# Integration of a biomechanical simulation for mitral valve reconstruction into a knowledge-based surgery assistance system

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## ABSTRACT

A mitral valve reconstruction (MVR) is a complex operation in which the functionality of incompetent mitral valves is re-established by applying surgical techniques. This work deals with predictive biomechanical simulations of operation scenarios for an MVR, and the simulation's integration into a knowledge-based surgery assistance system.

We present a framework for the definition of the corresponding surgical workflow, which combines semantically enriched surgical expert knowledge with a biomechanical simulation. Using an ontology, 'surgical rules' which describe decision and assessment criteria for surgical decision-making are represented in a knowledge base. Through reasoning these 'rules' can then be applied on patient-specific data in order to be converted into boundary conditions for the biomechanical soft tissue simulation, which is based on the Finite Elements Method (FEM). The simulation, which is implemented in the open-source C++ FEM software HiFlow[3], is controlled via the Medical Simulation Markup Language (MSML), and makes use of High Performance Computing (HPC) methods to cope with real-time requirements in surgery.

The simulation results are presented to surgeons to assess the quality of the virtual reconstruction and the consequential remedial effects on the mitral valve and its functionality. The whole setup has the potential to support the intraoperative decision-making process during MVR where the surgeon usually has to make fundamental decision under time pressure.

**Keywords:** Biomechanical FEM Simulation, High Performance Computing (HPC), Surgical Reasoning, Surgery Assistance, Mitral Valve Modeling, Mitral Valve Simulation, Mitral Valve Reconstruction, Medical Simulation Markup Language (MSML), Integrated Biomechanical Simulation Framework.

## 1. DESCRIPTION OF PURPOSE

Modeling and simulation of the human body by means of continuum mechanics has become an important tool in medical and clinical diagnosis, in computer-assisted surgery, and in surgery training systems. Especially during highly complex surgical operations, such as a mitral valve reconstruction (MVR), which among others requires an in-depth experience and medical expert knowledge, simulations have the potential to provide the surgeon with additional information[1]. They can simulate the behavior and physiological activity of the body, and thus enable valuable insights for diagnosis and therapy. For instance, soft tissue deformations and a body's stress behavior, caused by forces and momentums acting on the body in the context of surgical manipulation, can be estimated by means of an elasticity simulation[2].

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Biomechanical simulations also play an important role in the Collaborative Research Center SFB/TRR 125 *Cognition-Guided Surgery*[2], which is supported by the German Research Foundation (DFG), and in the framework of which this work was carried out. The project vision of '*surgery in the future*' is a surgery that is lead by machine cognition, i.e., where an intelligent surgery support system recognizes clinical situations and suggests adequate surgical actions to the operating surgeon. The basis of the project is a common *knowledge base*, as a part of which the imaging platform XNAT[3] is used to collect patients' image data, that are linked to resources in a semantic media wiki[3] in order to be enhanced by semantic knowledge and meta information. Besides a collection of image data, the knowlegde base consists of formalized surgical expert knowledge and a set of interpretation and processing algorithms to work on the data. Such algorithms might, e.g., provide reasoning procedures that infer instructions for subsequent operation steps, or, particularly related with this work, biomechanical simulations that intraoperatively simulate the behavior of soft tissue, and thereby provide surgeons with valuable patient-specific information on the body parts that are operated on.

However, from the medical and surgical viewpoint, the theoretical applicability and the usefulness of intraoperative simulations is controversially discussed. Mostly, the high complexity of simulation algorithms causes a lack of real-time capability[1], which is essential, though, for an intraoperative application. Furthermore, modeling and simulation are often based on simplifying and generalizing assumptions, which immediately involves that some fundamental biomechanical and physiological impact factors are neglected or even left totally unconsidered[1]. Also, surgeons usually adapt their course of surgical actions during an operation to the respective situations, and take decisions on subsequent steps in the course of surgery according to their experience and surgical expert knowledge. For instance, reconstructive cardiac valve surgery requires the accurate acquisition and interpretation of the complex geometry and functionality of the cardiac valve by the surgeon, in order to formulate an adequate repair strategy, and to thereby cause an improvement for the patient[4]. However, in the field of simulation techniques, to date, there is no adequate framework which integrates such essential expert knowledge in order to adapt model and simulation to the respective current surgery situation[5], or which provides the surgeon with appropriate support and a reasonably adapted proposition for a following surgical action[1].

