Chapter e20

Visual Computing for ENT Surgery Planning

20.1 INTRODUCTION

In this chapter, we will explain how general strategies for computer-assisted surgery are adapted, implemented, and employed to meet the needs of ENT surgery (ear, nose, throat). This special surgical discipline is characterized by a high level of technical support. The very first computer-assisted surgical assistance systems were developed in this area [Klimek et al., 1993]. Also, advanced early surgical simulators were realized for ENT surgery [Edmond et al., 1997, Weghorst et al., 1998].

The high density of crucial anatomical structures in the ear, nose, and throat makes surgery highly demanding. Accuracy is often essential, e.g., in implanting hearing aids, and esthetic considerations are often relevant. On the other hand, anatomical structures are relatively fixed and do not exhibit large displacements of tissue in surgery. This makes ENT surgery an ideal goal for computer-assistance. In ENT surgery, computer-assistance was focused for a long time on intraoperative navigation [Koele et al., 2002]. In this chapter, we focus instead on 3D visualizations used for surgical planning and interdisciplinary treatment discussions in ENT surgery. First attempts were made in the 1990s [Moharir et al., 1998], but only recently systems were developed that go beyond the prototype stage.

Organization We start with virtual endoscopy solutions for planning and training functional endoscopic sinus surgery (§ 20.2). This intervention is performed in the nasal region if patients suffer from sinusitis. Although this type of surgery is often a rather simple procedure that does not require advanced planning, it becomes risky in case of extended sinusitis when surgery needs to be performed close to the skull base or close to the optical nerve. In § 20.3, we discuss surgery in the filigrane ear region where implants and hearing aids are inserted in order to improve hearing. Implant selection and placement are essential aspects of this kind of surgery. The largest part of the chapter is devoted to the removal of tumors in the neck region, e.g., neck dissections where surgeons are interested in a detailed inspection of the spatial relations around primary tumors and metastases. We introduce neck dissection in § 20.4 and go on with discussing image analysis and interactive visualization for neck surgery planning (§ 20.5 and 20.6). The computer support in all three areas is primarily based on high resolution CT data. In addition, color images and palpatory findings from fiber endoscopy are employed.

Although we discuss specific problems and possible solutions, the reader is encouraged to think about transferring these experiences to other surgical disciplines. Virtual endoscopy of the sinus region is representative for intervention support in other anatomical regions. Likewise, neck surgery planning has many similarities in both requirements and viable solutions with other kinds of tumor surgery.

20.2 PLANNING AND TRAINING ENDOSCOPIC SINUS SURGERY 20.2.1 MEDICAL BACKGROUND

Sinus surgery is applied if patients suffer from chronic sinusitis—mucosal swellings that hamper ventilation. Figure e20.1 illustrates the target anatomy. Mucosal swellings may occur in all four paranasal sinuses, in severe cases even simultaneously. This state is called pansinusitis and obviously requires a comprehensive surgery. Since the 1980s, surgery is performed via an endoscope and with special instruments suitable for the small space. This procedure is called functional endoscopic sinus surgery (FESS) [Lloyd, 1989].

The ethmoid air cells and the sinus ostia are opened to restore the ventilation. This minimally-invasive approach does not only lead to faster recovery but is also clearly preferred over open surgery from an esthetical point of view. Minimally-invasive procedures, however, are challenging for the surgeon, since the direct visual access to the situs is missing. Instead, the situs is displayed at an endoscopic monitor. The surgeon uses a couple of anatomical landmarks, such as the middle turbinate and the uncinate process, for orientation. These landmarks, however, are missing when the disease comes back and relapse surgery is required. In these cases, the orientation is particularly difficult. In case of younger patients (12–14 years), the question arises whether the meatus (the airways) are large enough to move the endoscope through. If mucosal swellings close to the orbita, the optical nerve, or the skull base need to be removed, the operation is risky and intraoperative navigation support is desirable (§ 18.5). The most challenging situation occurs in case of malignant tumors where complete removal is essential (in case of benign mucosal swellings, a small remaining portion is acceptable if a severe risk to other structures can thus be avoided).

Preoperatively, a virtual endoscopy through the sinus may help to make the surgeon familiar with the patient's individual anatomy and to preview the actual surgery. Thus, virtual endoscopy may be part of the planning procedure but can also be considered as a training tool. The value of virtual endoscopy is determined by the amount of realism and by the insights it provides, e.g., the ability to see hidden structures along with obscuring structures. Color, texture, and wetness effects are essential ingredients of visual realism. For training purposes, where residents train the use of the endoscope and learn instrument-tissue interactions, realistic haptic feedback is essential as well [Pössneck et al., 2005].



FIGURE e20.1 Relevant anatomical structure of the sinuses (frontal and lateral view). Red: Sinus maxillaris, Yellow: Sinus sphenoidalis, Blue: Sinus frontalis, Green: Sinus ethmoidalis (From: [Krüger et al., 2008]).

20.2.2 VIRTUAL ENDOSCOPY FOR SINUS SURGERY

Virtual endoscopy (recall Chap. 13) requires CT data with high spatial resolution. Similar to other application areas, virtual endoscopy in the nasal cavity became viable with the advent of spiral and multislice CT data [Han et al., 2000]. The first virtual endoscopy system for the sinus anatomy was presented by DeNicola et al. [1997] using the ADVANTAGE NAVIGATOR from GE Medical Systems. The target anatomy must be segmented and a path for a fly-through must be computed and should be used as a basis for guided navigation (recall Chap. 13, where these steps were discussed in detail). Virtual endoscopy may be considered as:

- a diagnostic tool and thus as an alternative to fiber endoscopy,
- a planning tool for surgeons to evaluate risks and the feasibility of surgery in case of obstructed or stenotic nasal meatus,
- a training tool for residents to enable them to practice with virtual models, and
- a tool for patient consult, before endoscopic sinus surgery to explain them the procedure and the associated risk in a descriptive way.

As a diagnostic tool, virtual endoscopy is useful and has the advantage that it can be performed as a postprocessing step without the patient and without local anesthesia. Septum deviation and perforation and meatal obstruction are clearly seen. However, as Han et al. [2000] already pointed out, mucosal surface and secretions are hardly visible. On the other hand, virtual endoscopy might deliver additional information compared to fiber endoscopy in case of a very narrow nasal meatus.

Virtual endoscopy is useful as a planning tool if it is able to present the anatomy of the patient precisely and realistically, thus simulating the actual intervention. This requires to consider similar projection, e.g., a 45° or a 70° wide angle projection is frequently used. It is also desirable that the appearance of anatomical structures is similar to their appearance in the real world. Thus, colors and textures indicating a wetness effect for mucosa, for example, should be employed.

The use of virtual endoscopy for training and patient consult raises similar requirements: realism and simple interaction are essential. For training, haptic feedback and tissue deformation are essential additions not necessary for planning. On the other hand, training does not require patient-specific data.

20.2.3 THE SINUS ENDOSCOPY SYSTEM

In the following, we focus on the planning scenario and describe the development and evaluation of a the SINUS ENDOSCOPY that is focused on the requirements of FESS system [Krüger et al., 2008, Strauß et al., 2009]. The system employs high resolution spiral CT data (slice distance: 1.0 mm) to enable a faithful presentation of the anatomy. This results in 100–250 slices and with an in-plane resolution of 512 × 512 pixels to an overall data volume of 50–125 MByte. Pathologies include mucosal swellings, tumor, and polyps of different sizes. We discuss the requirements, the visualization options, the user interface, and a few planning components that are beyond pure visualization of the target anatomy.

Requirements Virtual endoscopy will be employed to assess anatomical variants and pathologies. The nasal sinuses comprise both large hollow shapes and fine labyrinths—both should be accessed with virtual endoscopy. Even small passages due to swollen or pathological structures should be accessible. A high accuracy of the visual representation is essential. Discussions with ENT surgeons lead to the following requirements:

- The preparation time should be less than 2 minutes.
- The system should be flexible to adjust to different hardware setups.

- Planning components, such as drawing on top of the anatomy and measurements, should be included.
- Virtual endoscopy should support archiving.

The first requirement clearly excludes any solutions that require the segmentation of the target anatomy. Instead, volume rendering with appropriate transfer functions is the only viable solution. The second requirement means that the system should be developed and tested with different hardware setups and the rendering quality should adapt to the performance of the underlying hardware—leading to fast update times even at slower computers. The third requirement states that the system should not only provide high-quality and fast rendering of the target anatomy. In addition, specific treatment planning questions should be directly supported. The most essential aspect is to enable surgeons to draw on the anatomy in an intuitive way to specify where to cut. This information should also be stored and thus be useful for documentation or discussion with a colleague according to the final requirement. In addition, there should be support for creating and storing snapshots and animations.

Visual realism and performance The size of clinical datasets (≤ 125 MBytes) enables to load them completely onto modern graphic cards for rather less complex models. The raycasting system consequently uses the graphics hardware. Semi-transparent volume rendering is provided, since the binary decision related to isosurface rendering seems not appropriate. Also, the filigrane anatomy of the nasal labyrinth would require a very large triangle mesh to represent the anatomy faithfully. Illumination, depth attenuation (fog effects), and other depth cues via texturing of the tissue surrounding the sinuses are provided, since they clearly enhance the shape recognition. Textures are based on digital photos and should resemble human skin. Other shading effects, such as wetness and the secretion level inside the nose, are provided to display the target anatomy in a familiar way by simulating the appearance from real endoscopy. An added lens distortion is also included to exploit the familiarity with fiber endoscopy.¹ They are incorporated as default settings, if a powerful graphics card is available. Otherwise, as default value they are disabled to avoid slow performance. Figure e20.2 illustrates the different appearance depending on the available graphics hardware. Better rendering quality on low-end systems is feasible in case the camera is not moved. Thus, in this situation the lowresolution image is automatically replaced by an image in better quality. First pass rendering and empty space skipping are used (recall § 13.4). Aliasing artifacts are avoided with interleaved sampling (the GPU realization of Scharsach et al. [2006] was employed).

Segmentation, and thus the integration of polygonal meshes representing segmented objects was not considered essential due to the inherent time constraints. However, a component to fuse volume data with polygonal meshes was integrated in the virtual endoscopy renderer for selected cases where additional preparation may be justified. The "Look behind the wall" effect when, e.g., segmented pathologies are visible behind walls, is the major benefit that is only possible with appropriate segmentation.

User Interface The virtual endoscopy system has two user interface components:

- the graphical user interface (GUI) that enables to adjust various parameters of the rendering, the layout of different viewing components and further options, and
- the control of the virtual camera.

