Development of a myocardial perfusion phantom

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Revision 0.2

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Preface

The system requirements specify all the requirements for the myocardial perfusion phantom. These requirements are based on research and interviews with stakeholders.

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Version

Table 1: Version control

Requirement	Old description	Date
R0.1	Initial version. Discussed in progress meeting of 2019/01/15.	2019/01/15
R0.2	Added following items: •TR-PR02, TR-PR03, TR-PR04, TR-PR05, TR-PR06, TR-PR07, TR-PR08, TR-PR09, TR-PR10 •TR-ER02, TR-ER03 •TR-IC04, and TR-IC05 •Added appendices C & D.	2019/01/16

Changelog

Table 2: Table of changed requirements

Requirement	Old description	Change reason
TR-IC01	A variable amount of contrast can be injected.	Rephrased.

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

[todo] This section

Abbreviations

AIF Arterial Input Function

CAD Coronary Artery Disease

CT Computed Tomography

LA Left Atrium

LV Left Ventricle

MPI Myocardial Perfusion Imaging

MRI Magnetic Resonance Imaging

MV Maximal Vasodilation

PET Positron Emission Tomography

RA Right Atrium

ROI Region of Interest

RV Right Ventricle

SPECT Single-Photon Emission Computed Tomography

2 Functional system overview

based on https://www.inflectra.com/ideas/topic/requirements-definition.aspx

This chapter goes into detail on the functional aspects of the myocardial perfusion phantom.

2.1 Drivers

Many factors influence the outcome of MPI. Some of these factors are:

Tracer	Patient	Technology	Software
- Concentration,	- Breathing artefacts,	- Modality,	- Package,
- Volume,	- Cardiac motion,	- Spatial resolution,	- Mathematical model,
- Molecule size,	- BMI.	- Temporal resolution.	- Filters,
- Injection speed.			- ROI.

The strength of a phantom is that small modifications, for example, in contrast concentration or volume, or the mathematical model, can be directly mapped to outcome. It provides insight into dependent and independent factors in perfusion imaging.

Current phantoms either require modifications to software packages or do not model defects in a physiological way. Defects are typically modelled by reducing the flow through the myocardium by reducing the pump rate, effectively ignoring the complex relation between stenotic and non-stenotic arteries. Therefore, a myocardial perfusion phantom is needed that is compatible with clinical software and is able to mimic cardiac defects in a physiological way. This will increase the similarity with patient studies resulting in more reliable validation.

In addition to being a tool for validation of scanners and/or software packages, the phantom can be used for educational and training purposes to demonstrate the impact of hard- and software variables (sampling rate, Region of Interest (ROI), mathematical model), patient variables (BMI, blood flow and -pressure), tracer variables (concentration, type, injection speed), and many more.

2.2 Approach

The V-Model defines the project's development cycle.

2.2.1 Concept of operations

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

Quantitative flow measurements is made possible due to dynamic scanning. Dynamic scanning is not a newly emerged technique, it has been used with CT in past research. However, dynamic SPECT scanning has recently emerged because of solid-state detectors, i.e. Digirad Cardius, D-SPECT, GE Discovery.

CT is a well established modality with the highest spatial resolution. However, its largest drawback is that the radiation dose is directly proportional to the number of images, therefore increasing the likelihood of complication due to radiation exposure. MRI does not rely an ionising radiation, but its lower temporal resolution makes it less suitable for dynamic imaging. SPECT and PET use radioactive tracers to image blood flow, thus exposing the patient to some degree of radiation. However, it is not directly proportional to the amount of images taken and is therefore less dangerous. The new D-SPECT promises significant dose reduction, due to more sensitive solid-state detectors, and better image quality.

In addition, traditional SPECT is, on average, 22% less expensive than the current gold standard, PET. D-SPECT is supposed to be less expensive and faster than SPECT.

In summary, although dynamic SPECT scanning is relatively new, its prospects are promising and potentially suitable for quantitative myocardial perfusion imaging. The D-SPECT has not been properly validated and provides an excellent opportunity to attempt validation of this new modality.

2.2.2 What must the myocardial perfusion phantom be able to simulate to validate quantitative MPI?

At the most basic level, the phantom must be able to create an Arterial Input Function (AIF), either via the left ventricle or via an aorta, and simulate the perfusion in the myocardium. Furthermore, the phantom must be able to simulate the complex relation between stenotic and non-stenotic arteries in the myocardium; simply reducing the flow to the entire myocardium is not adequate. It should be possible, in case of simulated stenosis, to visualise the ischaemic tissue along non-ischaemic tissue.

