HCI in Medical Visualization

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Abstract

Research in medical visualization lead to a remarkable collection of algorithms for efficiently exploring medical imaging data, such as CT, MRI and DTI. However, widespread use of such algorithms requires careful parameterization, integration of individual algorithms in *solutions* for real-world problems in diagnosis, treatment planning and intraoperative navigation. In the field of HCI, input devices, interaction techniques as well as a process for achieving usable, useful, and attractive user interfaces are explored. Findings from HCI may serve as a starting point to significantly improve visual computing solutions in medical diagnosis and treatment. We discuss general issues, such as input devices for medical visualization, and selected examples.

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1 Introduction

The visualization and exploration of 3D medical image data, such as CT, MRI, ultrasound or PET, is an important application area of scientific visualization. Developments in these areas drove research in volume visualization, mesh processing, tensor visualization and image filtering. With new and improved imaging modalities along with changes in the available graphics hardware there is still a need for improved algorithms with respect to visualization quality, accuracy and performance. However, there is an important trend towards more applied research focussing on specific applications, to provide visual computing solutions integrating image analysis, visualization and appropriate graphical user interfaces. Indeed, these issues are essential to achieve clinical use of medical visualization algorithms. The goal of regular clinical use requires to put the user in focus or – as HCI (Human computer interaction) researchers would call it – to adopt a user-centered design approach [33]. Users of medical visualization systems are primarily medical doctors from a specific discipline, such as radiology, surgery, nuclear medicine or radiation treatment, who use such tools for diagnosis support, treatment planning, intraoperative navigation and follow-up studies to evaluate the success of their treatment. In this article, we focus on these user groups. Thus, we do not address students of medicine who might use advanced 3D visualization for anatomy teaching, or researchers in medicine, biology and chemistry who optimize medical imaging with respect to sequences, protocols and contrast agents. The focus on medical doctors in clinical settings is justified, since this group is by far larger than medical researchers and students, and if these users can be provided with better tools, a direct and significant impact on patient health is possible. It is essential to be clear about the user group: The working place of a medical doctor in a hospital and particularly in the operating room differs strongly

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from the office of a researcher or the desk of a student. Thus it is naive to assume that computer support developed for the latter is also appropriate for the first user group.

To discuss these issues, we need to dive into human computer interaction, the discipline which deals with the process of generating usable and enjoying software systems directly supporting specific users and their tasks. Since HCI itself is a huge discipline, we focus on a few areas within HCI which are particularly relevant for the clinical use of medical visualization. These include:

1. modern task analysis methods, which carefully incorporate the context of use, usage scenarios, preferences and acceptance criteria,
2. an appropriate and refined use of input devices and input options, such as pen, touch display and, gestured input,
3. strategies and recommendations which improve the user experience [1],
4. an adequate use of the large variety of displays ranging from handheld devices to very large screens, and
5. prototyping and evaluation techniques which support the exploration of a wide variety of techniques, options and combinations.

After an overview of medical visualization (Sect. 2), we discuss task analysis (Sect. 3) and input devices (Sect. 4) in more detail and relate them to medical visualization in clinical medicine. We continue with a discussion of evaluation strategies (Sect. 5).

2 Medical Visualization: From Pure Research to Advanced Applications

Pioneering work in medical visualization was aimed at efficiently displaying a set of medical image data with direct volume rendering or isosurface rendering incorporating shading, efficiently using graphics hardware and improving image quality, for example with pre-integrated shading. Another branch of research focussed on non-photorealistic rendering, such as incorporating hatching to convey surface curvature [42]. NPR techniques have later been adapted and used in volume rendering [6]. With these and other developments a large set of powerful rendering techniques is available which provides – from an application's point of view – a sufficiently good performance and quality. However, basic algorithms alone do not provide adequate support for clinical tasks. Medical doctors often need to

1. follow an inner path of an elongated branching structure (e.g. airway tree, vascular structure, colon) to understand the branching pattern before an endoscopic intervention or to detect abnormalities along the wall,
2. closely examine the local surrounding of pathologic structures,
3. explore possible resection areas and resection planes [52], and
4. integrate the results from different examinations, such as fMRI and DTI.

We discuss general strategies of providing useful and appropriate solutions in the following subsections.

[1] The user experience (UX) extends the older term *usability* and covers also perceived attractiveness. Amongst others, a distinct visual design, typography, the careful use of colors, shapes, and animations contribute to the user experience [7].

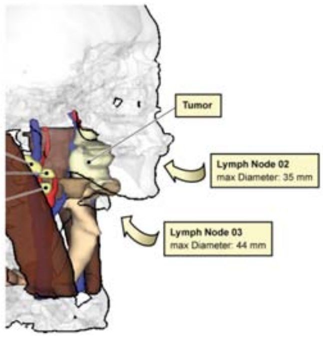

Figure 1 Labelled visualization for neck surgery planning. All labels relate to potentially pathologic structures and are placed automatically. Hidden structures are annotated using a bended arrow. Thus, the user knows where to look for further critical and important structures. Clicking on the annotation starts an animation that leads to a good viewpoint on the structure. (From: [30])

Incorporation of semantic information

A more user-centered approach was first adopted to support anatomy and surgery education [21, 36]. We do not dive into such applications, but a few trends emerging in teaching applications are relevant for the purpose of this paper. In particular, medical image data was connected with a large variety of semantic information which enables the user to explore data with respect to organ systems, nerve supply and other application-specific questions [45]. Based on such semantic information, anatomic structures may be labelled automatically [17]. Labelling is also useful for surgical planning (see Fig. 1 for an example carefully discussed with a surgeon).