In order to cope with this problem, we present a framework, which considers the above mentioned surgical expert knowledge and experience: So-called 'surgical rules' summarize surgical expert knowledge and semantically describe it in a knowledge base. It can be accessed for the setup and initialization of a surgery simulation, and thus have impact on the simulation in terms of mathematical 'boundary conditions'. We hence produce a set of possible simulation scenarios suitable for the respective patient-specific situation in the operation room. Based on the simulation results the surgeon can choose the most preferable scenario to be executed. The framework hence acts as a knowledge-based, simulation-supported assistance system. It serves surgeons in their decision-making process during surgical operations by providing situation-adapted simulations.

## 2. METHODS

The work at hand presents a framework for simulation-based support of MVR operations. A biomechanical simulation of MVR operation scenarios is augmented by surgical expert knowledge, in order to intraoperatively provide the surgeon with support for the re-establishment of the mitral valve's functionality. We describe (a) the medical context and common techniques used for MVR. Next, we explain (b) the biomechanical simulation which constitutes the basis of the framework, and (c) how this simulation is controlled and integrated into the surgery simulation workflow. Finally, we report on (d) state-of-the-art knowledge management systems that are needed to represent surgical expert knowledge.

### 2.1 Mitral Valve Reconstruction (MVR)

Today, MVR is a common alternative to valve replacement, since it is known to have a better surgical outcome, reflected by lower re-operation and mortality rates[6]. However, an MVR is a challenging operation for surgeons which requires them to have in-depth experience and expert knowledge, since important decisions can be taken just during the operation. An important step during MVR is the implantation of an annuloplasty ring prosthesis[4]. During this procedure, a stiff artificial ring is sewed onto the anatomic structure of the annulus, to which the valve leaflets are attached, in order to stabilize, re-model, or shrink the pathologic annulus, cp. Figure 1. Various ring models are commercially available and differ in size and shape[7], see, e.g., Figure 2. During the operation, the surgeon has to decide which prosthesis fits

2 Collaborative Research Center SFB/TRR 125 *Cognition-Guided Surgery*, Website: www.cognitionguidedsurgery.de

3 Imaging platform XNAT, Website: www.xnat.org

best to the patient-individual annulus in order to re-enable the valve to close again properly. The quality of the closing functionality is mirrored in the size of the leaflets' contact surface, the so-called coaptation zone[4]. We want to help surgeons answer the question of the best annuloplasty ring selection for MVR by means of a biomechanical simulation. The knowledge, which ring fits best to the current patient-specific anatomy, is represented and inferred by surgical rules.

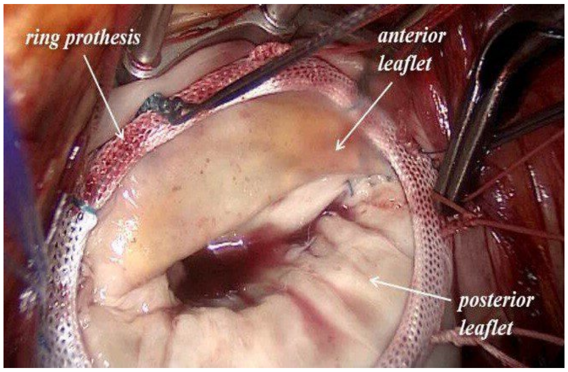


Figure 1. Endoscopic image captured during an MVR showing the fixation of an annuloplasty ring implant.

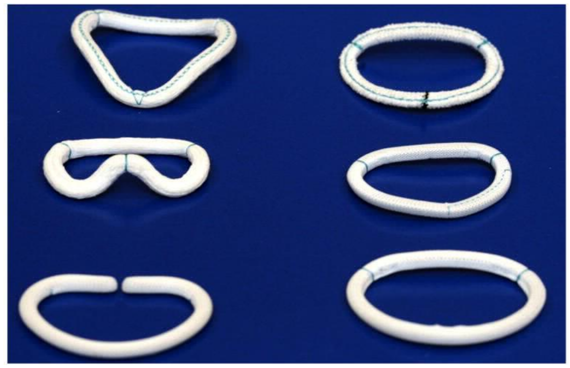

Figure 2. Set of commercially available annuloplasty ring types, source: Graser[7].