Different kinds of compartment models exist for tracer kinetics. Initially, the phantom should simulate the compartment model consistent with clinical protocol. Additionally, other compartment models should be realisable by, for example, interchanging components.

2.3 Business model

The development of the myocardial perfusion phantom is primarily for the purpose of validating MPI. An added benefit is the educational and training purpose. The phantom will distinguish itself from other phantoms due to its more true-to-nature design, ability to physiologically mimic cardiac defects, and the possibility of modelling different compartment models.

The primary focus remains on the current application of MPI as performed at the ZGT in Hengelo, Overijssel.

2.4 Requirements

The functional requirements are summarised in table 2.1.

2.5 Business and system use cases

The myocardial perfusion phantom is primarily used by researchers with varying goals. Primarily, the phantom set-up is a tool to validate perfusion imaging hard- and software and to educate on independent and dependent factors, see section 2.1. The researcher should be able to adjust the blood flow, both in the myocardium and in the aorta, and be able to set a cardiac defect.

Please note, setting the imaging and contrast parameters are not part of the phantom itself.

2.6 Architectural overview

A schematic overview of the flow set-up is shown in figure 2.2. The set-up consists of a flow generating system, e.g. mechanical pumps or pressure based, to generate the required aortic and myocardial flow, measuring systems, e.g. flow and pressure sensors, and the phantom itself, simulating the heart. The flow is controlled by means of a control system, over which the user has control. The flow parameters, i.e. flow and pressure, are measured by sensors which are monitored by a monitoring system. The monitoring system and control system cooperate such that user parameters are maintained. Figure 2.2 shows a distinction between high and low flow, which is not a requirement. Low flow can be created by means of pressure difference in high and low flow circuit; increasing pressure in low flow circuit results in less volume passing through.

Table 2.1: Functional requirements

This table summarises the functional requirements for the prototype myocardial perfusion phantom.

Requirement number	Description
FR01	The phantom must be able to simulate blood flow, either using water of blood-mimicking fluid, at high flow rates (aortic flow).
FR02	The phantom must be able to simulate blood flow, either using water or blood-mimicking fluid, at low flow rates (myocardium flow).
FR03	The high flow should be suitable for an AIF, either in a ventricle chamber or an aorta depending on the clinical software.
FR04	Cardiac defects should be simulated such that the complex relation between stenotic and non-stenotic arteries is modelled.
FR05	The phantom must be able to visualise both control and stenotic areas, similar to clinical scans.
FR06	The phantom must initially simulate the compartment model typically used in clinical scans, but be flexible enough such that other compartment models are achievable.
FR07	The contrast agent should be equivalent to that used in clinical scans.
FR08	Contrast should be mixed equivalently to contrast mixing in patients.