The extended use of semantic information is an important trend in other areas within medical visualization. Importance-driven rendering relies on a priori knowledge of the relevance of certain structures [51] and transfer function specification benefits from a user-centered approach and "knowledge" of the actual data distribution as well as frequently used settings [38]. In clinical settings, DICOM data are employed which come along with a variety of semantic information, e.g. with respect to data resolution, specific scanning parameters, which may be employed for annotation and parameterizing algorithms as well.

The essential role of segmentation

To provide advanced support, relevant structures have to be identified and delineated (to be *segmented*). Segmentations are used to label or emphasize them for example with importance-driven rendering. Segmentation is beyond the scope of this paper. However, similar to medical visualization, there is a trend to focus on HCI aspects in segmentation as well instead of purely developing highly sophisticated model-based approaches (the seminal paper of Olabarriaga and Smeulders [34] laid the foundation for a systematic exploration of interaction techniques in segmentation). Recently Heckel et al. [19] introduced a promising method for semi-automatic 3D segmentation, where users may provide input in arbitrary orientations. While many research papers are based on a comprehensive segmentation of many structures, in clinical medicine, segmentation is performed rather rarely due to the effort involved. Exceptions are advanced applications in cardiology and orthopedics as well as radiation treatment planning where segmentation of the target structure (a cancer) and surrounding vital structures is mandatory for optimizing the treatment plan.

2.1 Virtual endoscopy

With respect to specific applications, virtual endoscopy, in particular virtual colonoscopy for colon cancer screening, often serves as a showcase task, since it is highly relevant and convincing solutions have been developed [22, 2]. The success of virtual endoscopy depends strongly on application-specific aspects, such as an emphasis of suspicious structures by advanced image analysis [53], adequate overviews which prevent that crucial information is missed [50], and the presentation of actually hidden anatomic structures relevant for the particular intervention [31]. Virtual endoscopy is also an excellent example, for the successful use of a *metaphor*. This relates to the term "endoscopy", that is very familiar to medical doctors and to the specific visualization, e.g. the implementation of various lens characteristics, that mimic real endoscopy. We will discuss metaphors in Sect. 3.4.

2.2 Integration of image analysis, simulation and visualization

Other applications also require substantial image analysis prior to a visualization and exploration of patient-specific models. As an example, [46] describes the image analysis pipeline necessary for delineating all structures relevant for liver surgery planning. In a similar way, neck surgery planning [27] requires segmentation of many different soft-tissue structures, such as muscles, glands, and lymph nodes. Advanced visual solutions for surgical planning often include simulations as well. As an example, Zachow et al. [52] simulated soft-tissue deformations for different variants of facial surgical interventions. Similarly, Krekel et al. simulated the range of motion of a shoulder implant to guide shoulder replacement [25]. The most advanced visual support is now available in neurosurgery planning applications, where anatomic, functional and DTI data are combined [12, 4] and sophisticated visualization techniques, such as depth-enhancing illustrative techniques, are used [39]. Enders et al. [12] introduce a visualization of DTI fiber bundles which is carefully adapted to the information needs of a neurosurgeon with respect to planning tumor surgery. All systems, mentioned in this subsection, are good examples for carefully incorporating HCI aspects and focussing on real needs and problems documented also with expressive evaluations.

2.3 Visual exploration of 3D models for neck surgery planning

We will explain the example of neck surgery planning in more detail. The in-depth exploration of enlarged lymph nodes – potential lymph nodes metastases – and the primary tumor with respect to its shape, size, location and surrounding structures represents the core of preoperative planning. Specific solutions, such as cutaways for emphasizing lymph nodes, and silhouettes for presenting context structures turned out to be useful in clinical tests. However, our general approach of presenting as many anatomic structures as possible in a convenient way, was eventually considered not appropriate, since it does not fit well to the specific questions of surgeons. In extensive discussions we learned how careful possible infiltrations are assessed. Surgeons want to know whether there is an infiltration of a vascular structure for example, how likely the infiltration is, which portion along the vessel and which portion of the vessel's circumference is involved. The answer to each of these questions may alter the surgical strategy considerably. Therefore, we carefully designed a workflow with a sequence of 3D models to be used to assess the infiltration of different anatomic structures. Figure 2 shows two examples of such specific visualizations. We cannot claim that these are optimal visualizations for this purpose, but at least we have identified the visualization of (potential) infiltrations as an important research topic, probably relevant for a wide spectrum of surgical interventions.