GUI Components The GUI was designed to limit the necessary space and to leave the largest part of the screen for virtual endoscopy and related views. Moreover, the GUI components should not be spread over the screen, but be visually focused. Thus, they were integrated in one vertical column to be placed on the

¹ Users employed 45° and 0° fiber endoscopy.



FIGURE e20.2 Left: The viewport resolution is reduced, illumination and wetness effects are disabled to provide a fast rendering on cheap early graphics cards. Right: Rendering in full resolution with high quality on more recent and powerful graphics cards (From: [Krüger et al., 2008]).

left. The user interface for viewing fiber endoscopy at an appropriate monitor served as orientation—it has a moderate complexity and consists primarily of sliders, e.g., for contrast and brightness. Sliders enable fast numerical input with moderate accuracy.

The initial GUI incorporated all widgets necessary for a fine-grained control of rendering parameters. While this design was useful for development and testing, it was too complex for regular use. Thus, the most essential development in the GUI was reduction of functions by either omitting some functions or summarizing them at a higher level. The most notable example was the number of sliders for the control of rendering options that could be reduced from 13 to 5.

Camera Control The camera is moved manually and can be placed with a pointing device or be incrementally moved with appropriate buttons. Zooming and panning are essential features that are integrated as well. The current camera position is indicated as a crosshair in axial slice views—a standard technique to enable that the user relates the endoscopic view to the underlying slice images (see Fig. e20.3).

While realistic tissue deformation is not essential, collision detection was provided, since the user looses orientation if he or she moves through the walls. Approximate computations leading to fast but conservative results should be preferred instead of slow accurate distance measurements (recall § 10.4, where distance computation was discussed).

Integration of Planning Components The user can draw on the tissue surface, e.g., to mark where he has to cut in surgery or to discuss with colleagues or residents. Two tools are provided for painting: a small pen for marking outlines and a brush for roughly defining regions that appear as hatching. The painting on the 2D viewport plane has to be projected on the (closest) anatomical structure and has to be stored along with it (Fig. e20.4). In addition, distance measurements are supported, since they enable to estimate whether nasal airways are wide enough to insert a fiber endoscope.

20.2.4 EVALUATION AND CLINICAL USE

Informal Evaluations During the development, several informal evaluations and interviews were performed. As an example, we observed an ENT surgeon using the system for planning an actual intervention. He appreciated the similarity to intraoperative views and the usability. The surgeon optimized visualization parameters like transfer function setting, texturing attributes, and the visibility of secretion. The



FIGURE e20.3 Three orthogonal slice views and the endoscopic 3D view are combined in the SINUS ENDOSCOPY system. The crosshair cursor in the slice views indicates the camera position (From: [Krüger et al., 2008]).

SINUS ENDOSCOPY system was also demonstrated at a workshop with European ENT surgeons. There, it was employed with cadaver datasets. The cadavers could also be operated and investigated parallel with real endoscopes and instruments. The surgeons considered the clear visualization of the Rec. frontalis or the Concha nasalis medialis as essential. Such informal and formative evaluations were useful to detect minor problems. However, for assessing the usefulness of the whole system, a more comprehensive and larger study was conducted.

Systematic Evaluation The large scale evaluation of the SINUS ENDOSCOPY system was performed between 2007 and 2008 at two hospitals in Leipzig. In total, virtual endoscopy was performed in 125 patients in addition to fiber endoscopy. The system was employed by five experienced ENT surgeons. The SINUS ENDOSCOPY system was used for both surgical planning and patient consult. Eighty nine questionnaires from surgeons and 114 from patients were filled (see [Strauß et al., 2009] for more details).

Feedback from Surgeons Surgeons reported a better understanding of the patient individual anatomy and of the planned intervention compared to the traditional planning with 2D slices. The investigation of the Rec. frontalis benefits from the system due to the highly individual anatomy of this structure. The similarity between the preoperative virtual endoscopy and the real anatomy in the intervention was assessed on a 5-point Likert scale (1 represents identical visualizations and 5 no correspondence between them). An average score of 2.21 confirms a good correspondence. However, the ability to adjust the transfer function was considered as both an advantage and a limitation. On the one hand, the visualization could thus be adapted to the dataset. On the other hand, the actual appearance was considered somehow arbitrary, since the extent of visible swellings could thus be manipulated.



FIGURE e20.4 A snapshot of the drawn image is stored into a projection atlas texture, along with the tissue depth. By transforming the tissue position with the snapshot's view-projection matrix, texture coordinates are generated for the lookup (From: [Krüger et al., 2008]).

The surgeons welcomed the real-time behavior of the system combined with an extraordinary visual quality. On the other hand, they questioned the texturing, since it is globally applied, thus also to structures that look different in nature. This raises a fundamental concern: high visual quality including realistic texturing is essential. On the other hand, CT data as the only input does not provide sufficient information for discriminating structures and differentiating textures appropriately.

ENT surgeons also welcomed the functionality provided to maneuver through the nasal sinuses and considered them superior compared to fiber endoscopy. At the same time, and probably based on these powerful functions, they sometimes felt lost and—without proper points to reset—they started the whole navigation again from the very beginning. This clearly shows that users need simple functions to save and name views (camera position, orientation, and optionally lens distortion) in order to reuse these points later.

With respect to regular clinical use, not only the quality of virtual endoscopy as a planning tool is essential but also whether virtual endoscopy may replace fiber endoscopy as a diagnostic tool. A clear advantage with respect to reduced effort and more patient comfort is only possible if fiber endoscopy can be omitted. This, however, is not the case [Strauß et al., 2009]. Asked, whether they can renounce fiber endoscopy and rely on virtual endoscopy only, they answered "I disagree" or even "I strongly disagree"—the two negative choices available. To some extent, this subjective statement may be a matter of familiarization, but certainly the quality of virtual endoscopy with respect to diagnosis needs to be increased.

Feedback from patients The 114 questionnaires filled by patients reported almost exclusively encouraging and positive results. Patients could better understand the anatomical situation and the pathologies compared to views from fiber endoscopy presented to them. They also felt that the surgeons were better prepared based on virtual endoscopy.

Hints for Further Development A couple of ideas for future developments were uttered. Tissue deformation was desired to enable a better visualization of some structures, e.g., the bottom of the tongue. A combination with planning navigated surgery was desired. The major component of such an integration would be a flexible tool to specify the working space for surgery that can later be supervised with a NAVIGATED CONTROL system [Hofer et al., 2006]. However, since such navigation systems are not widespread and diverse, this connection is not a major "selling argument."

20.3 VISUAL COMPUTING FOR INNER AND MIDDLE EAR SURGERY

20.3.1 MEDICAL BACKGROUND

Severe hearing impairment is an important chronic disease and since hearing loss is often age-related more and more people are affected. There are various kinds of hearing impairments that determine the appropriate treatment [Gerber, 2013]:

- conductive hearing loss. Sound does not reach the inner ear, e.g., due to an interruption of the ossicular chain. Often malfunction of cochlear hair cells cause malfunction of the cochlear amplifier [Dammann et al., 2001].
- sensorineural hearing loss. The information transmission through the auditory nerve to the brain is impaired, e.g., due to infection or trauma.
- combined hearing loss. Conductive and sensorineural hearing loss occur simultaneously.

In addition to the patient's anatomy, the residual hearing ability has to be considered and maintained leading to a complex planning process.

Diagnostic Imaging Due to the fine anatomy, imaging with a high spatial resolution is accomplished. CT data that cover a small area but deliver submillimeter accuracy is used for diagnosis and treatment planning. A resolution of $0.1 \times 0.1 \times 0.1$ mm is currently feasible and widely used. This special kind of CT data is referred to as HR (High Resolution)-CT data. Figure e20.5 gives an overview of the relevant anatomy.

20.3.2 ACTIVE AND PASSIVE IMPLANTS

In severe cases, conventional (non-implantable) hearing aids are not able to sufficiently compensate for hearing loss. In particular, conductive hearing loss often require implantable hearing aids and thus a complex surgical intervention where a sufficiently large cavity in the temporal bone needs to be generated. Advanced surgical planning and intraoperative guidance primarily aims at reducing the need for such a large cavity.



FIGURE e20.5 Anatomy of the ear and its representation in HRCT data of the petrous bone region. (1) Auditory canal, (2) tympanic membrane, (3) tympanic cavity, (4) malleus, (5) anvil, (6) stapes, (7) cochlea, (8) arcade, and (9) auditory nerve (From: [Dornheim et al., 2008a]).

Implants may be passive, that is they just bridge over a gap in the ossicle chain or active meaning that they consist of multiple components, i.e., a microphone, a sound processing unit amplifier and a battery [Gerber, 2013]. The most important active implant is the cochlear implant that is implanted in the inner ear. Some active implants are placed in the skull base, e.g., the bone bridge. The bone bridge consists of an external audio processor, that is worn under the hair and an implant placed under the skin [Achena et al., 2012].

For treating hearing impairment in the middle ear, there are active and passive implants that bypass the outer ear and stimulate the ossicle chain directly. We will later show examples, where total ossicular replacement prosthesis (TORP) and partial ossicular replacement prosthesis (PORP) implants are used.

20.3.3 PREOPERATIVE PLANNING

The inner and middle ear represent the most complex and finest anatomy in the ENT domain. It is also strongly variable and fitting of hearing aids has to be carefully prepared for the patient-specific anatomy. Surgery in this area is accomplished to preserve or restore the sense of balance and hearing capabilities. Accurate preoperative planning may improve preoperative decisions and enable precise realization of surgery, e.g., supported by navigation systems or even robots [Bell et al., 2012]. Simple 3D visualizations, such as threshold-based isosurfaces and direct volume rendering are not appropriate to represent and explore the fine anatomy faithfully. Nevertheless they improve anatomic understanding compared to 2D slices only. Tomandl et al. [2000] and Yoo et al. [2000] discussed how volume rendering can be fine-tuned to explore the ear anatomy. A "clear and realistic depiction of the anatomical structures and medical devices is required." [Dammann et al., 2001]. This requirement can only be met based on an explicit segmentation of the target structures, as will be discussed in the following.

Surgery in the inner and middle ear, similar to sinus surgery, often occurs close to the N. facialis and, similar to neck surgery, close to the A. carotis. Middle ear surgery serves to implant hearing aids in case the ossicle chain exhibits a gap or unfunctional parts that need replacement. Access planning and implant placement are major tasks and thus similar to, e.g., some orthopedic interventions. Surgery is performed with an operation microscope. Three types of implants are currently used:

- A Partial Ossicular Replacement Prosthesis (PORP) replaces malleus and anvil.
- Total Ossicular Replacement Prosthesis (TORP) replaces all three ossicles. From the stapes only the elliptical base plate is preserved.
- Stapes prostheses replace the stapes. They are inserted between the anvil and the stapes base plate.

