Patient-Specific Simulation Model for Investigating the Impact of Aortic Valve Prostheses on Blood Flow

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ABSTRACT

SOCIAL IMPACT

Between 1998 and 2004 approximately 400,000 people died in Germany from cardiovascular disease, with heart valve disease playing a significant role. Heart valve disease can lead to stenoses or insufficiency. In 2006, heart valve operations nationwide increased to 20,000.
The implantation of heart valves demands great skill and experience of the heart surgeon. To date, location of implantation was selected so to provide best possible perfusion of the coronary arteries. Currently, no suitable tool has been available for the clinician to appreciate efficiency of implantation pre-operative.

INNOVATION

There are a lot of questions about the effect on blood flow of aortic prosthetic valves and patient-specific aortic anatomy. Due to the fact a network of cardio-thoracic surgeons, radiologists, cardiologists and engineers has developed a simulation model designed to investigate *preoperatively* flow-induced effects on aortic prosthetic valves, using Fluid Structure Interaction, so that the most haemodynamically appropriate valve and its positioning can be tailored to the individual patient.
Data acquisition via MRI spares the patient an effective dose of an ECG controlled CT scan of up to 10 mSv. The model reproduces the geometry of the left ventricle and thoracic aorta without compromising quality. Mimic© software provided the link between reconstruction of patient-specific anatomy from MRI data and its conversion into a CAD format. 3-matic© software was used to process the CAD model thus created and combine it with that for the aortic valve.
The current simulation model, using a stationary simulation, made it possible to compute a velocity profile and pressure distribution in an individual aorta.

ECONOMIC POTENTIAL

Ante and retrograde flow in aortic prosthetic valves have been described by Pennekamp et al., 2004, an earlier CFD investigation [Bongert et al., 2006] and this study. In addition, direct comparison of peak velocity confirms flow simulation as a useful medical examination method.
This simulation model is used to compute *preoperatively* alterations to blood flow attributable to a mechanical aortic valve, patient-specific, thereby permitting optimal implantation.

1. Introduction

In case of stenosis of heart valve (**Fig. 1**) left ventricel have to produce a higher pressure to guarantee a full supply with blood. A slow acent of pressure load causes swelling of the myocardal muscle (Hypertrophy).

Among other things atherosclerosis or bacterial disease of heart valves bring out an aortic valve insufficiency. Because of disability for a completly closure of aortic valve there is a blood flow from aorta back into the left ventricel during ventricular diastole. This effect causes an enlargement of the heart by expansion of the interior of the heart (Dilatation).

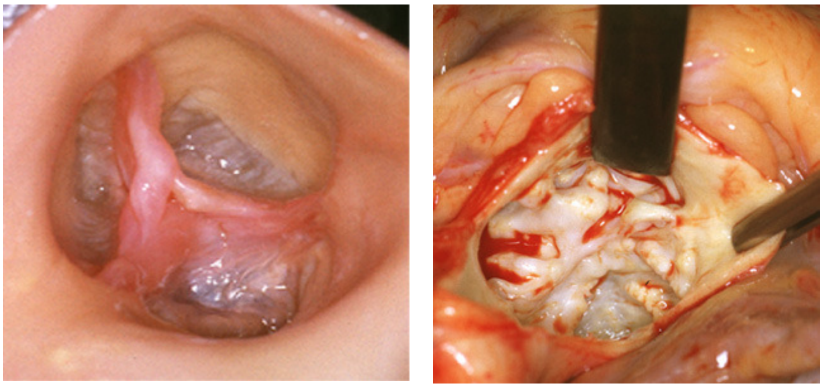


Fig. 1: Aortic valve (healthy, stenosis)

High-grade valve stenoses and insufficiencies are supplied with prosthetic heart valves. In 2006, heart valve operations nationwide increased to 20,000. [1]. This means an accession of 4.7% to previous year which is caused by increase of aortic valve surgery of older patients.

The implantation site which is selected should ensure optimal supply to the coronary arteries. Currently, no suitable tool has been available for the clinician to optimize implantation site pre-operative.