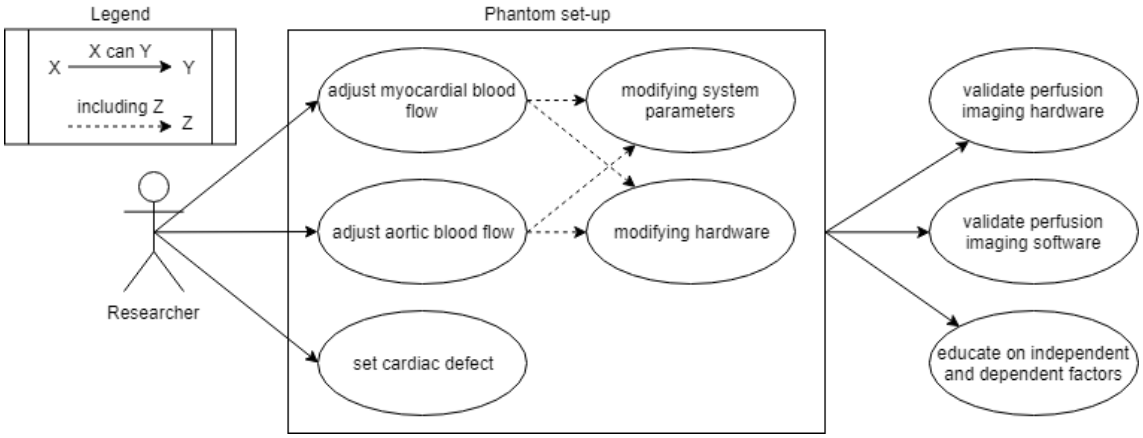

Figure 2.1: Use case diagram for the prototype myocardial perfusion phantom

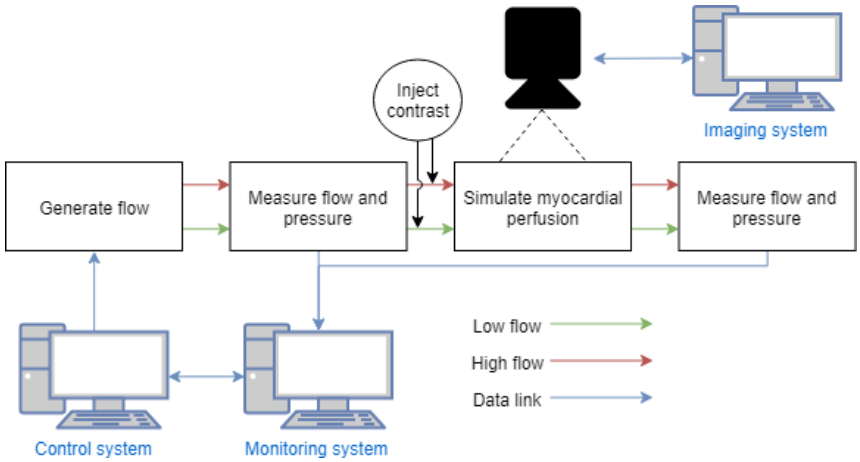

Figure 2.2: Functional architecture for the myocardial perfusion set-up

3 Technical system overview

3.1 Function requirements

This section specifies the requirements set for the functions mentioned in figure 2.2.

3.1.1 Generate flow

In the project plan, a literature overview is given on perfusion phantoms, for a variety of organs, but also on physiological factors: perfusion rates, blood pressures, rates of stenosis et cetera. The TFR-GF requirements are based on the estimates by Uren et al. (1994), summarised in appendix A, Chiribiri et al. (2013a), Ho et al. (2014), summarised in appendix B, and Slart (2015).

Table 3.1: Function requirements for function: Generate flow

This table specifies the requirements for the generated flow and pressure.

Requirement number	Description
TFR-GF01	A constant flow is to be generated, i.e. non-pulsatile.
TFR-GF02	Flow generators need to be interchangeable.
TFR-GF03	Minimum achievable upper limit of myocardial perfusion is 300 mL/min/100g.
TFR-GF04	Minimum achievable lower limit of myocardial perfusion is 60 ml/min/100g.
TFR-GF05	Minimum achievable upper limit of cardiac output is 8 L/min.
TFR-GF06*	Minimum arterial pressure is 56 mmHg.
TFR-GF07*	Maximum arterial pressure is 155 mmHg.
TFR-GF08	Flow generators are controlled via a flow feedback system.

** based on the diastolic and systolic blood pressures.*

3.1.2 Measuring flow and pressure

Table 3.2: Function requirements for function: Measure flow and pressure

This table specifies the requirements for the measuring of flow and pressure.

Requirement number	Description
TFR-MFP01	Flow measuring accuracy less than 5%.
TFR-MFP02	Pressure measuring accuracy less than 5%.
TFR-MFP03	Minimum absolute flow resolution of 1 mL/min.
TFR-MFP04	Minimum sampling rate of 100Hz.

3.1.3 Simulate myocardial perfusion

Table 3.3: Function requirements for function: Simulate myocardial perfusion

This table specifies the requirements specific for the phantom that simulates the myocardial perfusion.

Requirement number	Description
TFR-SIM01	An AIF must be extractable from either the aorta or the left ventricle chamber.
TFR-SIM02	Stenotic arteries are mimicked in a physiological way by physically narrowing (or increasing flow resistance) of certain arteries.
TFR-SIM03	Different stenotic severity, should be possible by, for example, variable flow resistors or interchanging components.
TFR-SIM04	Multiple chambers, or areas, should be present, such that ischaemic and non-inschaemic tissue can be visualised simultaneously. Typical software divide the heart into 17 chambers.
TFR-SIM05	Phantom's compartment model should match the currently practised protocol. Does the tracer diffuse, is it trapped in tissue et cetera.

3.1.4 Inject contrast

The injection protocol is not part of the development of the phantom. However, there are certain requirements to be monitored:

Table 3.4: Contrast requirements

This table summarises the requirements on the contrast and contrast injection protocol.

Requirement number	Description
TR-IC01	Contrast volume is variable.
TR-IC02	Contrast injection is reproducible.
TR-IC03	Contrast should match the currently practised protocol.
TR-IC04	Contrast concentration is variable.
TR-IC05	Contrast agent is variable.