### 2.2 Efficient FEM-based biomechanical soft tissue simulation using HiFlow$^3$

In the context of surgical applications, biomechanical simulations are intended to reproduce effects of forces and momentums on soft tissue subject to surgical manipulation or to natural organ motion. Elasticity equations describe the relation of stress and strain in soft tissues and yield adequate models, which allow for an FEM-based simulation of a body's deformation behavior. For an MVR simulation, we consider forces caused by the implantation of the annulus ring and by differences in the left ventricle pressure gradients during the cardiac cycle, and how these forces affect a deformation of the elastic mitral valve leaflets, cp. Figure 3.

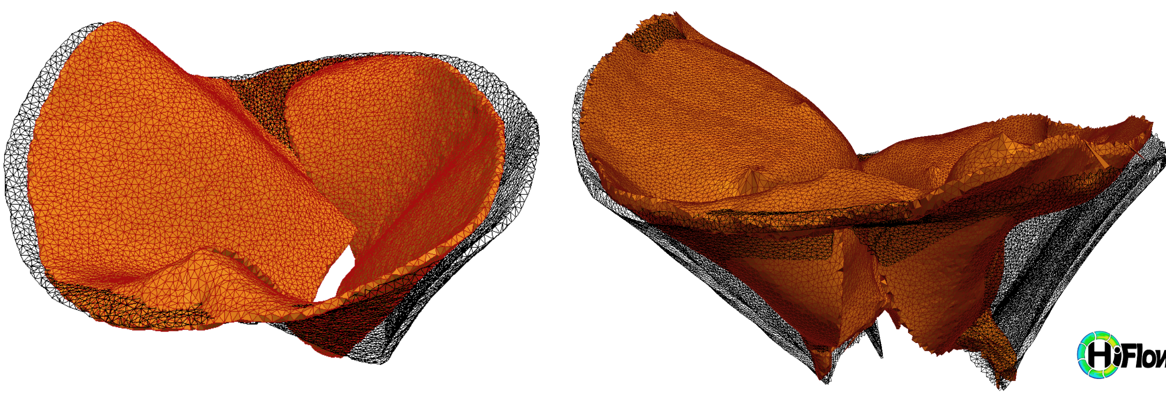

Figure 3. HiFlow$^3$-based elasticity simulation showing the deformation behavior of a mitral valve after an annuloplasty ring implantation, seen in different states during the cardiac cycle and from different angles. The initial segmentation-based input mesh, which represents the natural geometry of the valve is shown in wireframe.

To date, the accurate and efficient simulation of such deformation processes still is a challenging task[8]. Thus, for the real-time integration of simulations into the clinical workflow, efficient simulations make use of High-Performance Computing (HPC) methods and techniques. Using the open-source C++ FEM software toolkit HiFlow$^3$ [4], we apply dedicated and highly optimized numerical algorithms that are set up on the parallelization concepts of MPI and OpenMP, in order to facilitate the utilization of modern HPC infrastructure[9] to reliably address surgery support requirements.

### 2.3 The Medical Simulation Markup Language (MSML)

In order to supply surgeons with intuitive tools that cover the whole biomechanical simulation workflow, the presented framework employs the Medical Simulation Markup Language (MSML)[10], which enables the seamless integration and

4 Open-source C++ FEM software toolkit HiFlow$^3$, Website: www.hiflow3.org

formal description of a simulation and its setup in the context of the overall clinical simulation workflow: from imaging, segmentation and FE mesh generation, to the soft tissue simulation along with its corresponding mathematical constraints, and the visualization of simulation results. The modeling scheme of the MSML and the MSML HiFlow[3] exporter interface have been extended in order to formalize, e.g., pre- and intra-operative boundary conditions that shall influence the course of the simulated operation, or specific optimally calibrated preconditioner-solver-combinations, as well as the choice of a suitable HPC platform in order for the efficient calculation of the soft tissue behavior.