2. Material and Method

There is an effect on blood flow as well as aortic prosthetic valves and aortic anatomy [2, 3, 4]. On this fact use of engineering process Computational Fluid Dynamics (CFD) is recommend. However, numerical simulation in biomedical applications is challenged by formulating the extremely complex material properties, local influences and especially patient geometries for the virtual simulation model.

In this study the bileaflet-valve „St. Jude Medical©“ (**Fig. 2**, left) is used. Figure 2 shows the preferred implantation site for this typ of valve. The standard position selected should ensure optimal supply to the left and right coronary arteries. The straight red lines in Fig. 2 illustrate the rotational axes of the leaflets.

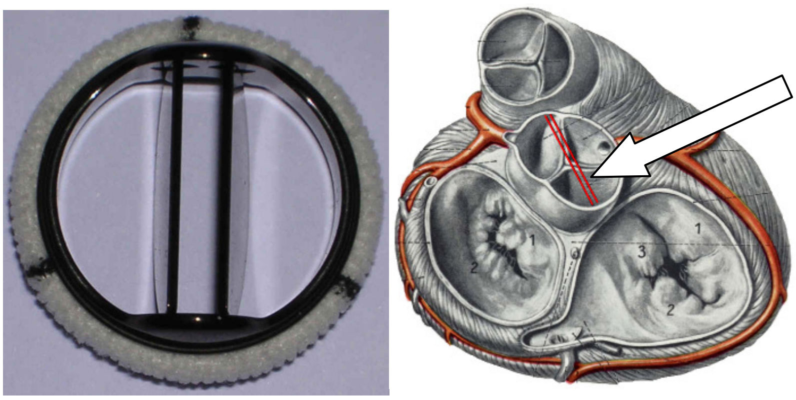


Fig. 2: St. Jude Medical© in standard position [5]

2.1 Acquisition

Until now acquisition of patient-specific anatomy occurs by Computer Tomography (CT). In this research project a new way is chosen to scan the anatomy. Magnetic Resonance Imaging (MRI) is now used to get the necessary data (**Fig. 3**). For a given point of time the whole 3D data block, which contains the total heart and thoracic aorta, is axial acquired. For this purpose Cardio-MRI-examination of clinical practice is applied. The examination is carried out with the Cine-SSFP-Sequence with Bright-Blood-View (SSFP = Steady State Free Procession). In this kind of sequences a contrast medium is not necessary.

Data acquisition via MRI spares the patient an effective dose (ED) of an ECG controlled CT scan of up to 10 mSv.

Fig. 3: MRI of University hospital

2.2 Segmentation

For medical diagnosis segmentation is carried out by workstations with special software of the particular MRI device. Information of the scaned individual anatomy is available in DICOM format. For further use they will be imported by the software Mimics©. An efficient as well as easy segmantation and editing of the several layers is enabled by this software tool in conjunction with high performance PCs (**Fig. 4**). These work steps have to be done very carefully because the created geometry model should be identical with the scaned patient-specific anatomy.

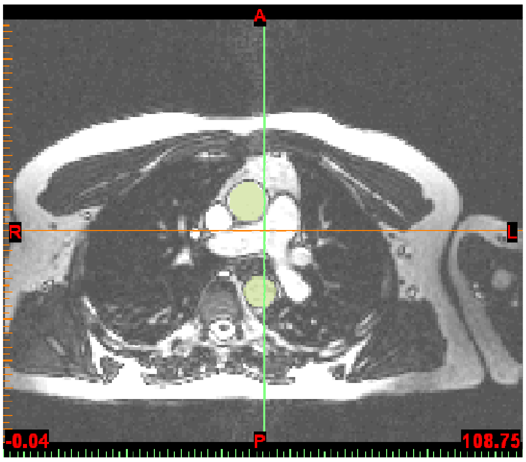


Fig. 4: Segmentation of aortic arch

2.3 Conversion

Every segmented layer has to follow up. Great attention must be paid to the fact that originality of the geometry must be warrented by editing the segmented layers (**Fig. 5**). After breakdown of the patient-specific anatomy in separate domains (left ventricle and aorta) geometry model will be exported in CAD format "STL" (Stereolithography format). This work step is done with software Mimics©.

Patient-specific data set provides a basis for further reseach such as CFD (Computational Fluid Dynamics) or CSM (Computational Structual Mechanics). Because of STL-format a 3D model of the scaned anatomy can be created by standard rapid prototyping systems.

