Virtual Reality and 3D Visualizations in Heart Surgery Education

(#2001-03054)

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ABSTRACT

Background: Computer assisted teaching plays an increasing role in surgical education. The presented paper describes the development of virtual reality (VR) and 3D visualizations for educational purposes concerning aortocoronary bypass grafting and their prototypical implementation into a database-driven and internet-based educational system in heart surgery.

Materials and Methods: A multimedia storyboard has been written and digital video has been encoded. Understanding of these videos was not always satisfying; therefore, additional 3D and VR visualizations have been modelled as VRML, QuickTime, QuickTime Virtual Reality and MPEG-1 applications. An authoring process in terms of integration and orchestration of different multimedia components to educational units has been started.

Results: A virtual model of the heart has been designed. It is highly interactive and the user is able to rotate it, move it, zoom in for details or even fly through. It can be explored during the cardiac cycle and a transparency mode demonstrates coronary arteries, movement of the heart valves, and simultaneous blood-flow. Myocardial ischemia and the effect of an IMA-Graft on myocardial perfusion is simulated. Coronary artery stenoses and bypass-grafts can be interactively added. 3D models of anastomotique techniques and closed thrombendarterectomy have been developed. Different visualizations have been prototypically implemented into a teaching application about operative techniques.

Conclusions: Interactive virtual reality and 3D teaching applications can be used and distributed via the World Wide Web and have the power to describe surgical anatomy and principles of surgical techniques, where temporal and spatial events play an important role, in a way superior to traditional teaching methods.

Presented at the Third Annual Meeting of the International Society for Minimally Invasive Cardiac Surgery, Atlanta, Georgia, June 8-10, 2000.

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INTRODUCTION

Cardiac surgery is facing a rapid development of new operative techniques and technologies. The growing complexity of the subject requires continuous training and education on the basis of up-to-date information. Computer-assisted learning and teaching play an increasing role in surgical education [Dunnington 1994, Chitwood 1996]. Different studies have shown that efficacy and efficiency of education and training for students, doctors and patients may be improved by the use of multimedia training programs [Devitt 1998, Lewis 1999, Summers 1999].

The WorldWideWeb (WWW) has evolved as an international communication and information platform for the heart surgery community. The most important web-sites to mention are The Heart Surgery Forum [http://www.hsforum.com/], CTS-Net [http://www.sts.org/] and The Virtual Operating RoomVideo-Library [http://www.webevents.broadcast.com/virtual-or/frameset.html]. They mainly provide scientific information and discussion lists for the professional heart surgeon by the use of text, colored images and intra-operative videos.

The latest generations of high-performance desktop computers are providing the basis for educational virtual reality (VR) and 3D computer visualizations and the possibility to simulate and interact with dynamic surgical activities and processes. This may further enhance the benefit of computer based educational environments in medicine [Torkington 2000]. The development of such applications requires tremendous financial and time resources but they are usually only usable for pre-defined user-groups in specified instructional contexts. To overcome this disadvantage, we are developing the educational on-line computer system *CardioOP*. This project is based on a database-driven knowledge management system where multimedia objects, e.g., 3D models, are intended to be flexibly used for different user groups in different educational contexts [Klas 1999]. The presented paper describes the development of VR applications and 3D visualizations for educational purposes concerning aortocoronary bypass grafting and their prototypical implementation into the *CardioOP* teaching system.

MATERIALS AND METHODS

After defining the educational content, we wrote a multimedia storyboard using the *COME*-tool (CardioOP-Mediotheque-Editor), a specially designed tool for electronic storyboarding. This storyboard contains the text-based educational content, geo-semantic hypertext structures, different knowledge levels (beginner, advanced, professional), hypermedia functions and the description of the used media (e.g., 3D visualisations, Video) in a computable form. Surgical procedures have then been visualized, according to the storyboard, by digital video sequences. They have been recorded with a remote-controlled, mobile video robot. The camera (3 IT-CCD 1/2, Panasonic) is equipped with a high resolution motor zoom (7 BMD-D4M, Fuji) and enables the user to zoom in on the small structures of the heart, e.g., coronary arteries in a manner sufficient for teaching purposes. The videos were recorded in digital video format (DV) with a DV-recorder (DHR 1000 VC, Sony) and electronically processed using a computer video-workstation equipped with a DV-Master™ video-card (FAST International), and the Ulead MediaStudio Pro 5.0™ software (Ulead Systems). To reduce their data size, the videos have then been compressed in the MPEG-1 format (Motion Picture Expert Group) [http://www.crs4.it/HTML/LUIGI/MPEG/mpegfaq.html]. A specific video streaming and buffering technique for the MPEG-1 format called MPEG-L/MRP has been developed and implemented during the project which allows the user to view the videos with minimum response time to user interaction over the internet without having to download the whole video. In a third step, the videos have been discussed with test persons: students, patients and surgical staff. The results of those discussions suggested that understanding may be facilitated by the additional use of interactive 3D visualizations. We started to model such applications then using computer workstations (Dell Computers, Silicon Graphics) and the following software: Softimage 3D™ (Softimage), Monzoom 3D pro™ (Monzoom), CorelDraw 9™ (Corel) and Cosmo Worlds™ (Platinum Technologies). The resulting models have been formatted in the Virtual Reality Modelling-Language (VRML-2) [www.web3d.org], QuickTime Virtual Reality-2 (QTVR-2) [http://www.apple.com/quicktime/qtvr/] and MPEG-1 for different teaching purposes and to enable the user to deal with different grades of interactivity.