These kinds of prostheses are available in different length and geometry. All three kinds of prostheses need to transmit oscillations. Thus, after being inserted, they should not touch the tympanic cavity. They are fixed at both ends but should not hurt the tympanic membrane in turn. For the stability of the prosthesis and an unaltered transmission of sound, the angle between the prostheses and its adjacent structures is also essential [Bance et al., 2004]. It is very difficult to extract enough information from CT slice views to preoperatively select implants of a proper size. Thus, this decision is currently taken intraoperatively. In the following, we describe concepts for supporting such planning procedures by appropriate 3D visualizations. Moreover, we briefly discuss further support by biophysical simulations that attempts to predict the hearing ability.

20.3.4 VISUAL EXPLORATION OF THE INNER AND MIDDLE EAR ANATOMY

Visual Exploration of the Inner Ear Anatomy The inner ear anatomy is crucial for a variety of hearing-aids implants. It should be displayed along with the geometric models of the necessary medical devices, e.g., transducer, microphone, and other implantable parts. Geometric surface models of the temporal bone, including the mastoid cavity and the implant should be presented along with interaction facilities that enable an interactive fitting. Such a tool was pioneered by Dammann et al. [2001] where rather simple but robust segmentation techniques from a commercial tool were employed and used to generate surface visualizations of implants and anatomical structures. Later, the same group came up with a more streamlined surface model generation [Salah et al., 2006].

Visual Exploration of the Middle Ear Anatomy The middle ear anatomy is essential for middle ear surgery as well as access for neurosurgery. The complex anatomy is very hard to understand from pure cross-sectional images, in particular in case of severe pathologies [Rodt et al., 2002]. A careful combination of 3D visualizations with 2D slice views, e.g., where some slices are incorporated as reference in a 3D visualization may support the mental reconstruction of the patient anatomy.

While for neurosurgical planning, transfer function-based volume rendering is appropriate, the small anatomical details of the ossicle chain cannot be presented in sufficient detail for implant planning. This is due to the notorious partial volume effects in small structures. Thus, Seemann et al. [1999] suggested hybrid rendering where volume rendering of the anatomical context is complemented by surface rendering of the segmented target anatomy. Segmentation of the skeletal structures is possible, in principal, with thresholding. Dornheim et al. [2008a] used a rough initial contour and applied a threshold of 700 HU to identify skeletal structures. Substantial post-processing is necessary to separate the individual bones and to represent surface details precisely enough. The cochlea inside the inner ear can also be segmented based on a threshold (-800 HU). The tympanic membrane is difficult to segment. In [Dornheim et al., 2008a] this step was performed manually. The auditory canal, however, can be segmented reliably with region growing. Figure e20.6 illustrates some visualizations based on these segmentations. Such visualizations form the basis for a geometry-oriented planning process that considers the access and size of the tympanic cavity. In Figure e20.7 the middle ear anatomy along with PORP and TORP is shown. For a real planning system, advanced support for this virtual placement is required (recall § 5.6.3).



FIGURE e20.6 3D visualizations of the middle ear anatomy. The tympanic cavity is rendered semitransparently as context for the skeletal structures of the inner ear. The inner ear anatomy (stapes, malleus, incus) are shown as opaque surface rendering (From: [Dornheim et al., 2008a]).



FIGURE e20.7 Visualization of the middle ear anatomy along with a TORP (left) and a PORP (right) (From: [Dornheim et al., 2008a]).

20.3.5 IMPLANTING A DIRECT ACOUSTIC COCHLEA STIMULATOR

Gerber et al. [2012] described the planning process for the implantation of the Direct Acoustic Cochlea Stimulator, a hearing aid that requires direct access to the middle ear. The drilling of the mastoid bone cavity (diameter 2–3 cm) needs to be planned and the risk, e.g., with respect to the distance to the facial nerve has to be considered (see Fig. e20.8). The mastoid bone is roughly segmented with a combination of thresholding and selection of an ROI. The facial nerve is roughly marked in the slices to define a curved planar reformation that is a suitable basis for a more elaborate segmentation. However, due to the small size of that nerve, it is not clearly recognizable in all slices and the segmentation thus exhibits some uncertainty.

Later, he used this planning system and extended it toward intraoperative guidance. With a strongly improved patient-to-image registration, their system is able to provide guidance information with the high accuracy and reliability that is essential for clinical use [Gerber, 2013]. It is interesting that the author found an increased need for preoperative planning based on the availability of improved intraoperative guidance.

20.3.6 VIRTUAL OTOSCOPY

In addition to interactive 3D visualization from an outside point of view, endoscopic viewing was considered useful to better assess abnormalities of the ossicle chain [Himi et al., 2000, Kikinis et al., 1996b]. Middle ear surgery poses a variety of requirements which are similar to sinus surgery. Again, a complex



FIGURE e20.8 Left: The drilling trajectory is planned along with the ear anatomy. It is also quantitatively analyzed, e.g., with respect to distances to the facial nerve and the external auditory canal. **Right:** The whole implant geometry is shown and may be interactively changed, e.g., prosthesis length and orientation (Courtesy of Nikolas Gerber, University of Bern).



FIGURE e20.9 Virtual endoscopy of the inner ear that is not accessible with a real fiberendoscope. The combination of a slice view and the endoscopic 3D view provides useful information (From: [Krüger et al., 2008]).

bony anatomy has to be represented. Wetness of tissue and secretion are again essential aspects. The special kind of endoscopy that deals with the investigation of the middle ear is referred to as virtual otoscopy. This term is related to otoscopy—the investigation of the middle ear with a microscope. As Rodt et al. [2004] pointed out, virtual otoscopy is also valuable to assess postoperative success, evaluating, e.g., the course of electrodes and the correct placement of a hearing aid.

During a workshop with ENT surgeons, virtual endoscopy of the ear with an adapted version of the SINUS ENDOSCOPY system was presented. In order to evaluate whether SINUS ENDOSCOPY is also applicable for this application area, we generated virtual endoscopy views for two cases. Therefore, the two HRCT datasets were loaded, and besides the reduction of the secretion value nearly to zero, no parameter adjustments had to be performed (see Fig. e20.9). The feedback of the surgeons was also positive with respect to the recognizability of structures. With real endoscopy it would not be possible to prepare an operation, due to the invasive nature of this task.

Standardized Endoscopic Views Rodt et al. [2002] discussed not only thresholds for generating endoscopic fly throughs but also a set of six viewpoints based on anatomical landmarks that should be employed to explore endoscopic views in a reproducible manner. These six viewpoints serve to systematically search for pathologies and to compare pathological situations with normal ones. Moreover, such a standardization facilitates a structured report of an endoscopic examination.

20.3.7 BIOPHYSICAL SIMULATION

For implant planning and placement it is desirable to predict the hearing ability and to compare various options to come up with an optimal strategy. Hearing abilities are characterized by a audibility curve that depicts the hearing level (in decibel) over the frequency (20–20,000 Hz). The hearing loss is often not uniform but varies significantly over the frequency range and the output of simulations is an audible curve and not just one average hearing level.

Therefore, biophysical simulations were carried out [Beer et al., 1999] and experimentally validated. As has been discussed in Chapter 19, simulations require accurate and smooth models with a good triangle quality. For performance reasons, the polygonal meshes should be carefully reduced. For an FEM simulation, the tympanic cavity as well as its transitions to adjacent structures, such as ligaments, muscles and tendons, and the internal structures need to be described as a set of volume elements, e.g., a set of tetrahedra. These volume elements are derived from an appropriate surface representation, e.g., a triangle mesh with good triangle quality. Figure e20.10 presents such surface models. The remeshing step to improve the triangle quality increased the minimum inner angle from 0.18° to 18.17° and thus the triangle quality from 0.11% to 28.41%. Biophysical simulation require also mechanical parameters like the elasticity of all the components and the thickness of the tympanic membrane [Decraemer et al., 2003].

20.4 NECK SURGERY PLANNING

The treatment of patients with head and neck cancer is challenging, since there is a growing number of treatment options, including various chemotherapies, radiation treatment and surgical removal (neck dissection). These treatment options may also be combined, e.g., a chemotherapy is applied to first downsize the tumor to make it resectable at all or to enable a more gentle strategy.



FIGURE e20.10 A surface model of the relevant anatomy (left, 110 K triangles) was simplified with error control (16 K triangles) and subsequent remeshing to improve the triangle quality (23 K triangles) (Courtesy of Stefan Zachow, Zuse Institute Berlin).

Neck dissection is a demanding procedure, where enlarged and potentially malignant lymph nodes have to be removed. The difficulty of the procedure is due to the complex anatomical relations in the neck region: muscles, nerves and various crucial vascular structures are very close to each other. Preoperatively, surgeons have to decide if a surgical intervention is adequate and whether or not a gentle strategy, preserving most anatomical structures, is feasible. Computer support for this intervention has to consider the following questions:

- Are there critically enlarged lymph nodes?
- Where are they located in relation to risk structures, e.g., major blood vessels?
- Do they even infiltrate these structures?

To answer these questions, all relevant anatomical structures, e.g., vascular structures, nerves, and muscles, have to be selectively visualized. Due to the sometimes low contrast to surrounding tissues, this is only feasible, if they are explicitly segmented. The segmentation information is also used for a quantitative analysis. Moreover, dedicated visualization techniques are necessary to analyze the spatial relations around selected lymph nodes.

Project Background To develop image analysis and visualization algorithms and to integrate them into a dedicated software assistant for the above-mentioned and related questions was the goal of two sequential national research projects starting in 2004 and lasting 5 years in total.² Research was focused on automatic segmentation of relevant structures, e.g., lymph nodes [Dornheim *et al.*, 2006b] and blood vessels [Dornheim *et al.*, 2008b] and advanced visualization of these structures, e.g., by cutaway views for emphasizing lymph nodes [Krüger *et al.*, 2005] and careful combinations of slice-based and 3D visualizations [Tietjen *et al.*, 2006]. In visualization, we first attempted to display as many anatomical structures as possible simultaneously, using, e.g., silhouettes and opacity mapping to support shape and depth perception. Later, it became obvious that the resulting visualizations are too complex. Intraoperative visualization was not tackled, since, in general, open surgery has lower demands for intraoperative guidance compared to endoscopic and interventional procedures. In contrast to abdominal, neuro, or heart surgery, the target anatomy in the neck is rather close to the skin. Thus, localization of tumors and relevant risk structures is fairly easy.