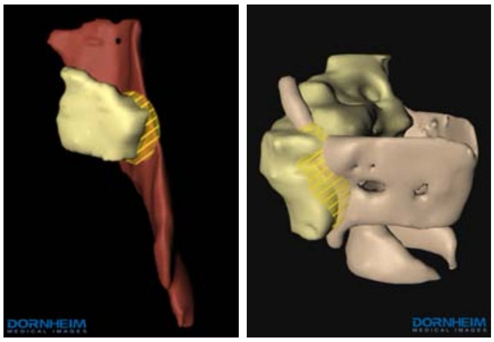

Figure 2 Specific visualizations of the neck anatomy. Both images indicate the possible infiltration of an anatomic structure by a lymph node metastasis (left: a large muscle, right: thyroid cartilage). The possible infiltration area is semitransparently visualized and hatched. (Copyright: Dornheim Medical Images)

2.4 Discussion

Successful applications require to deeply understand the characteristics of the underlying imaging data, the variety within such data, including pathologic situations and the specific diagnostic and treatment planning questions. From the huge variety of options to display such data, appropriate default settings are necessary to support users working under severe time pressure adequately. These default settings relate to colours, rendering styles, transparency and viewing directions. More often than not, different views to the data need to be carefully combined and synchronized, such as internal and external 3D views along with cross-sectional views in virtual endoscopy. Moreover, in diagnosis but also in treatment planning it is often essential to understand existing workflows (without advanced computer support). This enables to envision new workflows which are as as close as possible to the original workflow. In tumor surgery, for example, the location, shape and size of a tumor needs to be explored before possible infiltrations of important risk structures are analyzed in detail. We will discuss workflow analysis in Sect. 3.2.

3 User and Task Analysis

When research and development is indeed targeted at clinical applicability, user and task analysis are key elements. The failure of many attempts to create useful systems for clinicians is often largely based on an incomplete task analysis, where major requirements were not identified or their priority was underestimated. The naive approach to ask the users, what they need, may be a reasonable start, but there are several reasons why the immediate answer to this question is completely insufficient. Typical users have no idea what could be done with adequate technical support, they are accustomed to certain kind of technology and try to cope with it. Thus, user needs have to be very carefully elicited. HCI experts, specialized on this activity, are referred to as *user researchers*[2], a term which illustrates how complex, challenging and creative task analysis actually is.

Modern task analysis combines a variety of methods including observations, interviews and questionnaires. As a result, a hierarchical task analysis (HTA), workflow diagrams, or a set of (informal natural language) scenario descriptions eventually enriched with digital

[2] Very often, these persons have a Phd in psychology.

photos from important artifacts arise. Diagnostic and treatment planning tasks are complex and demanding. It is therefore necessary to carefully prepare the analysis in order to pose the right questions and follow-up questions to reveal the implicit knowledge of medical experts.

3.1 What has to be analyzed?

The details of a particular treatment are, of course, different. However, a few general questions may serve as orientation:

- Which pathologies should be diagnosed or treated?
- Which imaging modalities are used either in isolation or combination for diagnosis or treatment planning?
- How is the pathology described and which alternative pathologies are considered (confirm or exclude a certain diagnosis)?
- How is the severity of the disease described and which criteria are employed for this description?
- What are the therapeutic consequences of the diagnosis?
- Which treatment options exist, e.g. surgery, radiation treatment, interventional treatment? How can they be combined?
- Which criteria drive the decision for these treatment options?
- Which further details have to be determined prior to surgery or intervention, e.g. access path for a cathether or stent, extent of a surgical resection, necessity of vessel reconstructions?
- Who is involved in these decisions?
- What kind of technical support is used during the intervention, e.g. navigation or surgery assistance systems?
- Which decisions have to be performed during an intervention?

It is crucial to understand these questions, to verify the answers by discussing with several medical doctors, and to discuss the results of your analysis with them. More often than not, it turns out that some facts have been confused or the relevance of some aspects is not correctly understood. As a consequence, the computer support should focus on generating visualizations which support diagnostic or treatment decisions directly. Later in a project, evaluations should focus on the influence of computer support on these questions. Our experience indicates that observations at clinical workplaces are a mandatory aspect of task analysis.

3.2 How to represent the results?

Task analysis yields a wealth of data which needs to be structured, prioritized and consolidated before concise results can be extracted. Audio recordings from interviews or "think aloud" sessions, handwritten notes, schematic drawings of workplaces or tasks are typical examples. Recently, two different representations have been used and refined for medical visualization applications: workflows and scenarios.