### 2.4 Expert knowledge acquisition and formalization for MVR and setup of a knowledge management system

The experience of heart surgeons, standardized expert knowledge in heart surgery guidelines, patient-specific image data, and the information generated by medical simulations shall be modeled in a semantic knowledge data base. A part of this data base consists of a retrospective collection of structured and semantically represented perioperative patient data, including parameters with respect to, e.g., the cardiac diagnosis, the operation protocol, postoperative histories, etc. These parameters were collected by the Heidelberg University's cardiac surgery over the past 11 years. Additionally, surgical guidelines and established MVR surgery procedures are stored in an ontology. Along with patient-individual image data, annotated segmentations, and the therefrom extracted qualitative and quantitative information on the valve's material properties, geometry and functionality, these guidelines establish the base for an intelligent, patient-dependent reasoning: The information depicted in the knowledge base shall be accessed situation-dependently, read and interpreted in order for the setup of a patient-specific simulation. It can thus provide pre- and intra-operative support to the operating surgeon.

The knowledge data are semantically represented according to the principles of Linked Data[11] and Data-Fu[12]. Like this, the knowledge architecture can support data consolidation and integration, and also enables the combination and execution of data processing steps, flexibly composed to a clinical data processing pipeline. Data processing applications then mainly build their functionality on the utilization and manipulation of semantically represented and formalized data resources.

## 3. RESULTS

Based on the HiFlow[3] implementation of an MVR soft tissue simulation which is accessed and controlled via the MSML, we developed the concept of a framework that shows how surgical expert knowledge, that is represented in a knowledge management system, can be integrated into the surgery simulation. The framework thus improves the simulation and simplifies the operation by means of supporting and providing the surgeon with patient-specific simulation results, cp. Figure 4.

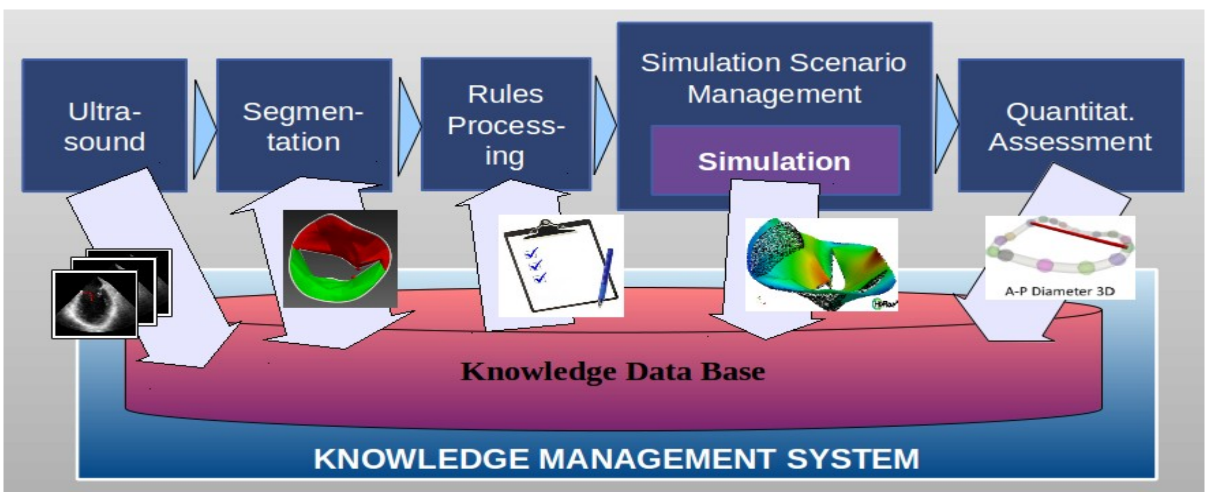


Figure 4. Concept of the simulation-based MVR surgery assistance system.

The simulation-supported MVR treatment starts with a pre-operative *transesophageal echocardiography* to record 3D+t ultrasound images of the mitral valve, which are archived in the *knowledge data base*. Subsequently, a patient-specific

3D valve model can be extracted from these images by means of interactive *segmentation* methods using the software plugin Mitralyzer in the open-source framework *Medical Imaging Interaction Toolkit*[5] (MITK)[13]. It additionally calculates qualitative and geometric information[14] (e.g. annulus diameter, curvature of the leaflets, size of the coaptation zone, etc.), as well as the IDs of specific landmarks of the valve.