Two research prototypes for segmentation and for interactive exploration and documentation were developed and used in clinical practice since 2006. Initial refinements were targeted at improved segmentation (more automatic segmentation methods), modifications of the graphical user interface and a direct support for the surgical workflow. First, the clinical partners started to present these systems internally, e.g., at the tumor board, and later at their workshops, and conferences, leading to additional and constructive feedback. Based on this feedback and interest from a leading industry supplier, and the continuous support of the clinical partners, a spin-off company, DORNHEIM MEDICAL IMAGES, was founded in early 2008 in order to transform the prototypes into product quality software. Even in this (late) stage, new demands arose while old ones had to be rethought, leading to further research. Instead of discussing technical details, we emphasize the lessons learned. Within this project, medical doctors and computer scientists collaborated from the initial stages. Questionnaires and other task analysis techniques (recall § 5.2.1), e.g., observation of surgeons during their work and oral interviews, have been employed to deeply explore user and task needs. Medical doctors acted as codevelopers who contributed essentially to any design decisions. They were involved in early prototyping of visualization and interaction techniques, primarily in informal discussions where different options were presented and compared. Later, similar to

the virtual sinus endoscopy project, the medical doctors performed evaluations at a larger scale leading to increased visibility among ENT surgeons and further insights for the development team. We start with a discussion of the medical background (neck anatomy and surgical strategies) in § 20.4.1 and derive requirements for computer support (§ 20.4.2).

20.4.1 MEDICAL BACKGROUND

Patients with a malignant tumor in the mouth and neck region are likely to develop lymph node metastases in the neck region where a large number of lymph nodes is concentrated. Up to 50% of such local metastases were observed [Fischer et al., 2009b]. For the long-term survival of the patients, it is essential that not only the primary cancer but also all metastases are early and completely removed—this intervention is called neck dissection.

Medical Imaging Neck dissection planning is based on high resolution medical image data. In routine diagnosis, CT as well as MRI data are employed. A very good soft tissue contrast is the major argument for using MRI. The soft tissue contrast enables, e.g., a good discrimination between inflammation and tumor. Skeletal and cartilaginous structures, however, are better visible in CT data. The higher resolution of multislice CT data (slice distance of 1 mm) is preferable to detect and characterize lymph nodes. Shape, size, infiltration, and vascularization are indicators for malignancy. Metastases are likely to exhibit a spherical shape, are larger and tend to infiltrate surrounding structures—these attributes can be well determined in CT data. Also, a central necrosis, a safe sign for malignancy, is obvious in CT data. Strong vascularization is an essential indicator for a malignant cancer. However, these vascular structures are too small to be visible in CT and MRI data. Only color Doppler sonography is able to represent the flow induced by smaller vascular structures (Fig. e20.11). Thus, sonography has a place in diagnostics and surgical planning, but is only employed by highly specialized medical doctors.

In some hospitals, radiologists present the cases to the surgeons and answer questions; actually leading to a joint discussion of surgical strategies. In other hospitals, basically the surgeons themselves interpret



FIGURE e20.11 Colored Doppler sonography delivers information in high spatial resolution and in addition particularly indicates the vascularization of a lymph node—an essential indicator for malignancy (Courtesy of Christoph Arens, University of Magdeburg).

the image data to come to their own decisions. CT data are much easier to interpret and therefore preferred by surgeons. While MRI provides a large space of choices for enhancing and suppressing structures, the correct interpretation of these images is a matter for experienced radiologists. A typical MRI study involves at least three scanning sequences, the images of which have to be mentally integrated. CT provides standardized Hounsfield values and only one CT neck dataset has to be analyzed instead of a series of MRI data. The decision on an imaging modality in case of (older) cancer patients is not influenced by the X-ray exposure of CT data.

Even better diagnosis and therapy planning may be performed with combined PET/CT data. This combination increases the sensitivity of the detection of metastases. However, it is still an expensive modality with limited availability. Thus, we focus on pure CT data and additional endoscopic intervention.

Surgical Strategies The choice of surgical strategies depends primarily on the existence and location of enlarged lymph nodes. If a patient with a known cancer in the mouth or neck region exhibits lymph nodes with a diameter beyond 1 cm, this lymph node is suspicious to be a metastasis. Judging the size of a lymph node, is difficult. Since lymph nodes exhibit low contrast to surrounding structures, they may be even difficult to recognize. Moreover, due to the limited resolution of the data, each measurement exhibits an inherent uncertainty of at least the spacing of a voxel (this value equals 0.5–2 mm in our datasets).

Lymph Node Levels The location of lymph nodes is described with respect to five lymph node levels. This characterization is important, since usually all lymph nodes in one level are removed if one of them is affected. Lymph node levels are a typical example for a classification that is employed to discuss the location of pathologies in a standardized manner. The liver segments defined by COUINAUD, as well as lung segments are other examples with widespread use in oncology. Anatomical classifications provide a common frame of reference for cooperation between medical doctors, e.g., between radiologists and surgeons.

In particular, the infiltration of a large muscle (M. sternocleidomastoideus), a nerve (N. facialis), the larynx or blood vessels determine the surgical strategy. If the Arteria carotis interna is strongly infiltrated (infiltration of a large portion of the circumference), the pathology is regarded as not resectable, since this structure is life-critical. The infiltration of other structures, such as muscles and nerves, is not prohibitive, but makes a radical strategy necessary which results in long-term impairment, such as paralysis if the N. facialis is resected or loss of voice if the larynx has to be completely removed. Figure e20.12 gives an overview on the neck anatomy. The identification and analysis of lymph nodes with respect to size, shape, and distance to vital anatomical structures is crucial for the surgeon's decision.

20.4.2 TASK ANALYSIS

As a major prerequisite for re-developing a research prototype into a practical tool for real world use, we entered again in a stage of in-depth task analysis (this process was first described in [Preim et al., 2010]). While a trade-off between scientifically interesting questions and real needs was required in the research project, a rigorous analysis of tasks, preferences, and priorities was necessary for the actual clinical use. This analysis was accomplished as a larger set of interviews at the ENT department in Leipzig as well as through observations of clinical processes including surgery. In principle, the same techniques have been used within the research project, but in a significantly lower scale. This analysis was focused on an understanding of:

- 1 individual surgical planning, particularly preoperative decisions,
- 2 integration of information derived from radiology data and other examinations,
- 3 collaborative treatment planning, in particular tumor board discussions,



FIGURE e20.12 3D visualization of the neck anatomy based on CT data of a patient. Bones are displayed in white, muscles are brown, lymph nodes yellow. The elongated red and blue structures depict the two major vascular structures: Aorta carotis interna and Vena jugularis (Courtesy of Christian Tietjen, University of Magdeburg).

- 4 patient consultation, and
- 5 documentation.

To represent the results, informal scenario descriptions have been created, discussed, refined, and verified by discussing them with the clinical experts [Cordes et al., 2009] (recall § 5.2.3.2). These scenarios describe different clinical cases, all examinations which are accomplished to come to a diagnosis, the planning process and the postoperative situation. Special care was necessary to cover a representative set of different diseases (different with respect to number and size of metastases, location of metastases, infiltration of risk structures). A few examples, related to selected issues of the list above, might highlight this process.

Infiltrations Potential infiltrations of anatomical structures by a tumor are investigated in detail with respect to the likelihood of an infiltration, the extent of an infiltration (Which portion of a vessel cross section is affected by an infiltration?What is the longitudinal extent of this infiltration?). Thus, dedicated visualizations are desired which contain just the risk structure, the tumor and the possible infiltration area. Radiologists often conclude that infiltration is likely even if not directly visible in case of a distorted outline of an adjacent anatomical structure.

Integration of Panendoscopic Findings Besides CT or MRI data, endoscopic interventions are the most important source of information. With an endoscope, the surgeon investigates possible tumors using optical information and touch sense. Laryngoscopy is an endoscopic examination that serves to evaluate possible larynx infiltration in detail. This information is represented in special sheets of paper, where schematic drawings of the neck anatomy are added with the findings. The task analysis clearly revealed a need for integrating this information with the electronic documentation and the findings from CT data.

Documentation is an essential aspect that was underestimated in the initial research project. For medical doctors in general, and for surgeons in particular, a careful documentation of diagnostic information, treatment decisions, and patient consultation is essential because of juristic reasons and of the account with social insurance. Such bureaucratic tasks are time-consuming and annoying for the surgeons. Therefore, it turned out that any support which shortens the documentation without degrading its quality is highly welcome. Thus, we carefully investigated, e.g., automatic tumor staging, based on measurements applied to all metastases and generated automatic visualizations for direct use in the documentation to reveal all relevant findings. This includes electronic versions of schematic drawings that are frequently used by medical doctors to represent tumor size and location.

In § 20.6.5 we discuss how these requirements are fulfilled in the TUMOR THERAPY MANAGER.

20.5 IMAGE ANALYSIS FOR NECK SURGERY PLANNING

The essential prerequisite for surgical planning is to segment the relevant anatomical and pathological structures. The segmentation enables the selective visualization and quantitative analysis of the patient data.

20.5.1 IMAGE ANALYSIS TASKS

Based on many discussions with various clinicians and an analysis of medical publications the following target structures were identified as being the most relevant for preoperative planning:

- Vascular structures (V. jugularis, A. carotis),
- Muscles (M. sternocleidomastoideus),
- Skeletal structures (mandible and clavicle),
- Pharynx,
- N. accessorius, N. vagus (if they can be delineated),
- Larynx,
- Primary tumor, and
- Lymph nodes.

In selected cases, specific requirements for computer-supported planning arise, e.g., the segmentation of additional structures or certain measurements. These requirements are indicated by medical doctors by filling a structured form [Cordes et al., 2006]. In the basic version of our dedicated image analysis software, livewire combined with shape-based interpolation [Schenk et al., 2000], interactive marker-based watershed [Hahn and Peitgen, 2003] and basic region growing methods have been employed [Cordes et al., 2006].

While the vascular structures, muscles, and the glands could be segmented with these semi-automatic methods, the relevant nerves could often not be identified due to their size in relation to the image resolution. In CT data with low slice distance, the N. accessorius and N. vagus could be identified manually in a few slices only. As only the approximate path of these nerves is essential for surgeons, the nerves are partially segmented and used for an *approximate visualization* (§ 20.6.1). Primary tumors were segmented manually as well. They exhibited low contrasts and could only be distinguished by exploiting considerable anatomical knowledge. The average effort for the segmentation of all target structures is about 90 minutes

(see [Cordes et al., 2006] for an evaluation with ten users and two datasets). The average length of the most time-consuming segmentation subtasks was:

- lymph node: 19 minutes,
- vascular structures: 19 minutes, and
- M. sternocleidomastoideus: 17 minutes.