Next, temporal and spatial annotation of the VR and 3D models have been performed with content-specific meta-information on the basis of a controlled vocabulary and the result has been stored in our database-driven knowledge base. For annotation we used the *CardioOP-Data-Clas* meta-thesaurus *(CDC)* [Friedl 2000] and a specially designed *Annotation-Tool* [Westermann 1999]. Using the authoring tool *CardioOP-Wizard*, we finally started an on-line authoring process in terms of integration and orchestration of different multimedia components to educational units.

RESULTS

According to the storyboard and the results of the video-analysis, different exemplary virtual models have been developed which can be divided into anatomical models, models related to ischemic heart disease and models about surgical techniques.

Anatomy

We designed a detailed model of the heart *(CardioOp-Heart)* with outer and inner surfaces, chambers, heart valves and the great vessels (Figure 1-5, ◎). As a VRML-application (Figure 1, ◎), it is highly interactive and the user is able to rotate it, move it, zoom in for details or even fly through by the use of in-picture, mouse-over commands. The coronary arteries can be displayed without other cardiac structures (Figure 2, ◎). The *CardioOp-Heart* can also be watched while beating and interactively explored from any perspective during the cardiac cycle (QTVR-2) with systolic contraction and diastolic relaxation. To demonstrate correct movement of the heart valves, a transparency mode (Figure 3, ◎) has been additionally rendered, which further represents a simultaneous visualization of the cardiac cavities, valves and the outer surface. The complex relationship of the cardiac chambers and the ventricular outflow tracts are also illustrated. Continuous and simultaneous blood-flow through the cardiac chambers (Figure 3, ◎), with "flying" arrows representing hemodynamic action, has been further implemented. The beating heart may be either displayed in QTVR-2 or as a continuous movie (MPEG-1) with a "frame by frame" control board, thus allowing the user to focus on certain details of this dynamic process.

Ischemic heart disease

Multiple different coronary artery stenoses (of LAD, RCA, RCX, marginal and diagonal branches) and numerous venous and/or arterial bypasses have been designed (Figure 4, ◎) to be interactively added to the surface model of the heart (VRML-2). This allows for a realistic simulation of different constellations of coronary artery stenoses and the resulting combinations of grafts. Another movie-like presentation (MPEG-1) demonstrates the principle of a coronary artery stenosis (proximal LAD) with subsequent myocardial ischemia and the effect of an IMA-Graft on myocardial perfusion (Figure 5, ◎).

Surgical techniques

To demonstrate the anastomotic technique of a distal anastomosis, a 3D-animation has been developed (MPEG-1) (Figure 6, ◎). It starts with a midline incision of the coronary artery with a No. 15 scalpel. The arteriotomy is extended at each apex using coronary artery scissors. To identify the actual coronary artery lumen, a coronary probe is employed. Finally, a distal anastomosis is sutured in forehand/ backhand technique, starting at the heel and parachuting down the graft to the coronary artery. Another 3D visualization (MPEG-1) demonstrates the principle of a closed coronary thrombendarterectomy (Figure 7, ◎): after a short longitudinal arteriotomy, the atherosclerotic core appears. Dissection of the thrombus is started between vessel-wall and thrombus with a spatula. A small clamp is passed around the thrombus, which is then divided with a scalpel. Finally, the distal and proximal ends of the thrombus are removed with a forceps under assistance of the dissecting spatula.

Some of the 3D models have been implemented into the first prototype of a multimedia textbook about operative techniques where text, sound, videos and animations are customized to interactive multimedia teaching applications (Figure 8, ◎). It contains three different levels of complexity (for students, residents and professionals) as well as safeguards and pitfalls of the operative steps, which may be selected facultatively.

DISCUSSION

The term "virtual reality" (VR) covers a wide range of topics and content and is often used in confusing ways. Szekely and Satava, both pioneers in the development of medical VR applications, summarized VR as follows: "the principal aim of VR technology is to present virtual objects or complete scenes in a way identical to their natural counterpart" [Szekely 1999]. In our opinion, this high-end definition is still a rather virtual reality. However, many attempts are undertaken in numerous research projects to achieve that vision. Altogether, VR based technology includes three dimensional computer graphics, head mounted displays or special holography display screens, interaction devices and trackers such as data gloves and three dimensional pointers, systems that focus on force and tactile feedback and, so far exclusively a research issue, olfactory and emotional feedback [Szekely 1999, Lange 2000]. Computer-based preoperative planning, image-guided surgery and telemedicine/telesurgery applications are sometimes also subsumed under VR.