3.2 Physical requirements

[todo] Determine size of seating of D-SPECT

[todo] Determine weight limit of seating of D-SPECT

[todo] Must it be completely anatomical?

[todo] Adjust requirements if the phantom does not have to be anatomical.

Size, weight et cetera.

Table 3.5: Physical requirements

This table summarises the physical requirements.

Requirement number	Description
TR-PR01	The phantom, and its set-up, must fit on the D-SPECT's chair.
TR-PR02	The phantom must be anatomically correct; four heart chambers, myocardium around the chambers, arrow shaped bottom.
TR-PR03	The phantom must be placed inside a thorax phantom, QRM TRX-116, with maximum diameter of 100mm.
TR-PR04	Total weight, on patient chair, cannot exceed 171kg.
TR-PR05	The flow set-up must remain horizontal, to prevent additional flow resistance.
TR-PR06*	The phantom must match the size of an average human heart, 12x8x6cm [LxWxD] (OpenStax College, 2013).
TR-PR07	The phantom must resemble the weight of an average human heart, 250-300g (female) or 300-350g (male) (OpenStax College, 2013).
TR-PR08+	The phantom's ventricles must match the volume of average human ventricles, between 40 and 180mL.
TR-PR09+	The phantom's atria must match the volume of average human atria, between 80 and 115mL.
TR-PR10**	The phantom's chambers must match the dimensions of an average human heart, between 60-90x30-50x60-90mm [LxWxD]

**Length (L): longitudinal axis (apex-basal), width (W): transverse axis (septal - lateral), Depth (D): transverse axis (anterior-inferior).*
***Length (L): longitudinal axis (apical-annular), width (W): transverse axis (septal-lateral (LV) or septal-medial (RV)), depth (D): transverse axis (apical-annular)*
+Chiribiri et al. (2013b) uses LA/RA of 105mL and LV/RV of 120mL.

3.3 Environmental requirements

[todo] Determine how much noise output it may have.

[todo] Determine the height of the chair of the D-SPECT

In what environment is the system operating.

Table 3.6: Environmental requirements

This table summarises the environmental requirements, i.e. the restrictions set by the environment to the phantom.

Requirement number	Description
TR-ER01*	No high-density or "High-Z" material is to be used.
TR-ER02	The phantom's left and front side must remain free such that the D-SPECT camera image around it.
TR-ER03**	Any part of the flow set-up and/or phantom, that does not fit directly on the patient chair, must remain horizontal with the remaining parts between 63 and 93cm.

** High-density and "High-Z" material, i.e. material with high atomic number, tend to block gamma radiation emitted by SPECT tracers. Examples are Titanium (Ti), Chromium (Cr), Vanadium (V), Iron (Fe), or Lead (Pb); atom number >22, Lead is 82.*
*** The patient chair's seating is adjustable between 63 and 93cm.*

3.4 External interfaces

Table 3.7: External interface requirements

This table summarises the requirements for the external interface.

Requirement number	Description
TR-EI01	Live plotting, at 10Hz, of system system flow and pressure.
TR-EI02	Ability to adjust the output of the flow generators.
TR-EI03	Serial communication between control/monitoring systems and external interface.

3.5 System qualities

[todo] Specify pressure threshold.

Define the quality of the system: such as reliability, availability, serviceability, security, scalability, maintainability.

Table 3.8: System qualities

This table summarises the system qualities.

Requirement number	Description
TR-SQ01	The flow set-up must perform an emergency shut down when the arterial pressure exceeds specified threshold.
TR-SQ2	The flow set-up must perform an emergency shut down when the flow cannot be controlled, i.e. erratic.

3.6 Constraints and Assumptions

Design constraints that have been imposed and assumptions that have been made by the requirements engineering team when gathering and analyzijng the requirements.

Table 3.9

This table summarises constraints placed on the design and assumptions made to yield the system requirements.

Requirement number	Description
TR-CA01	Cardiac artefacts, beating of the heart, is initially too complex. The phantom will be static.
TR-CA02	Breathing artefacts are not simulated in the phantom itself. A breathing thorax phantom can be used if available.
TR-CA03	Chest size, the amount of tissue between heart and scanner, is not simulated in the phantom itself. Thorax phantoms with modular rings are available to simulate tissue patients with varying BMIs.

A Appendix: Normal heart rate/blood pressure and myocardial perfusion rates by Uren et al. (1994)

The following tables summarise Uren et al. (1994).

Table A.1: Heart rate and blood pressure according to Uren et al. (1994).

This table shows the heart rate and blood pressure in (Uren et al., 1994) among 35 patients with single-vessel CAD and 21 control patients.