In extreme cases, overall lymph node segmentation may take up to 90 minutes. Since this is significantly more than can be afforded in routine clinical work, an acceleration of image analysis was aimed at and is described in the following subsections.

20.5.2 MODEL-BASED SEGMENTATION FROM CT NECK DATA

The necessary speed-up of the overall segmentation can only be achieved with model-based segmentation (recall § 4.5). Such model-based approaches are difficult to develop and very specific for a certain anatomical structure. The structures that lead to the longest segmentation times were tackled with high priority. There are various options, e.g., Statistical Shape Models (SSMs) or Active Contours.

Mass-spring Models We employed instead mass-spring models where geometric objects are defined by:

- a set of masses, characterizing the basic shape, and
- a set of springs with a certain elasticity that define to which extent the model may be locally stretched or compressed to adapt to particular image data.

A mass-spring model is derived from one template segmentation and thus the segmentation process is related to template-based segmentation (recall [Montagnat and Delingette, 1997]). Obviously, it is reasonable to employ one framework to segment all relevant target structures. An individual adaption to each individual structure is necessary, but by using one framework experiences gained in the adaptation to a single structure may be employed for other structures.

The development of appropriate segmentation models takes considerable time and requires a lot of experience, since many parameters are involved and the relation between initialization and model adaptation is complex. However, alternative approaches also require considerable experience, and, in addition, often a large set of trained examples. A major advantage of mass-spring models (MSM) is that they do not require such a training set and indeed the basic shape of the models is often derived by just one example referred to as prototype. This example, of course, is carefully chosen to be a typical representative of that shape.

Initialization in model-based segmentation is often performed by a rough specification of location, size, and orientation of the target structure. As an example, an average model might be projected over the image data and is dragged, scaled, and rotated to roughly fit to the image data. In contrast, with MSM the user selects a few *landmarks* that serve as hints for the model placement. Our experience indicates that this initialization leads to better results (see, e.g., [Dornheim et al., 2006a] for a quantitative analysis) and, depending on the number of landmarks to specify, tends to be faster. The higher accuracy is due to the fact, that landmark-based initialization leads to a non-linear, elastic fitting process, whereas affine transformations can only represent a global rigid transformation. Obviously, anatomical shapes from patient to patient do not only differ in size, orientation, and position, but instead many local changes occur.

Sensors in Mass-spring Models Mass-spring models are heavily used in soft tissue simulation and in surgery simulation where the response to forces exerted by the user are thus reflected. To use this concept in

segmentation, *sensors* are employed to capture certain image information, such as intensity values and gradients. In segmentation, however, no physical process is simulated. Model assumptions include expected intensity values, gradient magnitude, gradient direction, and curvature-related measures. The expected shape is represented by the initial configuration of masses. These model assumptions guide a simulation process where the positions of masses are iteratively adapted to the actual image information.

Thus, the process is similar to active contours where internal and external forces guide an optimization process to adapt a deformable model to image features. Internal forces represent assumptions related to the object shape. External forces represent user input, e.g., the initial placement of the model, and sensor information. The simulation stops when the internal and external forces are at equilibrium state. In practice, a stopping criteria is employed that terminates the simulation when all changes of positions are below a certain threshold. The choice of that threshold is a trade-off between speed and accuracy, that is usually carried out by the developers and hidden from the users.

Intensity and Gradient Sensors A sensor dragging their associated mass to voxels of a given gray value range is referred to as intensity sensor. A direction-weighted sensor steering toward voxels at gradients of high magnitude and expected direction is referred to as gradient sensor. Thus, in CT data, intensity sensors reflect that target structures exhibit a certain range of Hounsfield values, and gradient-related information is employed to attract the model to edges (large gradient magnitude) and to favor smooth shapes (slight changes of the gradient direction only) [Dornheim et al., 2007].

Stable Mass-spring Models with Torsion Forces A notorious problem of using MSMs for segmentation in 3D data is stability—the models tend to collapse easily, since the image information is weak and the springs do not sufficiently stabilize such models. Thus, the major idea introduced by DORNHEIM and TOENNIES is to use a stabilized version, referred to as *stable mass-spring models* (SMSM) [Dornheim et al., 2005b]. In an SMSM, the angles between adjacent springs are limited. Thus, not only the rest length of a spring is captured, but also its relative rest direction. Every change to that direction initiates a torsion force that try to compensate for that change and actually leads to stable directions.

Simulation Parameters SMSMs simulate a physical adaptation process that is steered by a couple of parameters. The choice of these parameters primarily determines whether the optimization process converges at all and how fast it converges. A damping factor (<1) ensures that the model actually converges. The stopping criterion is a combination of a maximum number of simulation steps, e.g., 1000 and a small ε -threshold that represents the minimum amount of change necessary to continue the simulation. Numerical simulation always requires a step size Δt that also needs to be selected carefully to provide accurate results (low Δt) and reasonable simulation time (avoid too low Δt). As a preprocessing step, all datasets were isotropically resampled to compute gradients in a normalized way [Dornheim et al., 2005b].

The use of SMSMs, however, is also not straightforward, since the models must be designed to be still flexible enough to adapt to the actual image information. In the following, we briefly describe specific instances of SMSMs used for segmentation of anatomical structures from CT neck data. We omit almost all details and thus the user might consider this method to be rather straightforward to use. Actually, the three segmentation tasks were developed in the framework of three Master theses—thus, it took half a year for very good and carefully supervised students to develop a segmentation method for one type of anatomical structure. While the development of the models is challenging, the use is often straightforward.

20.5.3 MODEL-BASED SEGMENTATION OF NECK VASCULATURE

For planning neck dissections, the carotid artery and the jugular vein are particularly important. Vessel segmentation is an active research area (recall § 11.4.1). However, existing methods, such as the vessel crawler [McIntosh and Hamarneh, 2006], do not consider the specific properties of the two major vessels in the neck region. The main vessels and the first bifurcations are essential, whereas other branches due to their small diameter are less relevant. Dornheim *et al.* [2008b] presented another instance of stable mass-spring models to segment these structures based on a few points selected by the user. They exploit the following properties of these vessels:

- Most blood vessels in the neck are roughly parallel to the body axis and thus exhibit roughly circular cross sections.
- The carotid artery and the jugular vein have few bifurcations, often just one major bifurcation.
- The outline represents a strong gradient. However, adjacent high-intensity structures may interrupt that high gradient.
- The interior intensity values are rather homogenous but may change gradually due to contrast agent inhomogeneity.

For the segmentation of neck blood vessels, the coherency across the slices is exploited. Thus, information from neighboring slices are taken into account to robustly determine the contour in a particular slice.

Initialization The mass-spring models are started at the center lines of the two target vessels. These center lines have to be specified as roughly as possible by the user. At least one start and end point as well as one point after a bifurcation need to be selected. In regions with higher curvature, further points should be selected. Before the SMSMs start their growing process, the centerline is estimated using cubic splines fitted to the points selected by the user. Since a cylindrical model bounded by four adjacent slices is used, one central axis point per slice is determined by sampling the spline (Fig. e20.13).

Model Adaptation The centerline voxels, determined in the initialization stage, are used to create a cylindrical SMSM that is designed to segment a vessel segment composed of four planes. Centerline voxels are located exactly in the slices of the underlying data reflecting its spatial resolution. The planes are cross sections along the vessel that are perpendicular to the vessel centerline. Thus, the planes are oblique and their orientation usually does not correspond to slices in the original data. The number of adjacent planes reflected in one model is a trade-off. With four planes, sufficient information from the surrounding slices are considered to exploit coherency without generating a too complex model that leads to long computation times. The overall segmentation result is just a composition of these segments. The circular model within one plane consists of two concentric rings (see Fig. e20.14), similar to the lymph node model (described in § 20.5.5). The outer ring, where gradient sensors are placed, serves to detect the edges represented by a strong gradient magnitude. The inner ring (a slightly scaled-down version of the outer ring) represents the homogeneous inner region of a vessel. Here, intensity sensors are employed to assess intensity values and homogeneity of these values. This inner layer is essential to stop the growing process before the model gets distracted by adjacent structures exhibiting a high gradient to the surrounding.

The local vessel radius and gray values are derived from a ray casting, starting from the centerline points (see [Dornheim et al., 2008b] for the specific homogeneity criteria and thresholds). The assumption of a circular cross section is incorporated by a filtering step that removes outliers at the contour. Figure e20.14 illustrates the growing process in 2D planes and in 3D. It is valuable to actually display this process and



FIGURE e20.13 Left: the centerline and one cylindrical segment of the overall segmentation model. Right: The overall vessel segmentation is composed by the individual segments representing two branches (From: [Dornheim et al., 2008b]).

the intermediate results, since it "explains" how the results are determined. If the actual process takes too long (more than a few seconds), a sequence of a few intermediate steps may be recorded and displayed when the user invokes these segmentation results for the first time.

Examples for resulting segmentations of the A. carotis are shown in Figure e20.15. As we have discussed in Chapter 11, easy-to-interpret vessel visualizations require either dedicated methods or aggressive smoothing with the drawback that accuracy may suffer. With SMSMs, segmentation results are determined at the subvoxel level. Thus, without any advanced visualization techniques it is sufficient to display just the resulting triangle mesh (Fig. e20.15).

Evaluation The segmentation method has been evaluated using 14 CT datasets with varying image quality, in particular with varying slice distance (0.7–5 mm). Thirty vessels were segmented from these datasets. The model-based segmentation was compared with one expert segmentation. The resulting deviations were compared with the differences between two (further) expert segmentations. It was hypothesized that the accuracy of the model-based segmentation was in the same order of magnitude than the expert accuracy reflected by the intra-observer variability. The usual accuracy measures mean surface distance, Hausdorff distance as higher bound for local inaccuracy, and volume overlap were determined. Mean surface distance was 0.78 mm ($\sigma = 0.47$ mm) compared to intra-observer variability of 0.62 mm (σ 0.83 mm). The Hausdorff distance was 7.00 mm ($\sigma = 6.04$ mm) indicating that stronger deviations may occur and thus quality control using slices is necessary. However, intra-observer variability 8.57 mm ($\sigma = 6.95$ mm) was even higher. Volumetric segmentation error was only 0.25% ($\sigma = 0.10\%$) and thus similar to intra-observer variability 0.21% ($\sigma = 0.07\%$). The segmentation interaction time is low: Users set 6–12 points within 15 seconds. The computation time for the system was 4 minutes per vessel (in 2008). However, the implementation was not optimized, e.g., using multiple cores.