The Internet has emerged as a powerful tool in medical education [Matthies 1999] and virtual environments are believed to satisfy the need for training in medical and especially surgical procedures [Ota, 1995, Satava 1995]. Using the WWW, one is able to address users all over the world but this also implicates some limitations and conditions: (i) the speed of physical data transmission is still reduced for most of the users (voice-lines); therefore, the lengthy transmission of high–volume data reduces the likelihood of a satisfactory teaching performance; (ii) the end-user (client side) usually uses multimedia personal computers (in contrast to high-end workstations) whose hardware capabilities strongly limit the support of additional devices, e.g., force-feedback devices or head-mounted displays; (iii) our visualizations and teaching presentations should be able to be displayed at the users' monitors without requiring additional soft- and hardware beyond the usual internet installation software; (iv) they therefore should be able to be downloaded and used on the basis of a low-cost internet-access.

Within the *CardioOP* project, we initially intended to focus on educational videotapes for demonstrating surgical techniques. High quality intra-operative videos have therefore been recorded with a specially designed video robot and digitized. Next, we performed interviews and discussions with different test-persons. This has not been performed on the basis of a formative evaluation but it became clear that the surgical techniques and underlying principles have often not been fully understood. For instance, in case of a suturing technique of an aortocoronary bypass-anastomosis, misunderstandings may be due to the fact that the camera is zooming in very closely to the coronary artery and the performed stitches thus hide the movements of the surgeon's hands and the change of the suturing ends or other details. Therefore, we started to develop 3D visualizations of operative techniques in movie-like scenes, which can be transmitted via the WWW using MPEG-1 coding or streaming (Real) video technologies [Boudier 1999]. These 3D movies are not really interactive in terms of self-interfering possibilities but have the power to describe the principle of surgical techniques, where temporal and spatial events play an important role, in a way superior to a textbook with photographs and 2D-drawings. So far, a 3D visualization of a complete distal anastomosis and a closed thrombendarterectomy have been implemented. They represent a virtual reflection of reality with special focus on important and pre-determined details. They further explain and describe the important points of the operative sequence from different perspectives and outline the basic principles of the performance.

"A picture is worth a thousand words" is a trite expression, and even more true for interactive 3D visualizations. VRML (Virtual Reality Modelling-Language) is a relatively new standard for 3D software developers in the Internet. It is a language that can be used to describe three dimensional objects for display in web browsers. These objects may be interactively explored in any way imaginable [http://www.web3d.org]. This makes it unnecessary to provide different images in 2D for viewing the same data from different angles [Samothrakis 1997]. They also can contain embedded links to other distributed worlds. In addition, VRML-worlds can react dynamically when containing animation scripts with sensors that cause a reaction when an event is sensed, such as a mouse click or mouse-over interaction [Dolata 1998]. Medical visualization data range from kilo-bites to gigabytes. The size of these data is a challenge both for hardware architectures and for software techniques. VRML data files are small, thus allowing for the rapid download even with small modems or voice lines. The end-user only requires VRML-player software, which can be downloaded easily and free from the Internet. Further devices such as headsets or data-gloves are not necessary.

One of the most obvious uses of 3D visualizations is to display and examine anatomical structures [Warrick 1998, Haluck 2000]. The knowledge about anatomy is also fundamental to understand and plan surgical procedures. Therefore, we started to compute a VRML model of the heart, which serves as a basis to explain anatomy, pathophysiological processes and surgical interventions in heart surgery. For example, a user will have the possibility to simulate basic principles of a surgical bypass procedure by interactively adding typical coronary artery-stenoses and different types of required bypass grafts. This model, however, can also be used to explain the necessary operation to a patient. In order to facilitate understanding, e.g., of plain coronary angiograms, which is of special importance in aortocoronary bypass surgery, a VRML model of the coronary arteries has been established as well. For technical reasons it has not been possible to create highly dynamic scenes, e.g., a semi-transparent beating heart with correct valve movement in VRML. Such a rotating model has therefore been implemented in the QTVR-2 format. This technique also allows for interactively exploring a 3D object similar to the VRML-technique and additionally supports a more photo-realistic appearance in contrast to the cartoon-like surfaces of VRML-models [Trelease 2000]. It consists, in contrast to VRML, of a relatively large data file consequently with much longer download times. However, the overall performance of QTVR in the Internet was found to be still very satisfying for teaching purposes in medicine when compared to other formats [Kling-Petersen 1999]. The *CardioOP-Heart* will be used to explain and demonstrate further more complex surgical procedures, e.g., valve replacement, repair of congenital defects or minimally invasive procedures.

There is evidence in the literature that teaching and training in medicine may be improved by the use of multimedia technologies. However, it should be avoided to stress mainly on technical aspects and effects. The focus of interest should be towards clear didactical and pedagogical concepts, which are adjusted to the target user groups [Waugh 1995, Friedl 1996]. Our 3D models can be downloaded as stand-alone versions, but they are worthy to be used in instructional courses or teaching applications where different media-types are tailored to interactive teaching scenarios. Our system architecture has been designed as a first prototype and will serve as a common multimedia teaching basis for the above mentioned user groups and different teaching scenarios. That way, an interactive 3D model, e.g., demonstrating the principle of aortocoronary bypass grafting will be used several times: during a lecture as a stand-alone version in a classroom equipped with on-line computer access, while navigating through the multimedia book or to illustrate a problem while solving a case in the case-based teaching module. It may be also used for patient education. The presented system and multimedia content are currently available to selected intranet-users in our department and are in the stage of evaluative research and further content production.