Workflow analysis and redesign is a core activity in business informatics where business processes should be designed, evaluated and optimized. Workflows are formal graph or network representations which contain actions (nodes in the graph) and their logical sequence (edges in the graph). The design of medical visualization may borrow from these experiences, notations and tools to manage such workflows to characterize treatment planning, interventional procedures and outcome control. Workflows may contain (a few) variants and may emphasized typical sequences of actions. They may also encode how often certain procedures occur, and

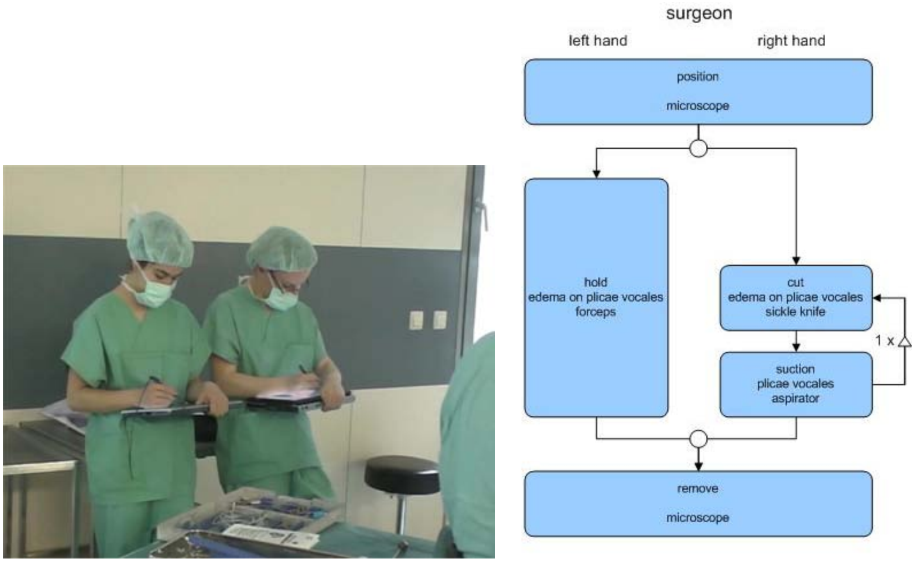

Figure 3 A workflow for a surgical intervention in cardiology resulting from careful observations (left with a tablet PC and dedicated software) in the operating room. (Courtesy of Thomas Neumuth, ICCAS Leipzig)

how long they are [32] – an information which is essential to consider which processes may improve from computer support. Workflows are described after observing several instances of a process (see Fig. 3). They may describe processes at various levels, thus allowing an analyis at different levels of granularity.

The formal character of this representation is a benefit which clearly supports the software development process. However, since this notation is not familiar to medical doctors, workflows are not particularly useful for discussions with them. Also, at different sites or even among different doctors at one side, there might be huge differences in their specific workflows. Unlike in manufacturing and administrative procedures, medical treatment is and must be more individualized with respect to the patient and the medical doctor. Workflow diagrams can hardly represent that variability but are often restricted to a somehow averaged instance.

Scenarios are now widely used in HCI, in particular to characterize and envision radically new software systems [3]. Scenarios are natural language descriptions which include statements about which technology or feature is used for which purpose. They contain different perspectives as well as motivations from users. Scenarios are more open to interpretation, which may be considered as a drawback. However, they are clearly useful as a basis to discuss with medical doctors. For three larger projects in computer-assisted surgery, scenario descriptions have been used, discussed within the development team and with medical doctors resulting in a large corpus of descriptions, annotations and refined descriptions [10]. Figure 4 shows different types of scenarios and their relations as they have been used for liver surgery training, neck surgery planning as well as minimally-invasive spine surgery. For a detailed discussion of these scenario types, see [10].

The following is a short portion from a longer user story and the derived scenarios for a SpineSurgeryTrainer (see Fig. 5 and [11]):

User Story: ?The doctor in training has to place an injection in the area of the cervical spine for the first time. He is insecure and he wants to train this procedure to test his skills

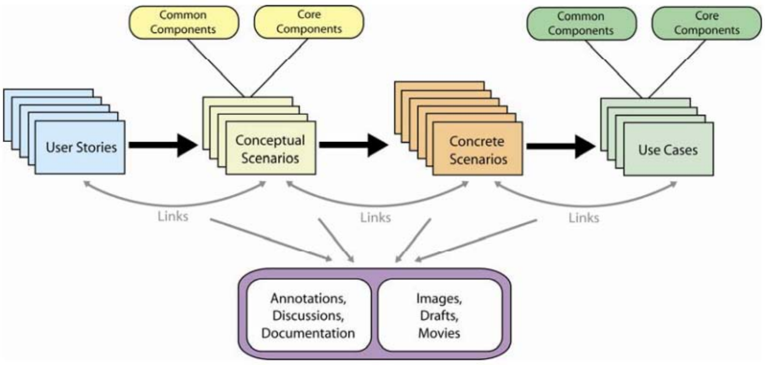

Figure 4 To envision a planned application, high-level user stories are stepwise refined by providing detail on *how* a function should be performed, and by considering constraints from the context of the intended system use. The links between the documents and the related annotations need to be managed. (From: [10])

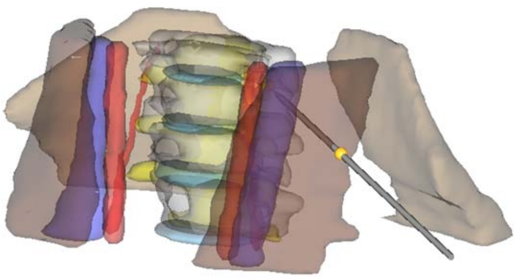

Figure 5 A screenshot from a training system for minimally-invasive spine surgery. A difficult decision relates to the access path and needle placement. (From: [11])

and to do the real injection with self-confidence. But there is no expert and no cadaver available at the moment. Because he is pressed for time and wants to start the training directly, he decides to train the injection virtually. . . . ?