Subject to the rapid prototyping system flexible 3D model are possible for in vitro testing.

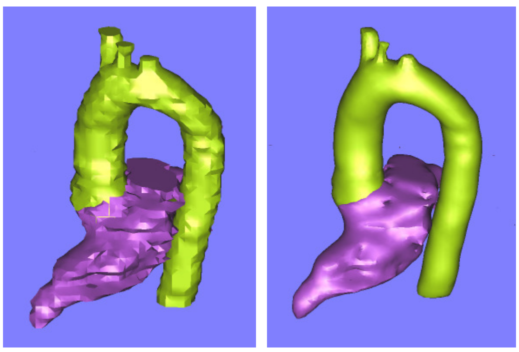


Fig. 5: Aorta and ventricel (segmented / edited)

2.4 Simulation Model

The simulation model consists of patient-specific geometry including aortic valve prosthesis, meshed fluid volume as well as physiological boundary conditions.

2.4.1 Individual Geometry

A 3D model (**Fig. 6**) of the Bileaflet valve St. Jude Medical© is modelled by scanning all geometrical point of interest on the original geometry (**Fig. 2**) manually. Existing curvature radii and the mobility of leaflets, with a maximum opening angle of 85° for the two fully movable leaflets of the St. Jude Medical© valve is incorporated into the model.
At valve inlet a cylindric volume is appended to warrant an equally approaching flow.

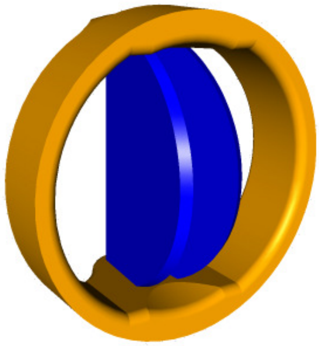


Fig. 6: „St. Jude Medical©"
(3D CAD-Model)

With their different file formats (IGS/STL) commercial software 3-matic© joins scaned geometry and CAD model of prosthetic heart valve. The geometries are differently positioned in space (**Fig. 7**, left). At first, the valve should be more or less correct according to the aorta. For this, the inlet face of the aorta is selected and a circle is fitted (see arrow). This circle together with the outlet face of the valve which is also circular is alligned now. Finetuning of the position of the valve is done interactive (translating, rotating) allowing freeform positioning (**Fig. 7**, right).

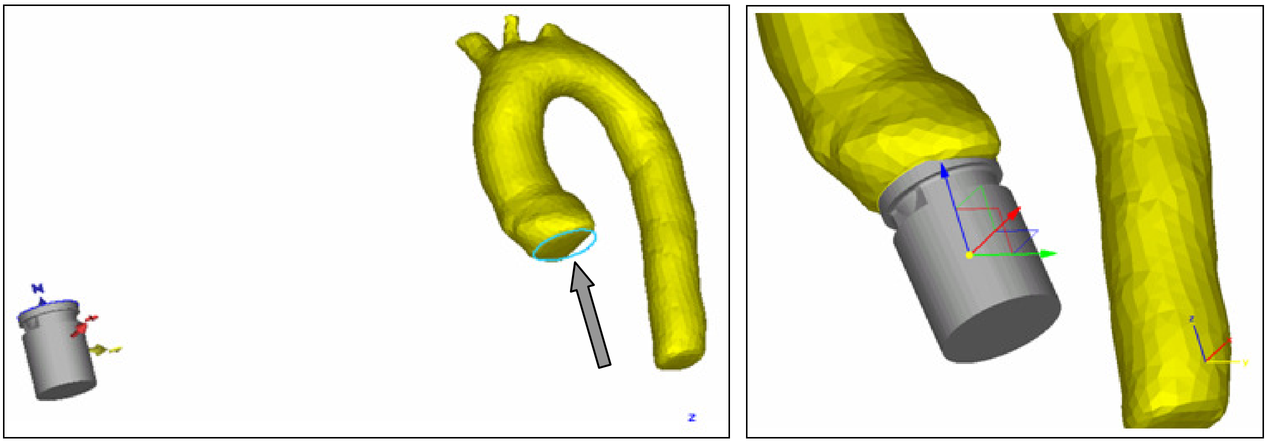


Fig. 7: Different position in space of the geometries / Finetuning of freeform positioning

The triangles at the inlet of the aorta are deleted. So it is possible to merge both geometries and triangulation nicely match. Results of this single work step are shown in **Fig. 8**.