The ultimate goal of VR applications in advanced surgical education is the real time simulation of operations with photo-realistic appearance and excellent force feedback capabilities while running on a desktop computer. Such systems, allowing total immersion, are not available so far [Haluck 2000]. However, we regard our VR and 3D models as being a step towards this direction, especially under the vision of network-delivered, ubiquitous availability.

Acknowledgment

This work was funded by the German Ministry of Research and Education, grant number 08C58467. We thank Dr. Peter Engels and Dr. Michael Schefer for their advice and review of the manuscript.

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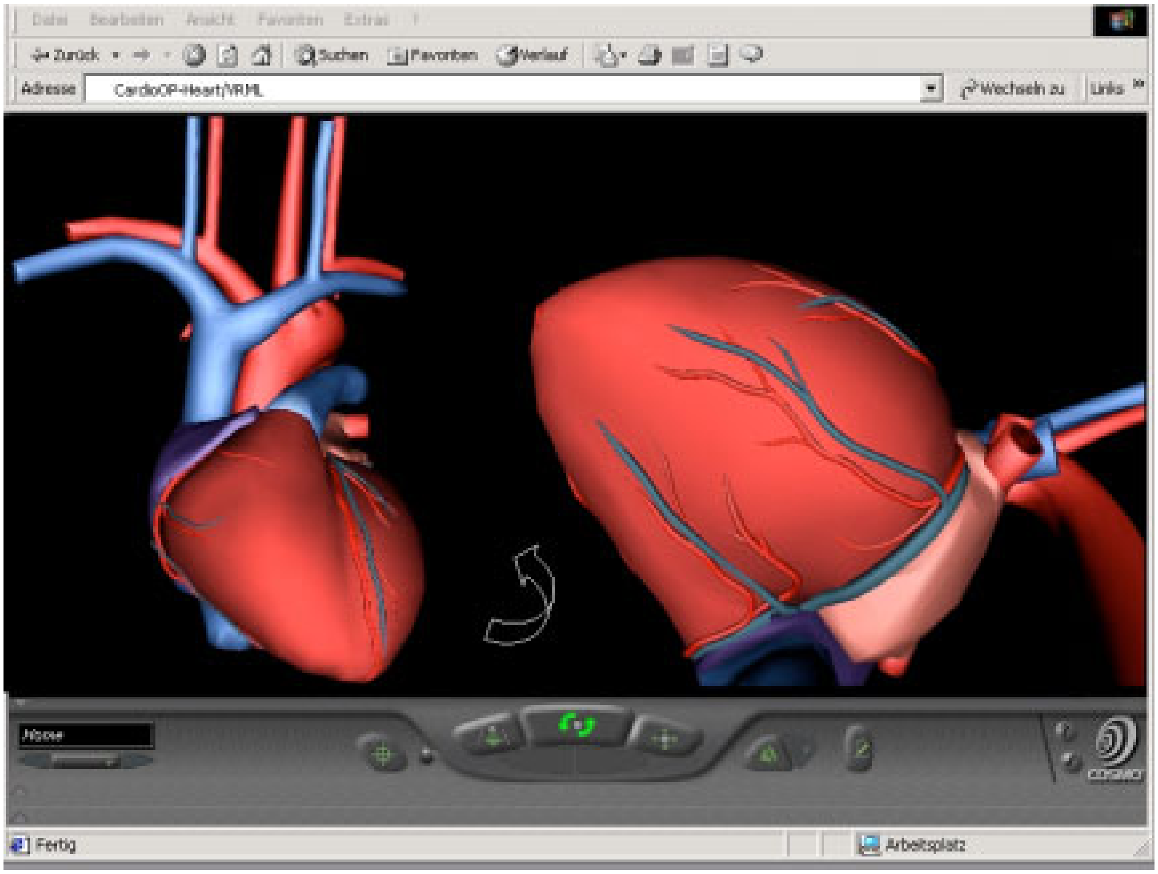

Figure 1 Screenshots of a VRML model of the CardioOP-Heart at different viewpoints displayed in a WWW-browser. It can be explored interactively by the user (represented by the arrow) who is able to freely move or rotate it in any position or zoom to details.