This information, semantically represented in the knowledge data base, holds for the subsequent *reasoning*, which takes place during the '*surgical rules processing step*'. Here, the information is accessed along with *patient-specific valve geometries*, in order to generate suitable '*boundary conditions*' for the HiFlow$^3$-based *biomechanical FEM simulation*. For instance, a 'surgical experience-based rule', saying that the variation of the ring shape near the commissure points may only be relatively small, affects a reduction of the number of potentially available annulus ring shapes and sizes to a smaller set of rings, which would potentially make sense for the respective patient to be implanted.

Via the MSML, it is now possible to set up *different simulation scenarios* that simulate the operation outcome with respect to the *implantation of different annulus ring types* out of the aforementioned set of suitable rings. In our '*ring shape geometry interface*' one only needs to specify a certain number of anatomic points on the surface of the mitral valve annulus and match them in MITK with the corresponding points on the surface of the virtual ring model[14]. Following, based on the set of ring types and the set of determined points on the valve's leaflets, the *MSML* manages the simulation input, i.e., the transformation of the MITK-based segmentation of the patient-specific valve geometry into an FE mesh along with appropriate material properties, and the respective ring-induced boundary conditions. It thus facilitates and automates the preprocessing steps and the definition of the subsequent simulation scenarios for different ring types. Moreover, the generic interface allows the setup of an optimal choice of a preconditioner-solver-combination and of a suitable HPC infrastructure distribution with respect to the specific set of scenarios and the valve's geometric domain decomposition in order for an *efficient parallel simulation*, cp. Figure 5.

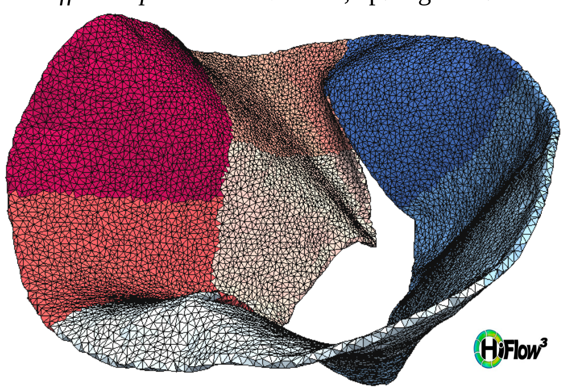


Figure 5. Symbolically color-coded parallel computation of the deformation behavior of a mitral valve geometry after application of geometry domain decomposition.

According to given ring shapes and respectively induced boundary conditions, the valve’s *elastic behavior* of course shows to be different. This behavior is important to be analyzed by the surgeon, in order to assess the success of an implantation or critical situations thereafter. For this purpose, we provide a *stress analysis*, considering the '*von Mises yield criterion*', which suggests that the yielding of a material begins when its von Mises stress reaches a critical value. The 'yield strength' is a scalar value that can be computed from the stress tensor, which is used for the FEM simulation in dependence of the leaflets' patient-specific material properties (so far based on mean values given in Mansi et al.[5]), and of the deformation affected by external forces during the cardiac cycle. We visualize critical values of the yield strength on the valve's surface according to given *stress distributions for different ring implantation scenarios*, cp. Figure 6.

The hence resulting virtual postoperative scenarios and the color-coded stress visualization can assist the surgeons to make the best choice of ring type they will implant in reality. In the proposed setup we hence extend the standard evaluation of quality using point-to-point distance measurements (such as Mansi et al.[5]), by investigating a functional that evaluates the von Mises stress with respect to material failure (such as Choi et al.[8]), therein considering practical surgery and surgical expertise. The simulation results are fed back into the knowledge base, such that another quantitative evaluation of the simulated anatomic structures after the virtual implantation can take place again using the MITK Mitralyzer[14].