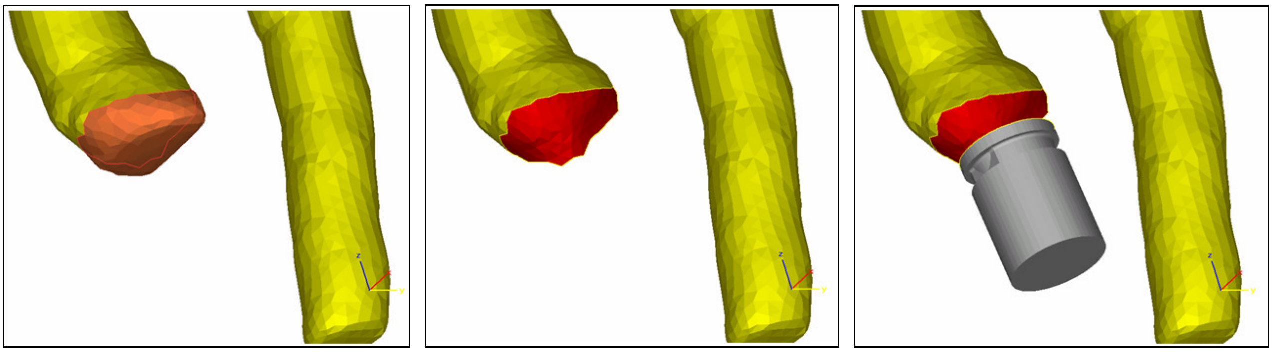


Fig. 8: Geometries fusion (work steps)

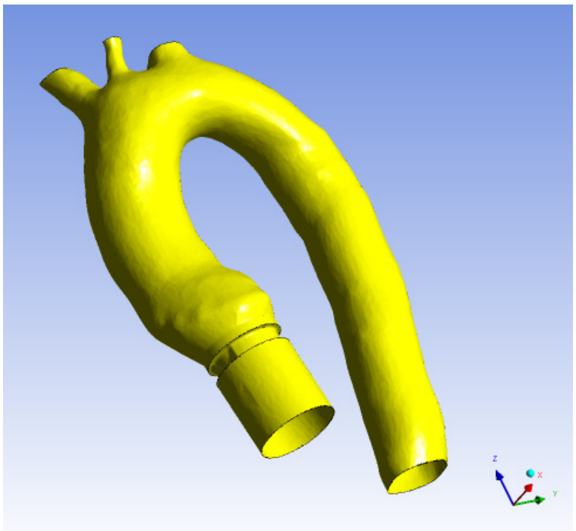


Fig. 9: Individual geometry model

Boundary conditions only can be associated with planar faces. So every outlet face of the aorta is edited to become a planar face. In **Fig. 9** the complete individual geometry is visualized. Its surface is meshed again.

2.4.2 Meshing

A surface mesh which consists of tetrahedral elements is laid onto the geometry model. Adapted from the surface mesh which represents exactly the contour of the valve and aorta a volume mesh is created with 3,881,959 tetrahedral elements and 708,402 nodes. This very fine mesh makes it possible to model the numerous fine curvature radii as exactly as possible and to break down turbulence as much as possible. In **Fig. 10** mesh of bileaflet valve located in the bulbus region of the aorta is visualized.