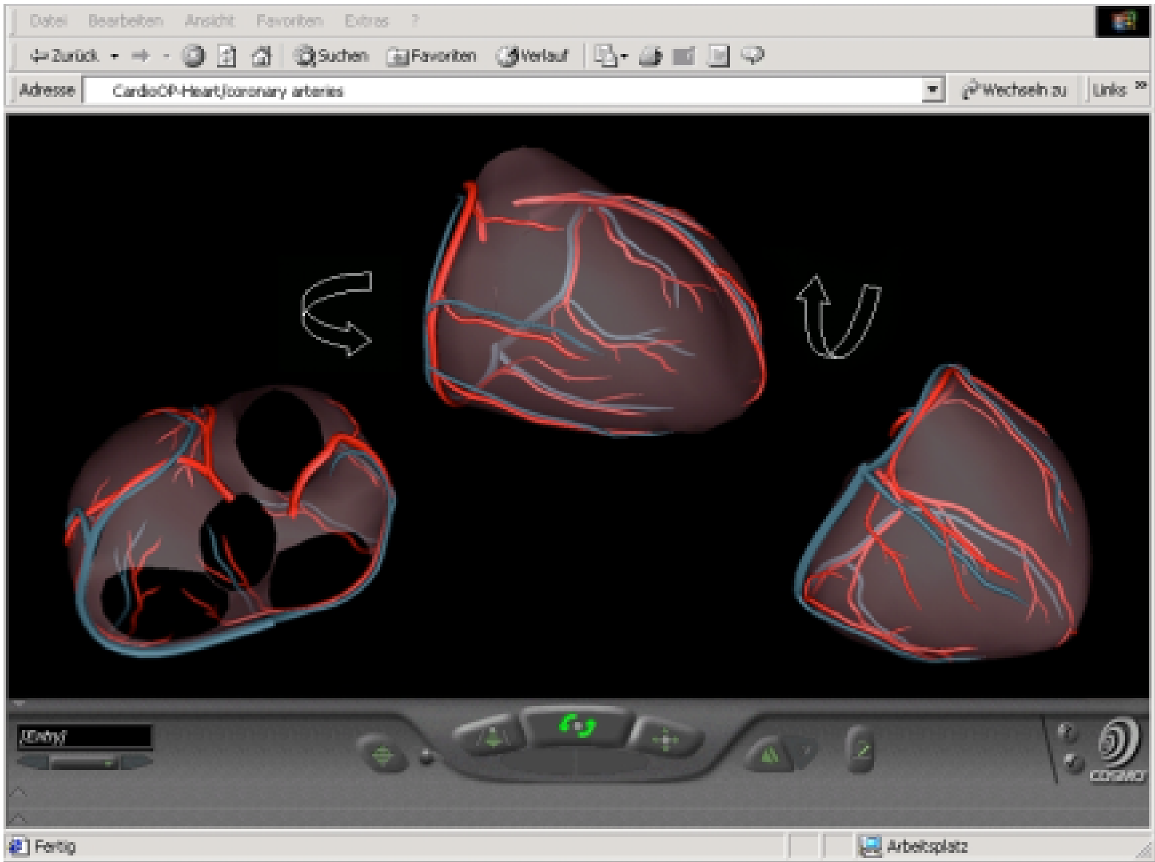

Figure 2 Screenshots of a VRML model of the coronary arteries at different viewpoints. Arrows represent the possibility for interactive exploration.