Conceptual Scenario: ?He starts with the survey of the patient data and anamnesis. After that, he decides for an injection as therapy and starts the training of the virtual placement of the needle [Concrete Scenario 1] based on the MRI data and the 3D model of the patient's anatomy. . . . ?

Concrete Senario 1: (Details of injection planning): ?With the mouse (left mouse click) he defines one marker for the penetration point and one for the target point of the needle in the 2D data. The needle takes up its position. In an animation the user can view the injection process of the needle to his defined position. . . . ?

In total, six scenarios related to cases with different levels of difficulty and different viable treatment options have been explored. The discussion of such scenarios with medical doctors revealed a variety of insights and ideas for visualization and exploration of the data, in particular when the decision between two alternative therapies depends on subtle details of the patient anatomy.

3.2.1 Experiences with the Use of Scenarios

The visualization group in Magdeburg employed scenario descriptions consequently for several comprehensive projects. The use of scenarios, in particular the discussions with medical doctors, lead to several unexpected ideas and features. As an example, it turned out that our NeckSurgeryPlanning-system is also relevant for patient consulting, where surgical options are explained to the patient and to family members. For this purpose, a large display device is useful and the set of available features may be strongly reduced. An essential lesson learned in these discussions is that user stories need to be combined with sketches, screenshots of a mock-up or storyboards to further strengthen the imagination of medical doctors. The purely textual character of all scenario types does not sufficiently support the discussion of the strongly visual components of a diagnostics and treatment planning systems. Fig. 5 is an example, which was created to support the reflection on the previously described user stories.

3.2.2 Combination of scenarios and workflows

A development team need not to decide whether (exclusively) workflows or scenarios should be used to guide the development process. Both methods provide useful and complementary information. While scenarios better support the discussion between user researchers and the target users, they do not inform the actual developers in a concise manner. For the developers, a validated workflow description is a valuable support, in particular for implementing wizard-like systems which guide the user in a step-by-step manner. The systems developed in Magdeburg were also based on workflow descriptions at different granularities. Surgical planning, for example, at the highest level follows often the workflow: diagnosis, assessment of the general operability (Can the patient tolerate anesthesia?, . . .), resectability (Is the pathology accessible and may be removed without damage of vital structures?), access planning, in-depth planning including vascular reconstructions.

3.3 Understanding the User

This stage in a user interface lifecycle aims at understanding users' qualifications, preferences, needs and attitudes in order to create solutions which are acceptable and appropriate for them. In medical visualization, users are primarily radiologists, radiology technicians, medical doctors from different operative subjects, such as orthopedics, neurosurgery, or urology.

There are significant differences between radiologists and medical doctors from operative disciplines. While the former use the computer for a large part of their work, the latter consider their cognitive and manual skills to perform surgery as the core of their activity and use the computer only for a small portion of their work, often considering this work as less important. This difference has huge consequences for what is considered as appropriate visualization and interaction technique and user interface. While radiologists prefer a very efficient interaction even at the expense of more complexity and a longer learning period, doctors in operative subjects prefer simple easy-to-use interfaces even at the expense of longer interaction sequences and reduced flexibility. Therefore, radiologists (and medical doctors from related disciplines as nuclear medicine and radiation treatment) efficiently use systems with rather dense user interface panels, invisible interactions, such as short-cuts, popup-menus and other interaction facilities that only appear in a certain context. On the other hand, doctors in operative disciplines favor simplicity and thus prefer strongly reduced interaction with only a few large buttons at the same time. For radiologists it is essential that they can stay focussed on a certain region in a 2D or 3D visualization while performing changes on the visualization parameters, such as brightness, contrast, transfer function, or the currently selected slice. Thus, they prefer in-place interaction with mouse movements, such as scrolling through the slices with mouse wheel and changing brightness/contrast with left/right up/down movements. Interfaces for surgeons perform the same task with a control panel, where (large) sliders enable control of these parameters.

3.4 Metaphors

The identification and use of appropriate metaphors is an essential aspect of a user-centered process. Beyond requirements, scenarios and workflows, the user and task analyis *may* elicit suitable metaphors. The suitability of metaphors depends on the familiarity of users, the structure and richness of the metaphor (what do people associate with a metaphor?) and the degree of correspondence between the source domain (where the metaphor is known) and the target domain (the new application where the metaphor is employed to label and visually illustrate application concepts). Successful applications of metaphors in medicine are virtual endoscopy (recall Sect. 2.1), digital microscopy (a metaphor for designing solutions for pathologists), the digital lightbox (a general metaphor for radiology workstations, particularly for X-ray based image analysis). The further study the use of metaphors in science and in interactive system the following sources are recommended [5, 8, 14, 28].

4 Input Devices

Input and output devices play an essential role for the usability of medical visualization systems. There is a large variety of input and output devices, potentially relevant for medical visualization applications.[3]. We focus here on input devices because there is considerable more experience documented in scientific publications. In the future, however, autostereoscopic displays and mobile devices need to be carefully analyzed with respect to their potential for medical visualization.