FIGURE e20.14 Cylindrical models are employed for vessel segmentation. An outer layer of gradient sensors and an inner layer of intensity sensors are used to guide the growing process. 2D and 3D view of the model adaptation process that proceeds from left to right (From: [Dornheim et al., 2008b]).

20.5.4 MODEL-BASED SEGMENTATION OF THE THYROID CARTILAGE

We briefly discuss the segmentation of the thyroid cartilage (a part of the larynx) that plays an essential role in neck surgery [Dornheim et al., 2006a]. The potential infiltration of this structure determines whether a surgical strategy is possible that preserves the patients' voice. A model-based approach is essential, since strong intensity variations occur and any simple segmentation approach is not promising. The model creation process is the most complex of all segmentation models described in that section. It is based on a sample segmentation, a prototype, that is converted in a surface model with the Marching Cubes algorithm. The resulting model is significantly smoothed and simplified to reduce its complexity. This postprocessing is performed with error control to limit the resulting inaccuracy. Simplification was performed with a target number of 50–200 vertices. The resulting vertices are employed as masses for the segmentation model and the edges as spring forces.

Initialization Due to the complex shape of the thyroid cartilage the initialization is rather complex. In total, six anatomical landmarks have to be selected by the user (in a predefined order). However, these landmarks are quite obvious and a user with sufficient anatomical background, e.g., a radiology assistant can easily select these points. The landmarks specified by the user serve as hints for an initial adaptation process. The transformation of the prototype to the landmarks is a non-linear (elastic) transformation.



FIGURE e20.15 Four examples of the segmentation of the A. carotis. Note that the smooth appearance is a direct result from the segmentation process and not due to subsequent smoothing (From: [Dornheim et al., 2008b]).

Model Adaptation The actual adaptation is performed very similar to the initialization. The landmarks set by the user are still considered as hard constraints. However, in this stage the sensor input is used to guide the adaptation, whereas in the initialization the sensor input was disabled and only the spring and torsion forces influenced the model. The spring length and directions from the initial stage are used as rest length and rest direction for the second stage.

Evaluation Again, two expert segmentations (from eleven CT datasets) were employed to assess intraobserver variability and one expert segmentation was employed to compare model-based segmentation with the current gold standard. The average surface distance (1.06 mm) is acceptable. The Hausdorff distance of 9.84 mm, however, is considerable and almost twice as high as intra-observer variability (5.23 mm). More severe deviations primarily occur in the lower part of the larynx (below the Adam's shape) where the hyoid bone may distract the larynx segmentation. Due to the complex shape of the thyroid cartilage, corrections of the segmentation in a few slices were often necessary. A set of postprocessing tools for intuitive correction of such results was later developed (recall § 4.6.2) [Proksch et al., 2010]. Although motivated by problems in this specific segmentation task, they are broadly applicable. The computation time was 0.5–1.5 min for the initialization and 2–4 minutes for the model adaptation (in 2006).

In the clinical application we noticed that there are sometimes severe problems with the accuracy and interaction effort. The affected cases had one important similarity: they all relate to female patients. The reason is quite obvious: the model was derived from the thyroid cartilage of a male person and the anatomical differences between man and woman in that structure are often too large. Thus, two models are needed and the DICOM header should be analyzed to judge whether the current case relates to a woman or not to select the "right" segmentation model.

20.5.5 MODEL-BASED SEGMENTATION OF LYMPH NODES

The efficient segmentation of lymph nodes requires the use of model knowledge. Simple semi-automatic procedures may segment isolated lymph nodes but are unable to cover the variety of lymph nodes (Fig. e20.16). The variety of anatomical situations is larger than in the vicinity of lung nodules in CT thorax data. Thus, approaches developed for the segmentation of these lymph nodes [Kuhnigk et al., 2004] are not applicable to neck lymph nodes. Model knowledge related to expected intensity values, shape, size, and gradients is required [Dornheim et al., 2007, Honea and Snyder, 1999]. On the other hand, the shape of lymph nodes is rather simple. Thus, SMSMs based on a sample segmentation are suitable. As basic model shape, two spheres are employed with an outer sphere using gradient sensors and an inner sphere using intensity sensors. The outer sensors search for edges, whereas the inner sensors try to preserve the object shape. Thus, the inner sensors avoid that the model outbreaks to nearby strong gradients. The model has 100 masses and 338 springs.

Initialization The model is initiated either with one click that is interpreted as a click inside the target lymph node, or with two clicks that are considered as selection of an insight and outside point. The optional second click may be useful in case of weak gradients to discriminate the lymph node from a surrounding structure.

Model Adaptation Based on a proper initialization the model adapts to the image information. It is essential that all model assumptions are employed. The intensity values may be similar for adjacent vascular structures, but these differ in shape. Assumptions with respect to shape and size (interval [1 cm, ..., 3 cm]) are also essential to prevent that adjacent lymph nodes are considered as one object. The lower size boundary is based on the observation that smaller lymph nodes are irrelevant for neck dissection planning. The upper size boundary was defined such that giant lymph nodes are excluded. Such lymph nodes likely exhibit atypical changes in shape and intensity—thus, they cannot be reliably segmented with that model.

Evaluation The segmentation model was evaluated with 40 lymph nodes from five CT datasets. The same evaluation scheme as for vascular structures was employed. The average surface distance to an expert segmentation was 0.46 mm (compared to the intra-observer variability of 0.37 mm) and the Hausdorff distance was 2.74 mm (compared to 2.48 mm variability between the two experts). Figure e20.17 illustrates the comparison—the expert used the mouse as input device, leading to jagged contours. The computer-generated contour is smooth and likely to be more accurate in most regions. The computation



FIGURE e20.16 Neck lymph nodes in CT data: (a) isolated neck lymph node, (b) neck lymph node adjacent to M. sternocleidomastoideus, (c) two adjacent lymph nodes, (d) lymph node touching high-contrast structure (blood vessel), and (e) lymph node with a central (dark) necrosis. (b), (c), and (d) exhibit partially weak gradients (From: [Dornheim et al., 2007]).



FIGURE e20.17 Comparison of expert segmentations with model-based segmentation. The rough expert contours result from jitter in mouse input (From: [Dornheim et al., 2006b]).

time was 2–30 seconds per lymph node (smaller lymph nodes are segmented faster). The evaluation indicated the necessity of all model assumptions. The segmentation quality strongly degraded if one of these assumptions, e.g., the roughly circular shape was not considered. Thus, it is likely that no simpler model would be sufficient for lymph node segmentation.

Pathological Lymph Nodes The model-based segmentation described above reliably detects "normal" lymph nodes of a certain size (that may be healthy or malignant). It was not trained to detect lymph nodes with central necrosis (appears as dark spot inside), or strongly deformed lymph nodes, or lymph nodes that exhibit a boundary that is very weak for a large portion. The segmentation approach was later adapted and refined to pathological lymph nodes [Dornheim et al., 2010b]. Actually, a new segmentation model was required, since pathological lymph nodes differ too strongly from "normal" ones to be covered by the same segmentation model.

20.5.6 DETECTION OF LYMPH NODES

Neck surgery planning strongly benefits from the automatic segmentation of (most) lymph nodes. However, users still have to find each lymph node to initiate the model adaptation. It is desirable if lymph nodes are also *detected* automatically. This would not only accelerate the process, but as ENT surgeons clearly state increase the likelihood that no relevant lymph node is missed.

The detection of lymph nodes is a typical computer-aided detection task (recall § 3.6.4). Due to the large variety in particular of pathological lymph nodes this can only be done with a certain sensitivity and specificity. A high sensitivity is more important than a high specificity (users should not miss an important lymph node but may ignore a few false positive detections). Dornheim and colleagues developed a system that employs the model-based lymph node segmentation techniques for automatic detection [Dornheim et al., 2010a].

The basic idea to accomplish detection with an SMSM is straightforward: model instances are placed in the whole dataset and the growing process is performed at all these positions. At some places, the model

may be adapted with a good quality of fit, whereas in most places, the quality of fit is poor, since no lymph node occurs there.

Performance Issues This basic idea has some obvious problems. The first is run-time and performance. In a large CT dataset, the whole volume needs to be sampled with a rather high density not to miss any lymph node and the complex model adaptation process is started several thousand times. The second problem is closely related to the experience with the model-based segmentation of lymph nodes: the variability of (pathological) lymph nodes is too large to cover all types of lymph nodes in one model. As a consequence, aggravating the performance problem, different models need to be started at any sampling position.

Using Expectation Maps to Reduce Search Space Fortunately, there are some strategies to cope with the performance problem. Lymph nodes occur primarily rather close to certain anatomical structures, such as vascular structures and muscles. Thus, if these other structures are already segmented, an *expectation map* may be generated around these structures to restrict the search for lymph nodes to these areas. The overall process, that may be transferred to many other object detection tasks, is illustrated in Figure e20.18. The actual dataset, the model information for a specific structure and additional information to restrict the search are used as input. The segmentation model is placed at various places and a couple of segmentations occurs at all places where the quality of fit reached a certain level. A final model selection process further restricts the results based on further model knowledge leading to a few segmented target structures.

Application and Results The detection scheme was evaluated using five CT datasets where an experienced radiologist has segmented the lymph nodes. The lymph nodes cover a wide range of shapes, sizes, and gradient magnitude. The lymph nodes were searched in four regions: around the left and right mandible and around the left and right V. jugularis. Expectation maps were created by combining two sorts of information: proximity to the four anatomical structures and thresholds for lower and higher intensity values. With this combination, the search space could be reduced by more than 90%.



FIGURE e20.18 General object detection scheme. At many places, objects are searched and the search results are filtered in the "Model Assessment" and "Model Selection" stage (From: [Dornheim et al., 2010a]).

In one dataset, 29 lymph nodes were present and all could be detected. The algorithm checked 13.500 positions, actually started 958 models and delivered 38 lymph nodes (29% false positives). This was achieved in exactly 2 minutes with a setup where four CPU cores worked in parallel. Misclassification primarily occurs when contrast-enhanced vascular structures exhibit similar intensity values and shape [Dornheim et al., 2010a]. Image quality and the detection rate are correlated: a high spatial resolution is required for a high sensitivity.