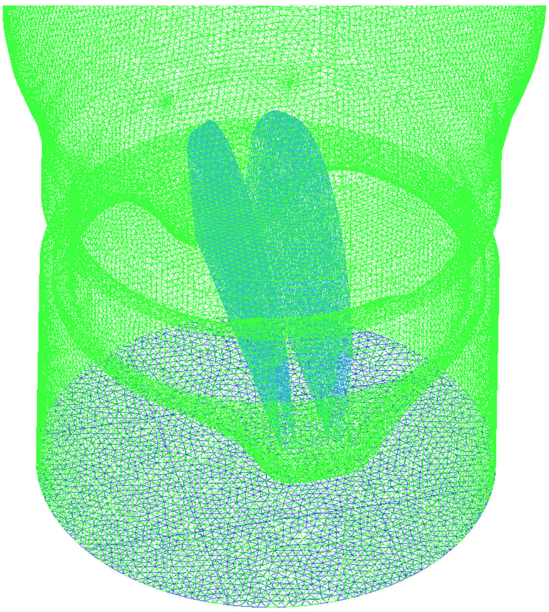
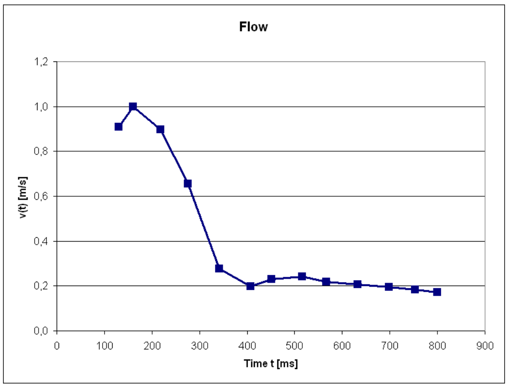


Fig. 10: Surface mesh in detail

2.4.3 Boundary conditions

So far at systolic point of time of maximum blood flow physiological boundary conditions are used for stationary simulations [6] (v_{max} =1.0 m/s I p_{Basis} = 80 mmHg I Non Newton Fluid I Standard implantation site).



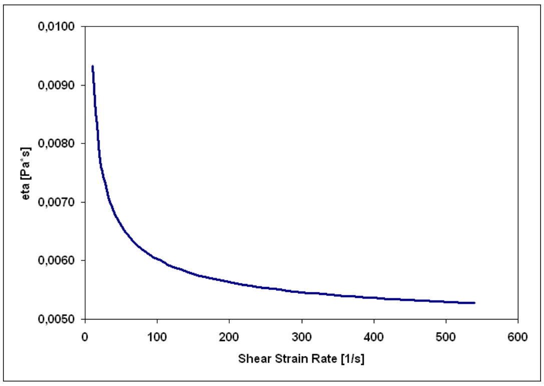


Fig. 11: Boundary conditions (Volume flow / Viscosity)

Viscosity of blood as Non Newton Fluid is calculated by functional relation with parameter „Shear Strain Rate" (**Fig. 11**, right).

3. Results

There are manifold possibilities in postprocessing. Analysis of simulation calculations are exemplary done for distribution of velocity, pressure as well as wall shear stress.