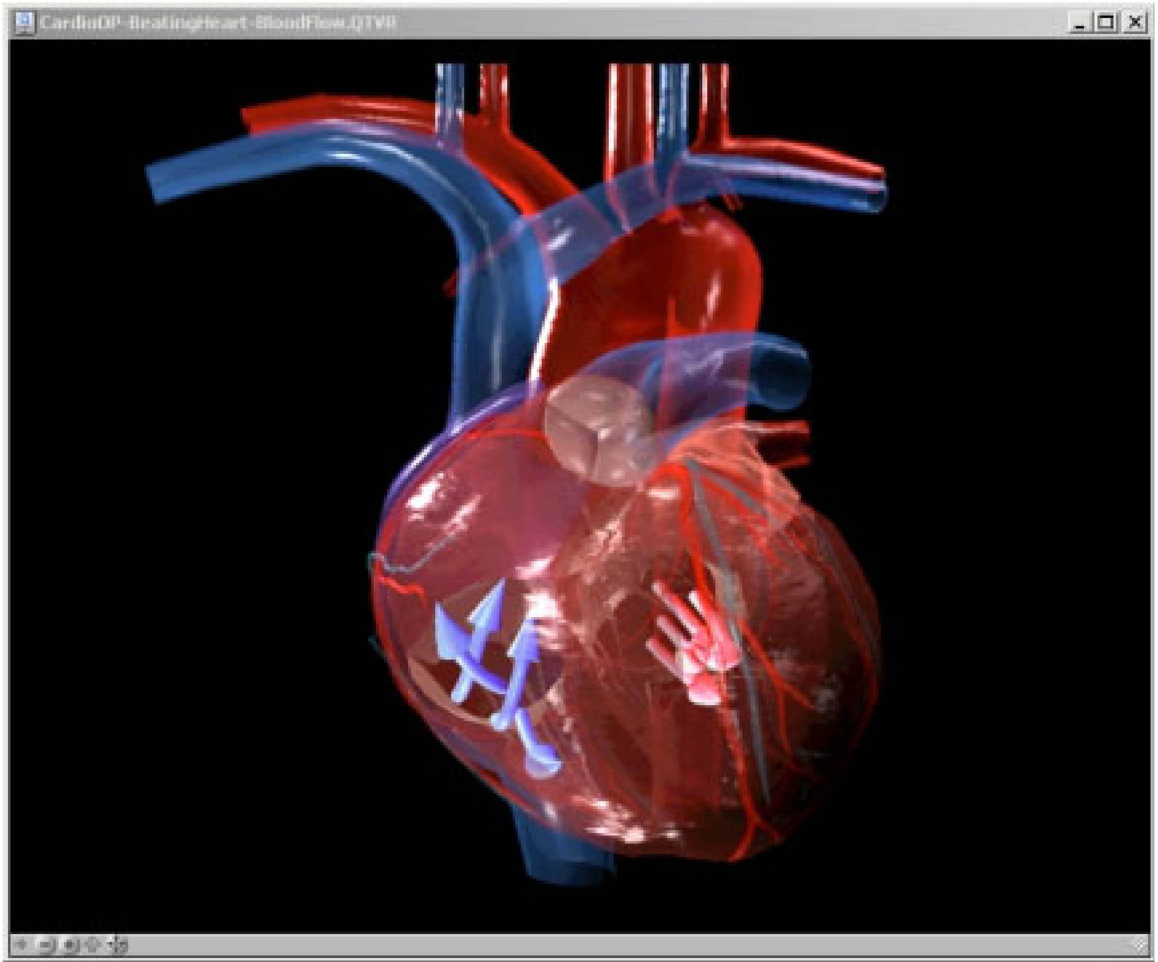

Figure 3 Screenshot of a QTVR-2 model of a semitransparent beating heart with simultaneous visualisation of the inner structures and the outer surface. Hemodynamic action and blood flow (“flying arrows”) arefurther represented.

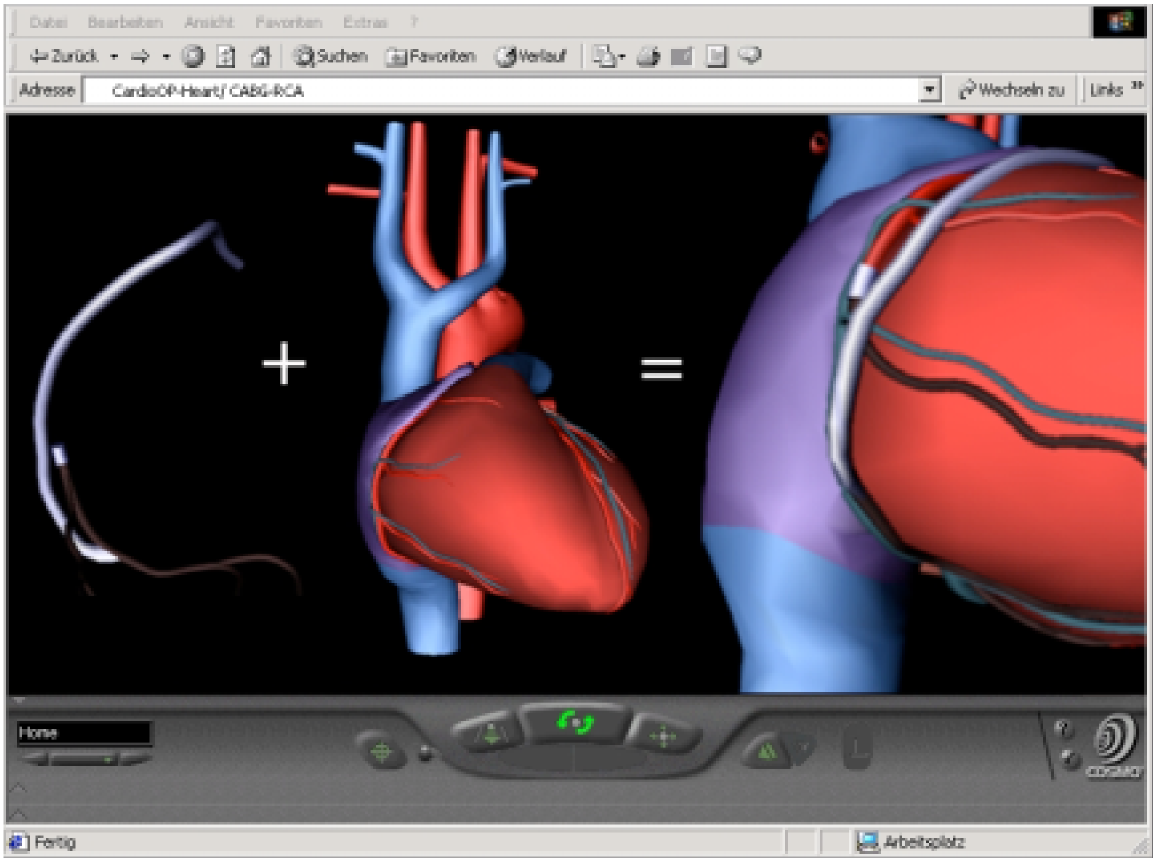

Figure 4 This figure represents the possibility to interactively add typical coronary artery stenoses and bypass grafts to the CardioOP-Heart in VRML technology.