[3] The virtual autopsy table with multi-touch input is an inspiring example, see the TED talk: Visualizing the medical data explosion at
http://www.ted.com/talks/anders_ynnerman_visualizing_the_medical_data_explosion.html

Figure 6 Left: A radiology technician performs segmentation and other analysis tasks on medical imaging data. Pen-based input meets her needs for precise, fast and convenient interaction (Courtesy of MeVis Medical Solutions). Right: Specification of resection lines on a 3D model of the facial bones by means of pen and graphics tablet (From: Zachow et al. [52]).

Software systems for medical diagnosis and treatment planning are almost exclusively operated by means of mouse and keyboard. This was reasonable in the past, since only a few different input devices were available and advanced devices have been very expensive. This situation has radically changed with the advent of a large variety of affordable input devices (see [20] for a recent and comprehensive overview).

For intraoperative use, mouse and keyboard are not appropriate, since all devices have to be sterile. As an alternative, gesture input and the use of the Nintendo Wii have been explored [23, 9, 40]. Before we discuss the special situation inside the operating room (Sect. 4.2), it should be mentioned that also for preoperative diagnosis and planning, alternative input devices should be considered. Pen input is promising for tasks where paths are specified manually, e.g. in case of edge-based image segmentation methods, such as LiveWire [13], where the user sketches the contours of anatomic structures. As an example, radiology technicians frequently use a graphics tablet with pen input (see Fig. 6). Similarly, Zachow et al. [52] used pen input and a graphics tablet to precisely specify resection lines. However, there was neither a systematic comparison of input devices for typical medical visualization tasks nor a solid set of recommendations for the selection of input devices.

Function key pads. Often, a few commands are frequently used in diagnostic and radiation treatment planning systems. These commands may, in principle, be invoked with the function keys of the keyboard or other shortcuts. However, this is neither intuitive nor optimal, since for consistency reasons with other software tools, some function keys cannot be used in a very application-specific way. Also, to invoke the keys, the visual focus has to be put on the keyboard. As an alternative, in an airplane cockpit or a car, a gear can be used without visual attention due to its specific shape which allows to use the tactile sense to grasp it. Thus, joysticks or function pads are a promising alternative. For an application in diagnosis of mammography images, a team around Anke Boedicker, MEVIS Breastcare, developed a special function pad where the size and placement of keys are carefully adapted to the frequency of use. In Figure 7, a general and a specific keypad for diagnosis of mammography are shown. It is likely that radiologists and experts in radiation treatment planning benefit from advanced input devices because the increased learning effort pays off for them.

In the future, other input devices and more variants of the existing devices should be considered for medical visualization. In particular, the popular interaction with gestures and touch screens should be considered to provide a convenient user experience. Moreover, the recent introduction of the Kinect-Controller for the Xbox has potential for intraoperative

Figure 7 Left: A general function pad may be used to provide fast access for the most important interactions. Right: A dedicated function pad has been developed and refined in various iterations to provide fast access to frequent commands in a diagnostic system for mammography data. (Right image: Courtesy of MeVisBreastCare)

use since the user may control interfaces just with body movements. Empirical evaluations are needed to compare the usability of different input devices for frequent medical visualization tasks.

4.1 3D Input

Many tasks in medical visualization require the interaction with 3D data. Patient-specific 3D models are rotated, 3D measurements are accomplished [37], 3D models of implants, biopsy needles or catheters are inserted (translation, rotation), the virtual camera is moved inside air-filled structures (virtual endoscopy) or virtual resection areas are specified [52]. Also the segmentation of medical volume data, discussed earlier, is a 3D interaction task, where 3D interaction techniques and 3D input devices are essential, in particular to locally refine an initial segmentation (recall [19]).

4.1.0.1 3D widgets.

To optimally support these 3D interaction tasks, 3D widget design and 3D input devices are essential. 3D widgets provide different handles and thus allow to decompose a 3D transformation ([37] discusses 3D widget design in detail for measurement tasks). Often, it is useful to restrict 3D transformation, e.g. by snapping to edges, vertices or faces, or by integrating a priori knowledge. In medical applications, implant placement is probably the most important application. For the sake of brevity, we cannot discuss 3D widget design in detail, but refer to [44].

4.1.0.2 3D input devices.

All interactions mentioned above may, in principle, be accomplished with a 2D mouse where a 3D transformation is somehow artificially decomposed in orthogonal movements. Six degrees-of-freedom devices, such as 3D Mouse, enable a more natural translation, thus reducing the mental effort.