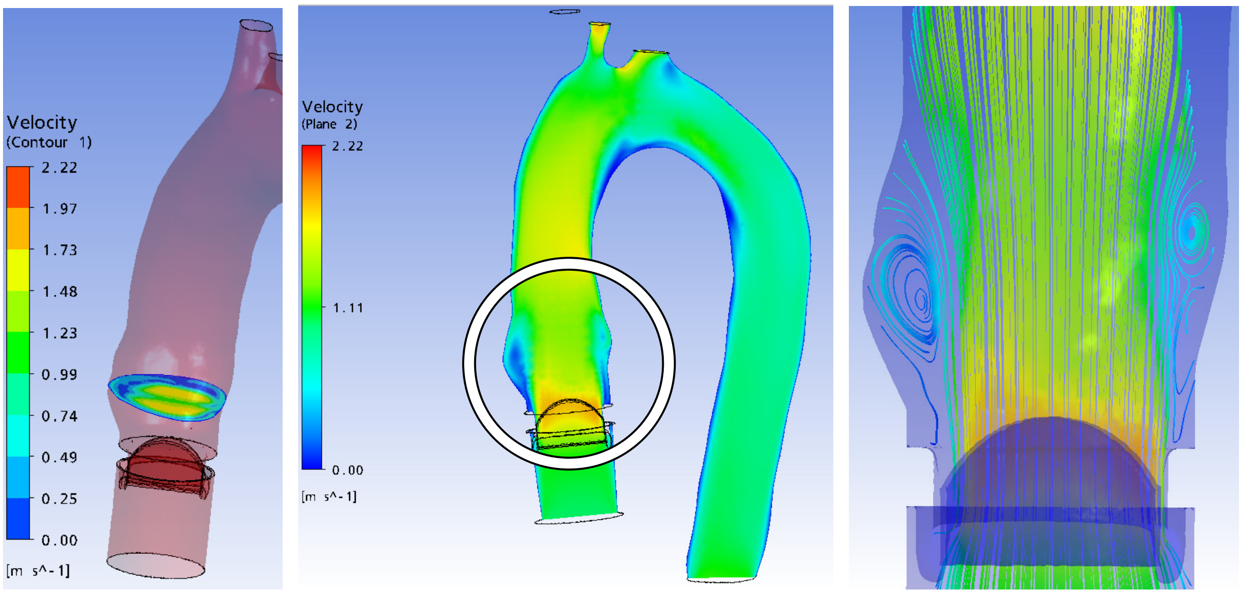


Fig. 12: Distribution of velocity

Characteristical velocity distribution in the reference plane of a bileaflet valve is shown in **Fig. 12** (left). A strong accelerated flow in the region of valve is also pointed out.
In **Fig. 12** (center) regions of different velocities in the whole area of aorta ascendens and aorta descendens are visualized. Zones of dead water are visible in the domain of bulbus and aortic arch. They are demonstrated in detail as streamlines (**Fig. 12,** right). In these regions retrograde velocity occurs. Retrograde flow in bileaflet valves are identified in this simulation as well as in previous studies [4, 7].

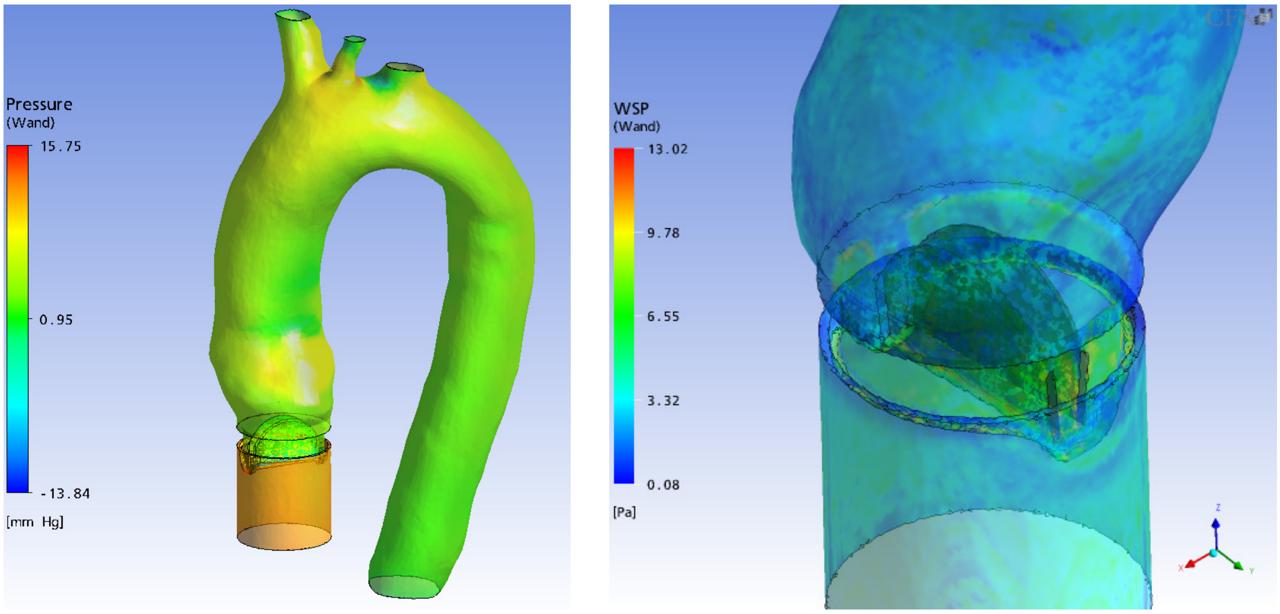


Fig. 13: Distribution of pressure and wall shear stress

Regions with enhanced pressure load appear in the domain of the bulbus and aortic arch particularly in the truncus brachiocephalicus as well as the arteria carotis communis sinistra (**Fig. 13**, left). In further transient FSI-simulations (Fluid-Structure-Interaction) the effects of steady oscillating pressure load have to be analysed for vascular wall.
Areas with high shear stress represent dangerous zones of hemolysis. **Fig. 13** (right) shows shear stress on vessel wall as well as surface of prosthetic valve. Especially increased values occur at the edges of leaflets and at the ring of valve.