20.5.7 DISCUSSION

Image analysis, in particular efficient and reliable segmentation, is a core part of computer support for neck surgery planning. Similar to other highly specific applications, there are no simple and easy-to-adapt solutions. Instead, image analysis is a major research and development task. Without model-based techniques that make the segmentation as robust, reproducible, and efficient as possible, the interactive visualization described in the following would not be possible in routine clinical practice. From a software development perspective, it is difficult to develop and later maintain completely different segmentation approaches. The family of segmentation methods described here was realized within a coherent software library providing substantial support for developing new or refining existing segmentation models.

20.6 INTERACTIVE VISUALIZATION FOR NECK SURGERY PLANNING

In the following, we describe selected examples of advanced visualization techniques that were inspired by the specific needs in neck surgery planning. They are selected based on their broad applicability.

20.6.1 APPROXIMATE VISUALIZATIONS OF NERVES

As has been discussed in § 20.5.1, nerves can only be identified in selected slices. Nerves usually proceed almost linearly and do not deviate strongly from the straight connection between positions found in some slices. Since it is important to prevent the injury of nerves, *approximate visualizations* were generated where the segmented portions are emphasized and the part in between is reconstructed as linear connection. The emphasis of the segmented portions is accomplished with small cylindrical disks, with a diameter of four times of the pixel spacing, e.g., 2–3 mm. The cylinders, connecting the segmented portions, have a diameter of two times the pixel spacing. With this method, the diameter does not convey information on the actual size of the nerve (see Fig. e20.19). In fact, if a nerve may be identified at all, usually one or two voxels per slice are attributed to the nerve (the two relevant nerves exhibit a diameter between 0.5 and 1 mm in the neck region). This visualization expressively reveals what is known from the image data and what is only approximated.

20.6.2 GRAPHICAL OVERVIEWS

Since slice-based visualizations play an essential role in computer-assisted surgery, we considered to enhance these visualizations by means of the segmentation information. In particular, we aimed at conveying the location of relevant (segmented) objects within the stack of slices to support directed (scrollbar) movements to the slices containing these objects. Our first idea was to provide a vertical bar, called a lift chart display, attached to the slice viewer where each object is represented as a bar indicating the slices where it is located (Fig. e20.20, left). The current slice is represented as a horizontal line to provide a link between the overview and the currently selected slice [Tietjen et al., 2006]. While such a visualization may indeed be helpful for surgical planning tasks, it is too complex in our specific example, as the feedback



FIGURE e20.19 Approximate visualization of N. facialis for neck dissection planning. The orange disks indicate the segmented portions. The connection between the disks is accomplished by means of cylinders—thus, the space between the segmented portions is linearly interpolated. The yellow structures represent the lymph nodes and the brown structures represent the M. sternocleidomastoideus. The vertically aligned structures in the central part show the larynx and the pharynx (Courtesy of Arno Krüger, University of Magdeburg).

from medical doctors clearly revealed. A variety of modifications turned out to be necessary to make it a useful tool (Fig. e20.20, right). The original name is not very expressive: in human-computer interaction, similar concepts were developed [Byrd, 1999] and are known as enhanced scrollbar, a name that clearly relates to a scrollbar widget.

Most of the modifications are aimed at a faster localization of enlarged lymph nodes. In general, in the head and neck region, the symmetry should be employed to distinguish objects in the left and right half. If there is a large number of such lymph nodes, it is not important which lymph node is represented in a particular slice. Instead, it should be clearly visible, in which slices enlarged lymph nodes occur at all. Therefore, we condense the information related to all lymph nodes, instead of indicating individual lymph nodes. Another refinement is the ability to add certain landmarks in the visualization as labels.

20.6.3 SMART VISIBILITY AND ILLUSTRATIVE RENDERING TECHNIQUES

Silhouette Rendering Silhouettes play an essential role for enhancing object recognition, in particular in case of dense object representations, as they occur in the neck region. Convexities, concavities, or inflections of contours in the retinal image allow the observer to draw reliable inferences about local surface geometry



FIGURE e20.20 Enhanced scrollbar to be used with a slice viewer. Left: Each bar represents one anatomical structure. The A. carotis interna and the V. jugularis (left and right) occur in all slices and are represented by the four long vertical bars (colored blue and red). Right: Only lymph nodes and the tumor are shown. The lymph nodes have been condensed (yellow bars). The horizontal arrangement is based on the symmetry: structures are represented at the side they are belonging to. Labels related to crucial anatomical landmarks, such as bifurcations of the vascular structures, have been added. (Courtesy of Christian Tietjen, University of Magdeburg)

(recall § 12.5.1). However, due to the simplified depiction, the perceived information on the surface is not complete. Therefore, it is primarily used to indicate the context objects, such as bones (Fig. e20.21).

In addition, silhouettes may be used to discriminate two classes of objects; those which exhibit a certain feature are rendered with silhouettes enabled, whereas the remaining objects are drawn without silhouettes. A reasonable use of this strategy is to enable silhouettes for objects, which are more "interesting," since silhouettes direct the user's attention. In neck surgery planning, many lymph nodes have to be explored by the user. In particular, lymph nodes which are enlarged and touch a critical structure are essential. In Figure e20.22, the lines where enlarged lymph nodes and a muscle intersect are rendered with silhouettes. ENT surgeons regard this as substantial help, since it is otherwise not recognizable, whether the lymph node is only approaching a critical structure or touches it. However, if a lymph node touches another structure, it is usually not clear whether the lymph node (only) displaces this structure or actually penetrates it (infiltration).

Smart Visibility Rendering The exploration of volume data can benefit from cutaway views and ghosting [Viola et al., 2005] (recall § 12.10). Inspired by their work, we use cutaways in neck surgery planning to emphasize lymph nodes and their neighborhood. For visualizing lymph nodes, we generate cylindrical cutting volumes with the cylinders aligned orthogonal to the viewing plane. The cylinder is scaled such that the target lymph node is completely visible with an additional and adjustable safety margin. To clearly indicate the chosen illustration technique, we display a thin bright silhouette at the border of the cutaway region. The lymph node is also visually enhanced by increasing the saturation of color.

The process of efficiently computing these cutaway views based on convex hulls, OpenGL 2.0 and the fragment shader functionality from modern GPUs is described in [Krüger et al., 2005]. A more powerful solution for cutaway rendering with better performance and more visual realism, e.g., illumination was



FIGURE e20.21 Silhouettes are generated for the bones and muscles which serve as anatomical context (Courtesy of Christian Tietjen, University of Magdeburg).



FIGURE e20.22 Silhouette rendering reveals lymph nodes which touch and potentially infiltrate a critical structure. The brown muscle is rendered with semitransparent fibers (Courtesy of Arno Krüger, University of Magdeburg).



FIGURE e20.23 The lymph node emphasized with a cutaway technique in the 3D visualization (see the circle) is simultaneously emphasized in the original slices also with a circle to indicate the extent and position of the cutaway (Courtesy of Arno Krüger, University of Magdeburg).

later described by Kubisch et al. [2010]. The cutaway region is considered as a conventional object which is superimposed on the 2D slice visualization—resulting in a circle colored in the same way as in the 3D visualization (see Fig. e20.23).

Discussion Cutaway views support the localization very well. However, the infiltration of adjacent anatomical structures cannot be assessed, since these are removed. For assessing infiltration, ghostviews are better suited. The use of both, cutaways and ghostviews, is useful to expose emphasized structures. Emphasis and spatial understanding can be achieved in a visualization with constant camera position or by applying minor rotations. However, large scale rotations in ghostviews or cutaway views are confusing, in particular when the cylindrical region is large in the *z*-direction. Therefore, the removal of anatomical structures should be restricted to situations when the cylinder height required to expose the target structure is small.

20.6.4 COLLECTIONS

A special concept, originally developed for neck surgery planning might be useful for a wide range of applications, even beyond surgery planning. In order to accelerate the planning process, we allow to summarize a subset of anatomical or pathological structures together with their appearance, e.g., color, transparency, and the current viewing direction. We refer to such a subset as a *collection*. Collections may be stored, named, and later reused. Collections are presented as a list with a label and a representative snapshot. On the one hand, collections represent a flexible concept, since the additional collections may be added (see Fig. e20.24). On the other hand, collections contribute to a standardized process dedicated to the surgical decisions. They might also be used for a guided step-by-step planning process, where the individual collections are displayed in a sequential manner. This concept was introduced by Mühler et al. [2010].

20.6.5 TUMOR THERAPY MANAGER

In this subsection, we discuss how the requirements stated in § 20.4.2 are actually fulfilled in a comprehensive software assistant, that we refer to as TUMOR THERAPY MANAGER. Compared to earlier versions of that tool, the name suggests that primarily general functions for tumor surgery planning and documentation are included, not only highly specific functions for neck surgery.

Infiltrations Tumor segmentation involves a large amount of uncertainty, thus, the overlap between a tumor and an adjacent structure might strongly underestimate the actual infiltration. Thus, it is valuable



FIGURE e20.24 Collections for neck surgery planning represented as icons and related verbal description. By selecting a collection, the related subset of objects is displayed at once (Courtesy of Konrad Mühler, University of Magdeburg).

if the potential infiltration area is explicitly indicated by a radiologist and shown along with the anatomy. Since the infiltration area is not an anatomical region that may be identified with an automatic approach, manual effort is necessary. However, since this region is rather small and needs to be defined only roughly, a few minutes are sufficient for this task. Infiltration areas should be displayed strikingly different from anatomical surfaces and thereby indicate the vague character. One possibility is the display as a hatched semitransparent object. A design study that illustrates this concept is shown in Figures e20.25 and e20.26. Infiltration areas should also be displayed in 2D slices. Display parameters, such as color, transparency and texture, should be chosen such that the relation to the 3D display is clearly recognizable (Fig. e20.26).

Infiltrations of muscles, nerves, blood vessels, and the larynx are crucial in neck dissection planning. The larynx is the most complex of these anatomical structures. Thus, a 3D model including just the larynx, the potential infiltration area and a tumor is more appropriate to investigate whether it may be conserved to preserve the voice of the patient.

Figures e20.25 and e20.26 illustrate how visualizations support the assessment of (possible) infiltrations. Such visualizations are part of a step-by-step planning approach where a series of simple visualizations is generated to understand how surgical procedures may affect anatomical structures.

Besides 2D and 3D overview visualizations, virtual endoscopy views are essential to support the assessment of infiltrations. Figure e20.27 presents an example where a potential infiltration is displayed in a 3D overview and a virtual endoscopy view simultaneously.