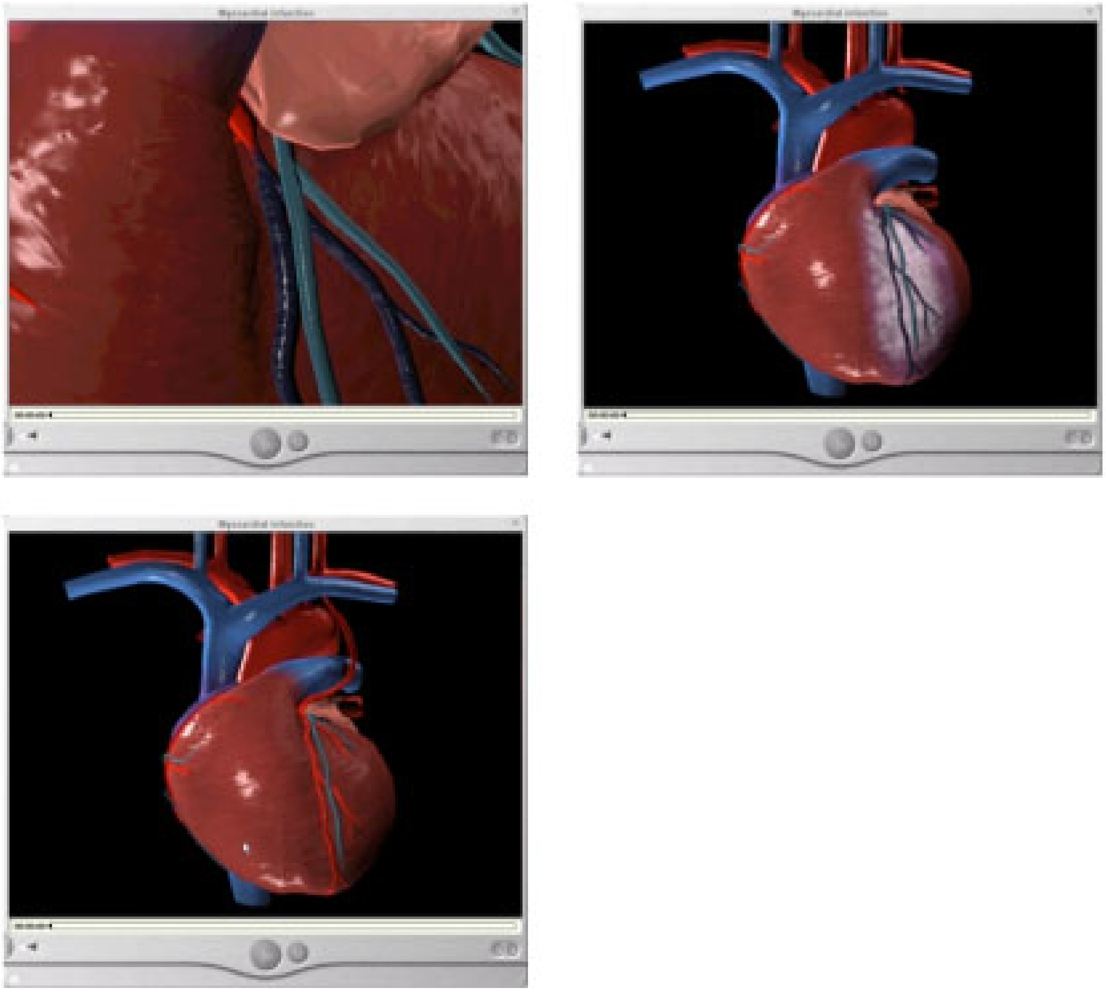

Figure 5 3D model (MPEG-1), demonstrating the principle of a coronary artery stenoses (proximal LAD) with subsequent myocardial ischemia and the effect of an IMA-Graft on myocardial perfusion.

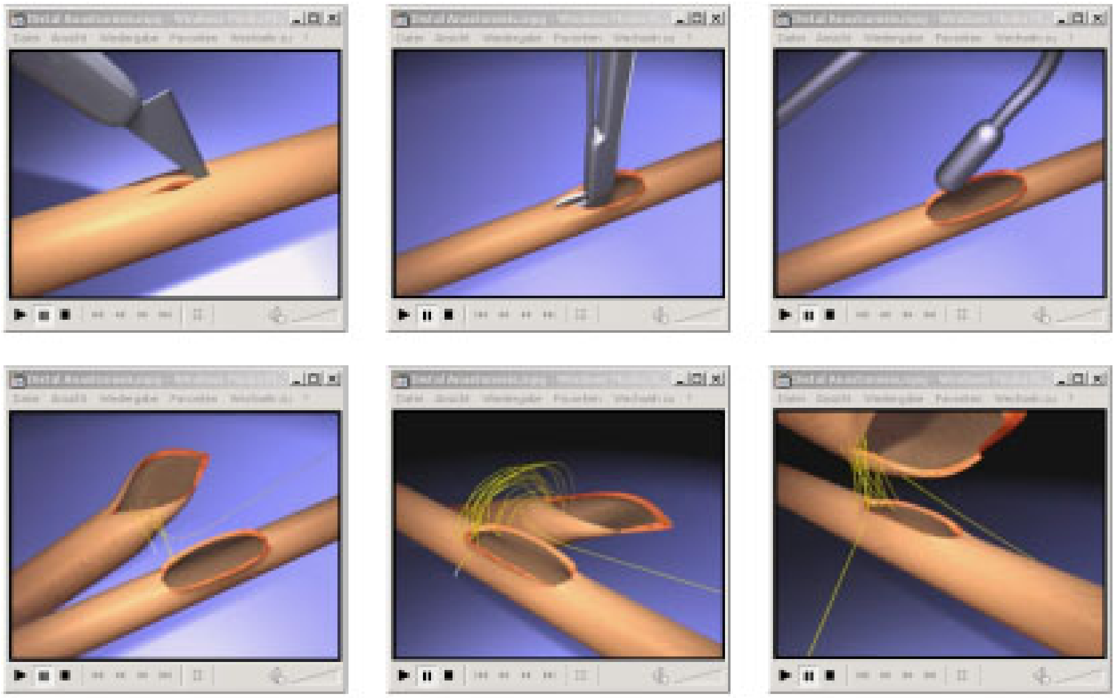

Figure 6   3D animation (MPEG-1) of a complete distal anastomosis including arteriotomy, probing and all stitches in forehand/ backhand technique.