A 3D mouse may also be used in addition to the 2D mouse to support bimanual interaction. Humans are very effective in coordinated movements of both hands, thus bimanual interaction is very promising. Hinckley et al. developed a successful neurosurgery planning system, where bimanual interaction and physical props were employed [16]. Later, Ritter et al. [41]

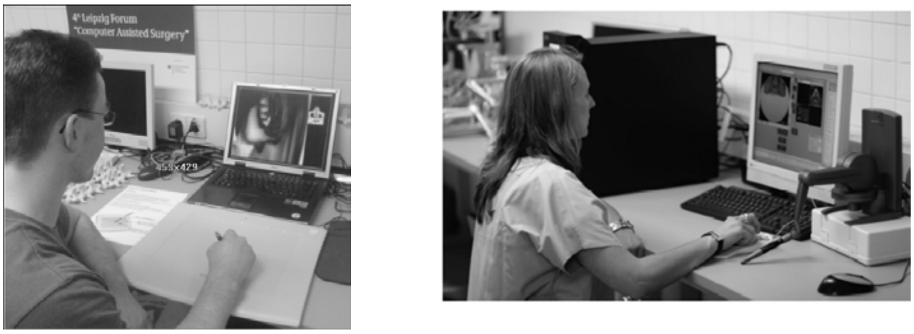

Figure 8 Different input devices such as the graphics tablet with a stylus and the Phantom which provides haptic feedback, graphics tablet with a pen and 3D mouse have been explored for controlling virtual endoscopy in the sinus.

presented an anatomy teaching system, where bimanual interaction was employed successfully as well. As an example, simultaneous rotation and zooming was very effective and satisfying for medical doctors. For virtual endoscopy, a recent investigation of different input devices revealed that after a short learning period, surgeons could track a given path more accurate and faster with a 3D mouse [26]. Haptic input is also essential since it allows the user to better understand complex spatial anatomy such as in the paranasal sinus (Fig. 8).

For the sake of brevity, the area of surgical simulation can only briefly be touched. 3D input devices and haptic feedback are essential in systems to train puncture and needle placement for regional anesthesia or catheter-based interventions. Besides haptic input, usually still with Phantom devices and bimanual control of devices, often complete VR systems are used to provide high degrees of realism (see [49] for a recent example). In particular, if soft tissue structures are involved, elastic deformations play an essential role in surgery simulation. A faithful and efficient realization of this behaviour and its integration in a surgical simulator, is a key aspect.

There is a great need to systematically explore the use of advanced input devices for frequent medical visualization tasks. It might be expected that the use of other input devices give rise to using other interaction techniques. Besides input devices, input techniques also have to be carefully considered. As an example, the transformation of a mouse cursor to a 3D rotation is realized in a strongly different way in popular 3D graphics and visualization toolkits, such as VTK, Open Inventor and 3D Studio. Different usability problems arise in these variants, as a systematic comparison shows [1].

4.2 Interaction Techniques for Intraoperative Use

Time-consuming planning of surgical interventions is primarily accomplished in case of complex and severe surgical interventions, e.g. when rare anatomic variants occur or surgery close to vital risk structures is necessary. In these situations, it is often necessary to compare the intraoperative situation with the preoperative plan, to rehearse preoperative planning or to adapt the plan due to new findings, such as an additional metastasis. Meeting these requirements is challenging in different ways. Accurate navigation systems are needed, intraoperative data has to be precisely registered to the patient, registration has to be updated fast and reliably when the anatomic situation changes, e.g. due to brain shift or soft tissue deformation. Computer-assisted surgery research is focussed on these algorithmic challenges [35]. With respect to the user interface, an important question is the selection

Figure 9 During a navigated intervention of the paranasal sinus the surgeon has to shift his attention from the patient to the endoscopic monitor which presents the images from inside the patient. When he operates close to critical structures he has to focus on the monitor of the navigation system which indicates the instrument position in relation to preoperatively acquired CT data.

and placement of a proper display in an operating room which is already heavily overloaded with various equipment, e.g. from anesthesia. Challenging ergonomic issues arise, e.g. when endoscopic surgery is performed and the monitor has to be placed such that it is not too distracting to look at it during surgery [18]. Even more challenging is the choice of a display solution when a navigation system is used, since an additional monitor has to be carefully placed (see Fig. 9). Visualizations used in these settings have to be carefully adapted to this situation, e.g. by avoiding a too dense display of information. The user has to operate software intraoperatively meeting the requirements of sterility. Voice control has been extensively studied but seems not promising, amongst others, because the environment is noisy. More promising is gesture input, which is a research focus in various groups. Ritter et al. [40] use the Wii interface to operate 3D visualizations (see Fig. 10), whereas [9] employed gestures to operate a touch screen. All of these solutions are based on intensive clinical cooperations, with extensive observations in operating rooms and are now in a state where first trials in realistic settings showed the feasibility.

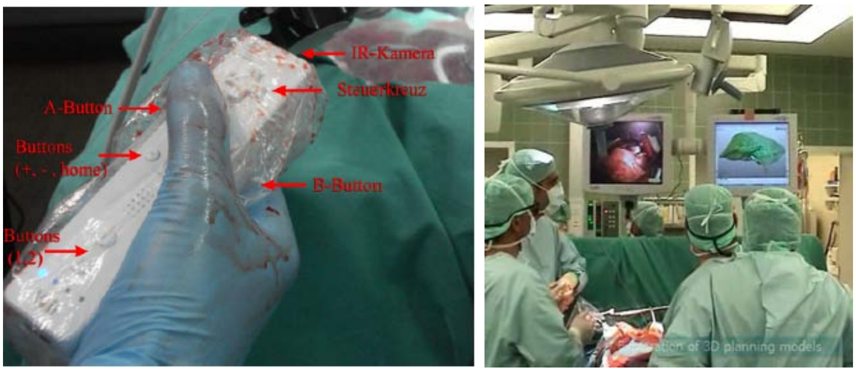

Figure 10 Nintendo's Wiimote is used under sterile conditions in the operating room to perform simple gesture-based interactions with the 3D model derived in the planning stage. (From: [40])