Integration of Panendoscopic Findings Endoscopy is performed as a diagnostic procedure after the acquisition of CT data. The complementary information from endoscopy needs to be integrated with the information from CT data. The ideal solution, as ENT surgeons explained us, is to register endoscopy information with CT data to provide one *coherent 3D model* and thus also to document the endoscopic intervention. At



FIGURE e20.25 3D visualization to explore the spatial relations between the larynx and a metastasis. Since the removal of the larynx would have severe consequences, a careful analysis is accomplished to explore whether at least parts of the larynx may be conserved. The potential infiltration region is shown as a semitransparently hatched object (Courtesy of Dornheim Medical Images).



FIGURE e20.26 2D and 3D visualization of a large muscle, an enlarged lymph, node and the potential infiltration area (Courtesy of Dornheim Medical Images).

the time of writing, this is attempted in a research project, but since this is an ambitious goal it is not clear whether it could be done in a sufficiently reliable manner. A less ambitious but also useful goal is to enable the user to manually cross-reference snapshots from endoscopy with CT data (Fig. e20.28). In a similar way, it is desirable to integrate biopsy results at the location where the biopsy was taken in order to further integrate the relevant diagnostic information.

Another useful function for integrating panendoscopic and palpatory findings is an easy-to-use editing tool that enables a modification of shapes [Boehm et al., 2009]. Thus, shapes determined from segmenting CT data may be adapted to the impression from endoscopy and palpatory examination—a function that



FIGURE e20.27 Virtual endoscopy and 3D context in side-by-side view. Left: Safety distance colorization of inner pharynx surface reveals outside contact areas. **Right:** Red glyph indicates view position and direction. A glass-like effect provides better visual perception than simple transparency. The small red arrow indicated the viewing direction of the camera in the left endoscopic view (Courtesy of Dornheim Medical Images).



FIGURE e20.28 In a virtual endoscopy derived from CT data, a photo of the corresponding real intervention is added at the corresponding position (Courtesy of Dornheim Medical Images).

is primarily motivated by the tumor appearance that might be significantly different. These differences are crucial if infiltration of risk structures occurs (see Fig. e20.29).

Documentation is the last step in a workflow-oriented planning process. Currently, this step is the least supported step and is carried out manually. For documentation, a typical sheet of paper is reproduced as an electronic sheet. If possible, all entries are automatically filled in by results from the analysis and



FIGURE e20.29 The tumor model derived from CT data (left) is modified according to the endoscopy findings. The user simply outlines regions of the larynx that are likely infiltrated and the tumor shape is fitted to that region effectively enlarging the tumor shape (right). Thus, the integrated information may be employed for planning surgery (Courtesy of Dornheim Medical Images).

the planning process. In addition to verbal comments, in many hospitals schematic drawings are used to integrate sketches that depict tumor size and location (see Fig. e20.30). These schematic drawings are electronically reproduced as well and are used to enter additional information by drawing. Thus, the whole documentation can be realized in an electronic manner. The documentation is further enhanced with automatically generated screenshots. As an example Figure e20.31 shows the location of a tumor and its automatically derived measures. In Chapter 10, we employed further examples from neck surgery planning to illustrate the importance of measurements.

Figure e20.32 illustrates the GUI design of the TUMOR THERAPY MANAGER. It is designed to provide a good usability but also to provide a good user experience with an attractive layout, comprised of carefully designed visual components. Feedback at various occasions clearly indicates that perceived attractiveness is indeed important to gain acceptance for a new kind of software support.

20.6.6 CLINICAL USE AND DISCUSSION

The TUMOR THERAPY MANAGER has been used for planning more than 100 neck surgery interventions (in early 2011 according to [Rössling et al., 2011]).³ Eight surgeons (all at the University Hospital Leipzig) used the system. The datasets acquired for neck dissection planning contained a tumor in the head and neck region and were suspected of containing lymph node metastases as well. Datasets stem from three different radiology departments, thus representing a typical spectrum of clinical datasets. The quality of the datasets was diverse with respect to the signal-to-noise ratio, motion artifacts as well as the slice distance (0.7–3 mm).

In most cases, only a subset of functions was used to segment, quantify, and visualize the tumors. In some 40 cases, the full set of functions—including the virtual endoscopy and the documentation functions—was used. The computer-assisted planning process was initially performed in addition to the conventional planning process based on CT slices. This is not necessary but serves to compare the different workflows [Preim et al., 2010]. More recently, the software partially replaced the conventional planning

³ The following discussion of the clinical use is primarily based on an initial report in [Preim et al., 2010]. Aspects that are based on a more recent study [Rössling et al., 2011] are explicitly marked.



FIGURE e20.30 Schematic drawings of the neck anatomy are provided in electronic form (bottom thumbnail images) in order to annotate them with findings from endoscopy. The currently selected drawing (large central image) may be modified with the tools on the right (Courtesy of Dornheim Medical Images).

[Rössling et al., 2011], which was possible due to better support of the software and more experience and trust of the users.

In approximately 10 cases, the 3D visualizations were employed in the tumor board for interdisciplinary discussions. In general, the surgeon feels safer with the computer-assisted planning and better prepared for surgery. Only in rare cases, however, he changes the surgical strategy with respect to radicality and access.

The computer-assisted planning process is accomplished in difficult cases where the tumor disease is at a later stage and therefore treatment is particularly challenging (roughly 70% of the patients in the study exhibit a tumor in the late stages III and IV, and 10% exhibit metastases). The system is used in one hospital, although care was taken in the task analysis stage that it is not overly specialized for this specific setting.

The TUMOR THERAPY MANAGER is considered particularly useful for planning treatment of surgical interventions at the larynx. This is because all relevant target structures (cricoid cartilage, thyroid cartilage) can be segmented and discriminated well. With respect to tumors in the oropharynx, not all relevant structures can be separated and thus the 3D visualization is less helpful. Primarily one surgeon describes that he particularly appreciates the precise documentation function. This allows for the first time to communicate precisely the findings of the panendoscopy, in particular the estimated depth-infiltration of vascular structures and other tissue. He reports that with these functions he is more careful in the endoscopy, since more findings can be reported.



FIGURE e20.31 Left: The object-oriented bounding box of a tumor, which represents its extent, is determined and visualized as part of the documentation. Right: As an alternative, the extent of a tumor may be shown like a tooltip (Courtesy of Dornheim Medical Images).

Rössling et al. [2011] discuss the experiences of the clinical use in more detail, including measurement, annotation and PACS integration. They also report that the average time for computer-assisted planning (provided that all segmentation results are provided) only increases by 2 minutes which is likely to be an acceptable effort.

Discussion Despite the long-term effort described here, still not all clinical needs are fulfilled in an optimal way. In some hospitals, ultrasound or MRI are primarily used for diagnosis and treatment planning. Thus, it is desirable to adapt visual computing solutions to the peculiarities of such data. Multimodal visualization, including information derived from different image data, is at least in some hospitals a useful extension. In particular, if radiation treatment or chemotherapy are part of the overall treatment plan, treatment response has to be carefully evaluated, which gives raise to comparative visualization solutions highlighting how the shape and size of tumors have changed over time.

20.7 CONCLUDING REMARKS

Segmentation is essential to enable selective visualization and quantitative analysis of anatomical structures in the head and neck region. We described model-based approaches that are highly specific for certain structures, thus they are not broadly applicable. However, this high level of adaptation to data and anatomic structures was required to meet the demands of clinical practice. Virtual endoscopy is essential in all three areas we have discussed here: middle ear, neck and sinus surgery. It provides information in an intuitive way and supports planning and patient consult. However, the amount of additional information derived from virtual endoscopy does not justify a lengthy preparation. Thus, we also described a method that does not incorporate prior segmentation.



FIGURE e20.32 User interface of the tumor therapy manager. Most of the available space is used for the visualization area, where 2D or 3D visualizations may be displayed. Major tasks, such as tumor staging, are available via the icons on the left side, whereas detailed interactions relating to the visualization are provided in a toolbar (right) (Courtesy of Dornheim Medical Images).

We discussed two issues of uncertain information and its visualization: incomplete segmentation results, e.g., nerve segmentation, and potential infiltration areas. In particular, the optimal visualization of infiltration areas is an open issue. The approach presented in this chapter (hatched semitransparent surface) should be seen as a starting point to design and develop alternatives and use them for a rigorous user study.

Throughout the chapter we discussed examples, where medical doctors demanded and used drawing facilities to record their findings, either in relation to schematic drawings or in relation to 3D visualizations, such as virtual sinus endoscopy. To support convenient drawing, also with modern input devices, is thus an essential aspect of surgical planning systems.

FURTHER READING

We discussed segmentation of CT neck data in considerable detail using mass-spring models. In recent years, several alternative approaches were described. Teng et al. [2010] combine thresholding with 3D active contours for lymph node delineation. They target primarily at radiation treatment planning where the target region is larger than the actual tumor. Atlas-based approaches were developed and clinically evaluated [Lee and Rosowski, 2009, Stapleford et al., 2010]. An automatic classification for lymph nodes according to the lymph node levels is highly desirable. Som et al. [1999] introduced such a system. Moreover, Teng et al. [2006] introduced a system that supports the segmentation of a couple of further structures, such

as the mandible and the hyoid. PET/CT data are essential for head and neck surgery planning. Wu et al. [2012a] describe a method to locate and delineate nasopharyngeal carcinoma automatically. They analyze the CT data to automatically locate the (thin) neck region and search for relevant structures also guided by the uptake values in corresponding regions from PET data.

The following hints are focused on ear surgery, since we discussed that portion of ENT surgery rather briefly. Anatomical reconstructions of the middle ear with HR-CT are discussed in [Decraemer et al., 2003]. Semi-automatic segmentation of the mastoid bone—an essential step for ear surgery planning—is described by Salah et al. [2006]. Virtual otoscopy was developed early and refined carefully. In addition to the papers already mentioned [Rodt et al., 2002, 2004], the work of Klingenbiel et al. [2000] and Neri et al. [2001] is outstanding. With respect to surgical training for FESS, we refer to [Pössneck et al., 2005].

The determination of boundary conditions for biophysical ear simulations is discussed by Gea et al. [2010] using a combination of animal experiments and measurements in humans. For understanding hearing disabilities and planning surgery, the middle ear pressure and its local distribution along the tympanic membrane is essential. Among the methods used to determine that pressure is Laser Doppler Velocimetry, [Lee and Rosowski, 2001]. The largest series of virtual otoscopy examinations (213 patients) based on CT and MRI data is documented in Rodt et al. [2004]. A careful analysis of 33 patients with conductive deafness let Pandey et al. [2009] conclude "that virtual otoscopy improves evaluation of the ossicular chain particularly that of smaller structures such as the stapes superstructure which may influence decisions regarding planning of ossiculoplasty."