		Control	**Stenosis**
Heart rate [BPM]	Base line	65 ± 7	63 ± 10
	MV*	84 ± 10	88 ± 16
Blood pressure [mmHg]	Diastolic (B)	76 ± 8	74 ± 11
	Diastolic (MV)	75 ± 12	72 ± 12
	Systolic (B)	132 ± 19	148 ± 22
	Systolic (MV)	140 ± 20	153 ± 21

** Maximal Vasodilation (MV)*

Table A.2: Myocardial blood flow according to Uren et al. (1994).

This table shows the determined perfusion rates in (Uren et al., 1994), converted to ml/min/100g.

	Control	**Stenosis**			
		<40%	40-59 %	60-79%	>80%
Base line	113 ± 26	96 ± 19	125 ± 34	123 ± 57	92 ± 33
MV*	337 ± 125	344 ± 147	207 ± 83	151 ± 37	122 ± 36

** Maximal Vasodilation (MV)*

B Appendix: Normal heart rate/blood pressure and myocardial perfusion rates by Ho et al. (2014)

The following tables summarise Ho et al. (2014).

Table B.1: Heart rate and blood pressure according to Ho et al. (2014).

This table shows the heart rate and blood pressure in (Ho et al., 2014) among 35 patients with documented CAD and 35 control (low-risk) patients. The 35 documented CAD patients are from a previous study.

		Control	**Stenosis**
Heart rate [BPM]	Base line	66 ± 10	73 ± 14
	MV*	88.54 ± 11.45	82 ± 16
Blood pressure [mmHg]	Diastolic (B)	63 ± 13	–
	Diastolic (MV)	56 ± 10	–
	Systolic (B)	111 ± 17	–
	Systolic (MV)	105 ± 21	–

** Maximal Vasodilation (MV)*

Table B.2: Myocardial blood flow according to Ho et al. (2014).

This table shows the myocardial perfusion rates by Ho et al. (2014), given in mL/min/100g.

	Low risk	**Historic ischaemia**	**Previous infarction**
Global rest	74.08 ± 16.3	82.29 ± 16.87	81.98 ± 18.54
Global stress	141.92 ± 30.83	107.95 ± 25.25	106.93 ± 32.91

C Appendix: heart chamber volumes by Lin et al. (2008)

The following tables summarise Lin et al. (2008) who investigated the ventricles and atria of 103 non-obese adults using 1D, 2D, and 3D techniques.

Table C.1: Heart chamber volumes according to Lin et al. (2008).

		End-systolic volume [mL]	**End-diastolic volume** [mL]	**Average wall thickness** [mm]
LV	2D	65.2 ± 20.9	150 ± 35.6	7.3 ± 1.3
	3D	52.6 ± 19.2	143.6 ± 36.4	
RV	2D	–	–	2.4 ± 0.7
	3D	82.10 ± 29.2	174.9 ± 48.0	
LA	2D	86.5 ± 29.1	-	–
	3D	102.3 ± 24.4	–	
RA	2D	–	–	–
	3D	111.9 ± 29.1	–	

Left Ventricle (LV), Right Ventricle (RV), Left Atrium (LA), Right Atrium (RA)

Table C.2: Heart chamber sizes according to Lin et al. (2008).

	LV [mm]			**RV** [mm]	
	End-Systolic	End-Diastolic		End-Systolic	End-Diastolic
SL	–	47.4 ± 4.7	SM	29.6 ± 5.3	37.0 ± 5.7
AI	–	57.7 ± 5.5	AI	29.6 ± 5.3	72.6 ± 9.0
AA	–	87.6 ± 9.3	AA	62.0 ± 8.8	77.7 ± 10.4

Left Ventricle (LV), Right Ventricle (RV), Septal-Lateral (SL), Anterior-Inferior (AI), Apical-Annular (AA), Septal-Medial (SM)

D Appendix: heart chamber volumes by Maceira et al. (2006a,b)

The following table summarises Maceira et al. (2006a,b), who investigated the left and right ventricles, respectively, of 120 patients.

Table D.1: Heart chamber volumes according to Lin et al. (2008).

		End-systolic volume [mL]	**End-diastolic volume** [mL]
LV	All	47 ± 10	142 ± 21
	Female	42 ± 9.5	128 ± 21
	Male	53 ± 11	156 ± 21
RV	All	50 ± 14	144 ± 23
	Female	43 ± 13	126 ± 21
	Male	57 ± 15	163 ± 25

Left Ventricle (LV), Right Ventricle (RV), Left Atrium (LA), Right Atrium (RA)

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