5 Evaluation

HCI researchers make a basic distinction between *formative* and *summative* evaluations. Formative evaluations are carried out during the development based on prototypes and serve to initiate discussions to receive feedback for guiding the further development. Summative evaluations characterize the final system with respect to ease of use, ease of learning and other usability factors. At most minor problems may be addressed in this late stage. For medical visualizations, both kinds of evaluations are essential. Formative evaluations usually take less effort, they are accomplished with a few users in an informal way. Preparation includes the selection of tasks to focus the evaluation and to carefully think about questions to be answered, including more open questions that stimulate discussions. In early stages, sketches and mockups may be used. Ongoing continuous formative evaluation is essential for research projects where many aspects are not clear and a large design space is explored. Again, [7] gives many convincing examples. One general recommendation is to let users compare alternatives. Users are more critical and discuss much more intensively if they may select between a few alternatives instead of having to comment on the only one solution presented to them.

The "think aloud" technique, like in early task analysis, is helpful. Logging protocols which represent the actions taken by the user are often an invaluable help. Eye-tracking may be a useful ingredient, e.g. to compare visualization techniques with respect to their effect on viewing patterns. However, for most solutions it is not necessary and the interpretation of eye-tracking results is quite challenging.

Summative evaluation often aims at a statistic analysis with a larger number of participants. Many aspects of such an evaluation need to be carefully considered, such as the selection of test persons, the specific questionaire design and the statistical methods used for evaluation. Such summative evaluations have rarely been accomplished in medical visualization. The few such evaluations were web-based questionaires and–as a trade-off-between the number of test persons and their suitability–often not only medical doctors were included.

As a consequence, more insights usually result from formative or informal summative evaluations where a few users are carefully observed and interrogated. In medical visualization, typical tasks include the description of the morphology and spatial surrounding of a pathology, its classification and the assessment of its operability. How long medical doctors need for their decision, how secure they are and whether their assessment is actually correct, are among the aspects which might be explored. Readers interested in evaluation of medical visualization systems should consider the general thoughts on user studies in visualization by Kosara et al. [24] as well as the insight-based evaluation by Saraiya et al. [43]. Ideally, medical visualization systems are evaluated with medical doctors not only as passive sources of information but instead as those who guide the evaluation towards relevant medical problems. Among the few examples of such evaluations are [29] who investigated advanced 3D liver surgery planning and [15], who evaluated virtual endoscopy solutions for surgery planning.

6 Concluding Remarks

The development of visualization systems for clinical medicine requires in-depth analysis of interventions, equipment, usage scenarios and user characteristics. The design of new solutions should comprise a substantial prototyping stage where variants of visualizations, view arrangements and interactions are discussed early and correspondingly refined. The scope of input devices should be carefully considered. This includes a combination of devices

Figure 11 Mobile use of medical image data based on wireless internet connectivity is a huge benefit for the doctor and the patient. (Courtesy of Claus Knapheide, SIEMENS Healthcare)

which may be used bimanually. Graphical user interface design is also an important issue even in research settings. Medical doctors, like many others, expect easy to use and attractive user interfaces, which are perceived as engaging and motivating. Visualization researchers usually do not have an appropriate qualification for all tasks mentioned above. Therefore, cooperations with HCI researchers and practitioners are highly recommended. People with a background in psychology, visual design and user interface programming may be part of interdisciplinary teams to progress medical visualization in a user-centered way. Although this article is focussed on medical applications, it is likely that for advancing other highly specialized professions, such as those in engineering or natural sciences, a similar strategy is needed to improve the impact of medical visualization.

With respect to foreseeable future developments it is very likely that mobile devices in connection with wireless LAN and multitouch input plays an essential role. Leading manufacturers, such as BrainLab, Medtronic, and SIEMENS, already provide systems tailored for use with the Apple iPad (see Fig. 11). These systems enable the selection of cases and image data, zooming in selected data and specifying measurements. In particular, the ability to access medical image and other patient data at the bed of the patient and to enter additional information in digital form is highly welcome by medical doctors. Moreover, the fluent interaction provided by gesture- and touch-based interfaces is considered very attractive by a large majority of them.

There are more HCI-relevant topics to be included in future medical visualization systems (see [47] for an excellent introduction in HCI). An important aspect is whether medical doctors trust the visualizations and analysis results presented to them. In other security-relevant areas, such as aviation, a *level of trust* is determined in order to evaluate this aspect. First attempts to apply these principles to computer-assisted surgery are described in [48]. Finally, treatment decisions in severe cases, such as cancer, are often cooperative decisions where doctors from different disciplines are involved. An open question relates to the optimal support in terms of input devices, displays, visualization and interaction techniques.

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