Results from the simulation computation require checking against measured values to ensure that mesh quality is adequate and the correct boundary conditions have been selected. Reference measurements to validate simulation results for the valve were determined using Magnetic Resonance Imaging (MRI). For this flow sensitive phase contrast sequences vertical to the axis of the ascending aorta are used and in a numerous process steps flow velocities and absolute blood volume flow in regions of interest (ROI) within the ascending aorta are determined as vector values [2]. The reference plane in simulation [4, 6, 7] is in flow direction 30 mm distal from valve level and therefore identical with the measurement level for MRI [3] (**Fig. 14**).

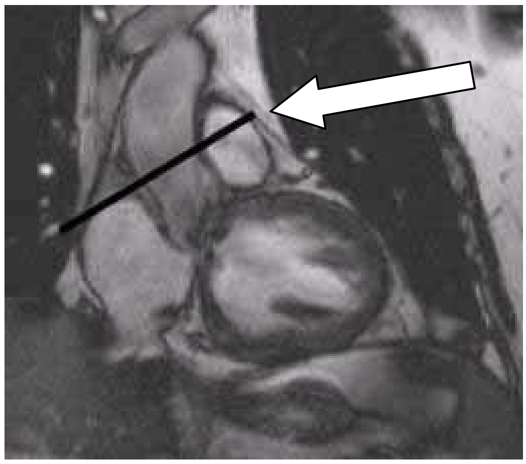


Fig. 14: Reference plane MRI

The results of measurements for the parameter „Peak-Velocity" [3] are shown as chart in **Fig. 15**.

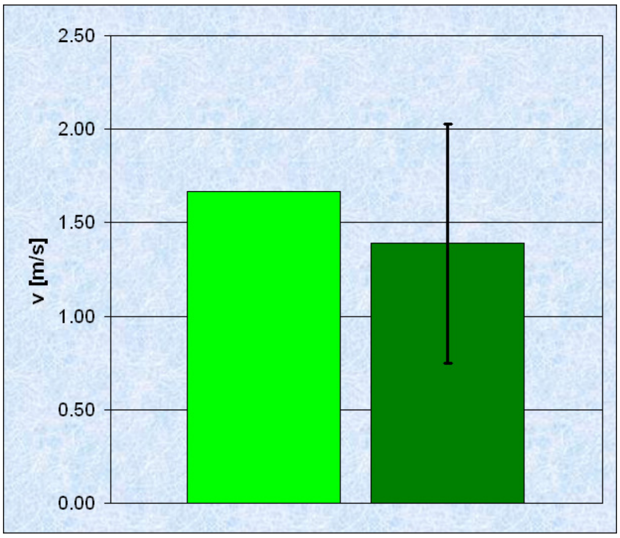


Fig. 15: Simulation validation

The left-hand column shows the parameter value for *peak velocity* computed by CFD. The right-hand column summarizes all *in vivo* measurements. The vertical bar indicates variation of values.

In addition, direct comparison of peak velocity confirms flow simulation as a useful medical examination method.

4. Discussion

Previous studies document effect on blood flow as well as aortic prosthetic valves and patient-specific aortic anatomy. So data acquisition via MRI is essential and it spares the patient an effective dose of an ECG controlled CT scan of up to 10 mSv. This technology reproduces the geometry of the left ventricle and thoracic aorta without compromising quality.

In this study the software Mimics© as well as 3-matic© have proved oneself during reconstruction of the patient-specific anatomy, their conversion into a CAD format and their processing. These software products close the gap between imaging process and simulation techniqes as well for flow as stability.

For cardio-thoracic surgeons this simulation model will be a tool to compute *preoperatively* alterations to blood flow attributable to a mechanical aortic valve, patient-specific, thereby permitting optimal implantation.

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