5 Open-source framework Medical Imaging Interaction Toolkit (MITK), Website: www.mitk.org

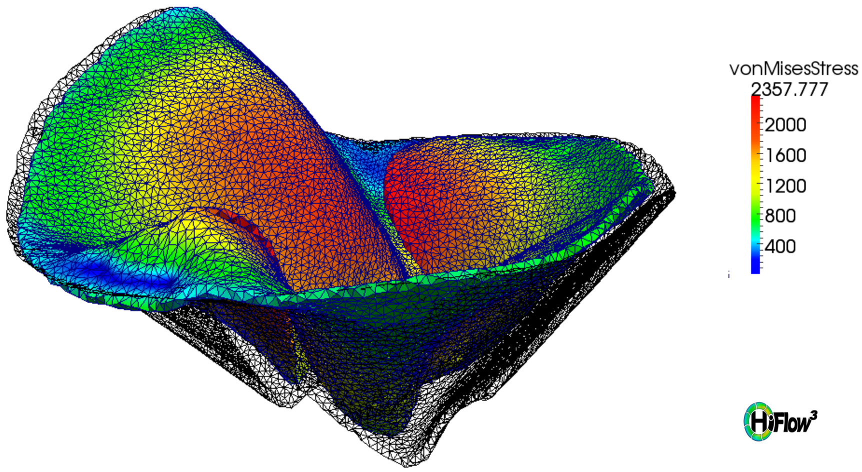


Figure 6. Simulated deformation of a mitral valve, subject to blood pressure and to the constraints given through the implantation of an annuloplasty ring. The artificial annulus ring fixes points near to the commissure points and displaces other specific parts on the natural annulus, in order to thus allow for a varying range of activity of the leaflets and hence a different opening and closing behavior of the valve. The color indicates the von Mises stress distribution (in Pa), caused by the virtual ring implantation and the forces acting during the cardiac cycle. The wireframe mesh shows the natural valve before the ring implantation as segmented from ultrasound images in MITK.

## 4. DISCUSSION

We presented a framework for a knowledge-based, simulation-supported MVR surgery assistance system, that has been constructed according to general MVR requirements and to surgeons' needs. Different components of the framework, such as the FEM-based simulation, the simulation scenario control, or the surgical MVR techniques have been implemented, applied and evaluated separately, as stated above and in the references.

We expect a substantial added value given through the use of such a system during highly complex operations. The virtual investigation on different ring implantation scenarios before the real implantation, along with the visual review and assessment of the virtually modified valve geometry, can help surgeons avoid the selection of a suboptimal ring prosthesis. Such suboptimal choices may lead to stenosis, ring dehiscence, or obstruction of the ventricular outflow tract in the worst case. We also expect to improve MVR surgery carried out by less experienced surgeons, who are given valuable support by such simulation-based surgery assistance systems.

In addition to the aforementioned consideration of the von Mises stress distribution for different ring shape scenarios, the most important quality criterion for a successful MVR is given by the prosthesis-induced increase of the size of the resulting coaptation zone, and hence by the valve's re-established closing functionality. Therefore, future work and enhancements to the framework may contain an improved contact simulation that allows for the virtual computation of the coaptation zone, in order to enable an even better assessment of the annuloplasty ring implantation result and performance using different rings.

Also, as mentioned earlier in the introduction, even when provided highly sophisticated biomechanical simulations, there are still limitations to their applicability and usability. For instance, due to the leaflets' fast movement during the cardiac cycle, and the hence rapidly varying geometries for the contact search between the two leaflets, the time steps for an instationary simulation need to be kept small in order to catch all occurrences with respect to the leaflets' contact, which in combination with the need for high accuracy lets the mathematical problem dimension and computational complexity drastically increase. This causes high simulation time requirements, claiming for further improvement of the HPC setup. We also clearly emphasize the simplifying and generalizing model assumptions made for the valve's tissue behavior, which can be enhanced in several ways, e.g. with respect to the elasticity model or to patient-specific material parameters, in order to yield more realistic results.

## 5. CONCLUSION

This work presented a framework for a knowledge-based, simulation-supported MVR surgery assistance system. A biomechanical simulation of MVR operation scenarios is augmented by surgical expert knowledge which is semantically represented in a knowledge base. It can thus be accessed situation-adaptively for patient-specific simulations, in order to intraoperatively provide the surgeon with support for the re-establishment of a mitral valve's functionality.

## ACKNOWLEDGMENTS

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