1-, 2-, or 4-chamber design. The 1-chamber design simulates only the left ventricle with the myocardium. The 2-chamber design simulates either the left and right ventricles, or the left atrium and ventricle. The other combinations, i.e. left ventricle and right atrium, and any combination without the left ventricle, does not hold any additional benefits. The 4-chamber design contains all heart chambers to simulate the flow as physiological as possible. A 3-chamber design is not considered since it has no physiological structure nor does it have an added benefit over a 1- or 2-chamber design.

3.2.4 Tracer

As described in section 3.1.3, the tracer protocol is fixed.

3.2.5 Flow

Generator

The flow in the phantom can be realised by a various of methods (or combinations thereof):

- Peristaltic pump,
- Gear pump,
- Air pressure,
- Dedicated myocardial generator,
- Branching aorta.

Supply

The supply can be realised by a direct connection to the tap (water mains) or via a reservoir which can be filled directly from the tap or manually, e.g. using watering pots. In case of a closed circuit, see section 3.2.5, the reservoir can be filled by the outflow of the phantom.

Disposal

Proper disposal of contaminated, with nuclear tracer, will be a vital. Any fluid, or materials, that come into contact with the radioactive tracer, needs to be isolated for a period of multiple days. Spills should be avoided at all costs. Waste fluid can be stored in reservoirs, wheeled (closed) containers, or wheelie bins (Dutch "Kliko"). In case of a closed circuit, see section 3.2.5, the outgoing flow can be directed to the input reservoir.

Configuration

The flow set-up can be designed in either a closed circuit or open circuit. The closed circuit characterises itself by having no disposal flow, see figure 3.2. The optional filter can extract, if possible, the tracer from the perfusate such that first pass perfusion is realised. Otherwise, the tracer is recirculated which causes the bolus to disappear. An alternative is an open circuit, see figure 3.3, which guarantees first pass perfusion due to the absence of any form of recirculation.

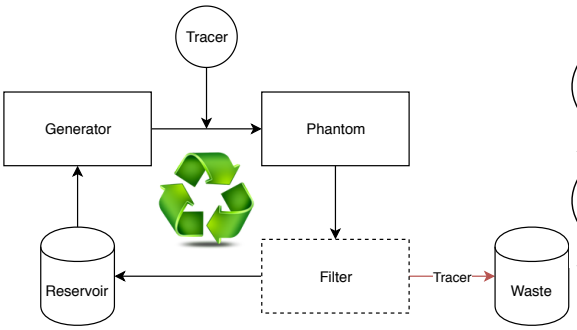

Figure 3.2: Closed circuit schematic design

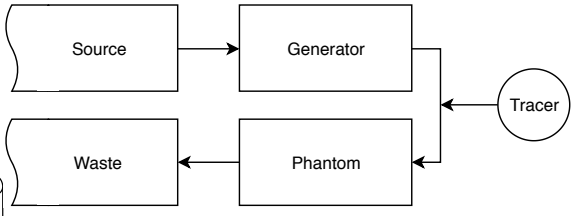

Figure 3.3: Open circuit schematic design

Type

As described in section 3.1.4, the flow type is fixed.

Perfusate

Two types of perfusate can be chosen from: water and blood-mimicking fluid (BMF). Water is most practical since it is available in a steady supply. However, BMF is more physiological since it is of the same viscosity as human blood but needs to be made before performing any experiments. In an open circuit configuration, see section 3.2.5, BMF will be rapidly put into the waste collection making it very costly. In an closed circuit, if the tracer can be filtered from the BMF, it will potentially be a more accurate simulation.

200 ## 3.3 Concepts

201 ### 3.3.1 Concept 1

202 ### 3.3.2 Concept 2

203 ### 3.3.3 Summary

Table 3.1: Concept overview

	Concept 1	Concept 2	Concept x
Myocardium	Shape		
	Model		
Modality			
Design			
Tracer			
Flow	Generator		
	Supply		
	Disposal		
	Configuration		
	Type		
	Perfusate		

4 Detailed design

A Appendix: Mind map

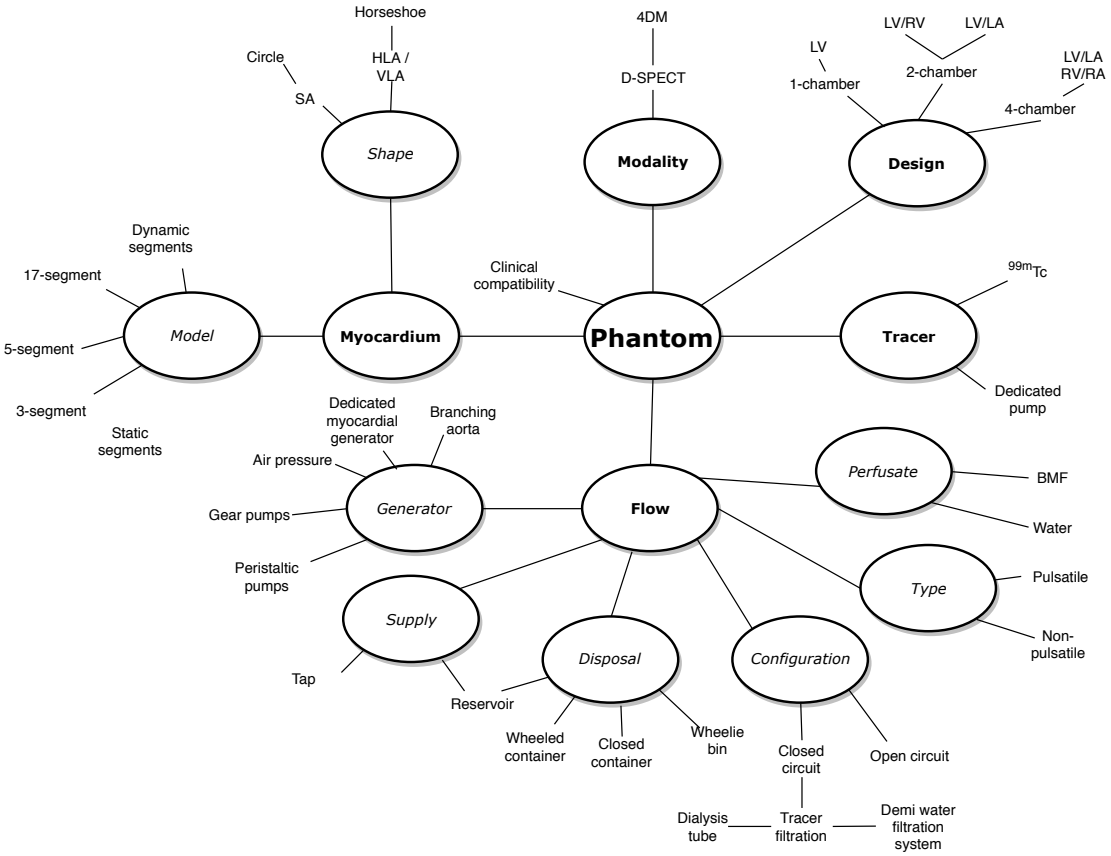

Figure A.1: Mind map for concept designs

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Niwaz, T. (2015). Nuclear cardiology: braunwald's chapter 16, disease detection, risk stratification, and clinical decision making.