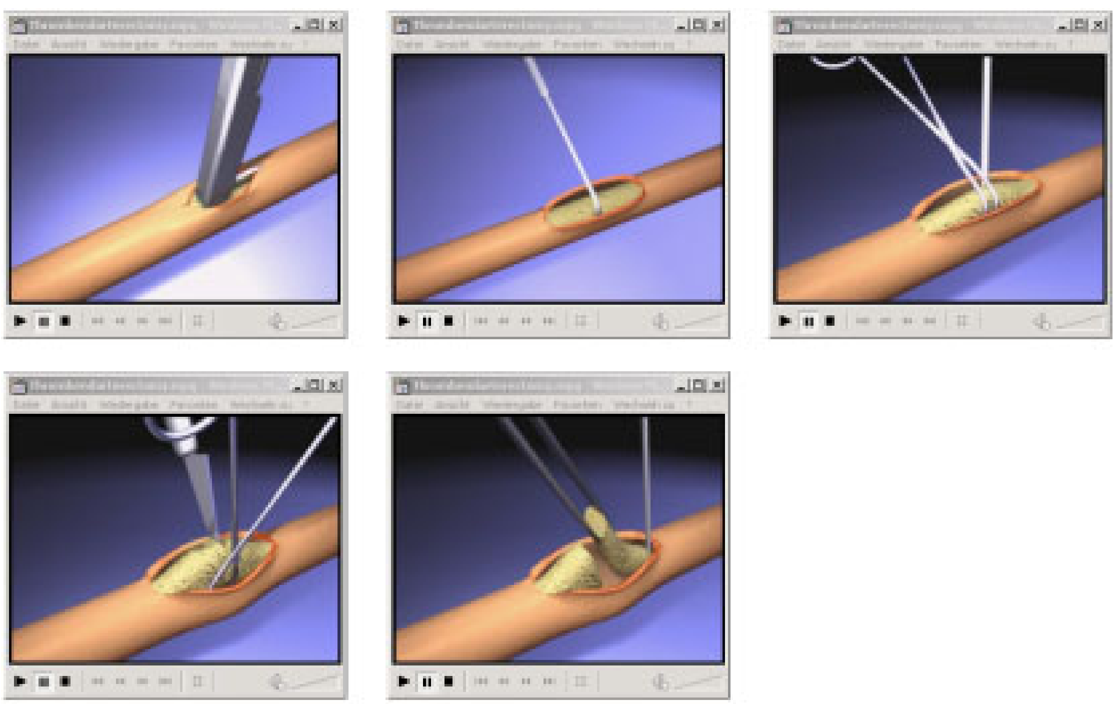

Figure 7   3D animation (MPEG-1) of a complete closed thrombendarteriectomy

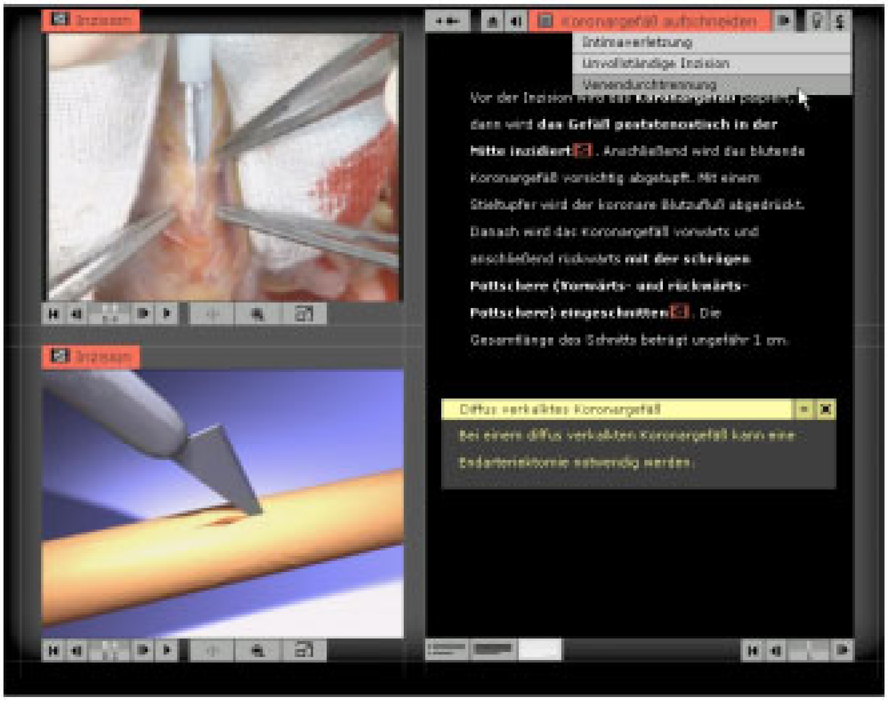

Figure 8 Screenshot of the prototype of a multimedia textbook about operative techniques where different media-types are authored to a multimedia teaching application at different instructional levels.