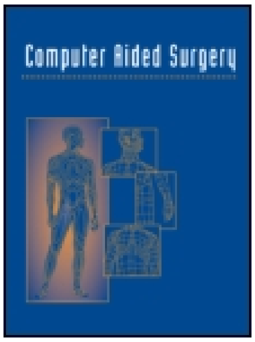

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Computer Aided Surgery

ISSN: 1092-9088 (Print) 1097-0150 (Online) Journal homepage: https://www.tandfonline.com/loi/icsu20

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To cite this article: Filip Schutyser, Vincent Vander Poorten, Johan Van Cleynenbreugel, Pierre Delaere & Paul Suetens (2000) An Image-Based 3D Planning Environment for Hemicricolaryngectomy and Reconstruction by Tracheal Autotransplantation, Computer Aided Surgery, 5:3, 166-174, DOI: 10.3109/10929080009148887

To link to this article: https://doi.org/10.3109/10929080009148887

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Computer Aided Surgery 5:166–174 (2000)

Clinical Paper

An Image-Based 3D Planning Environment for Hemicricolaryngectomy and Reconstruction by Tracheal Autotransplantation

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ABSTRACT **Objective: A new conservation method for unilateral glottal cancer with significant subglottal extension consists of a hemicricolaryngectomy and subsequent reconstruction of the laryngeal defect with a transferable patch of revascularized cervical trachea. In order to restore the three crucial functions of the larynx — airway patency, speech, and swallowing — the reconstructed larynx should resemble a situation with one paralyzed and one intact vocal fold at the glottal level. We hypothesize that this result can be achieved when the tracheal patch meets a typical surgical constraint — the so-called paramedian position at the glottal level — and when the patch is rigidly applied. This hypothesis was tested by developing and using an image-based planning system in a number of situations.**

Materials and Methods: An image-based surgery simulator was developed according to the working hypothesis. To validate the transfer from planning towards actual surgery, a cadaver study was set up. Based on a patient case-study, the sufficiency of the hypothesis for obtaining good functional results was evaluated. Finally, post-operative images of patients who were doing well after being operated without pre-operative planning were compared with retrospective planning to check the necessity of the hypothesis in obtaining good functionality of the neolarynx.

Results: We were able to design an efficient surgery simulator. The transfer from planning towards actual surgery is accurate, and satisfactory functional results were obtained from the patient case-study. The results from the retrospective planning showed that the hypothesis is not necessary to obtain good functional results, and that the smallest possible resection is preferred from the oncological point of view.

Conclusion: The working hypothesis is sufficient for good functional results, but is unnecessary and often undesirable from an oncological point of view. Important lessons are drawn concerning our long-term goal of pre-operative determination of the shape and position of a tracheal patch suitable for optimizing the (neo-) laryngeal functions. Comp Aid Surg 5:166–174 (2000). ©2000 Wiley-Liss, Inc.

Key words: **image-guided therapy, surgery simulation, hemicricolaryngectomy, tracheal autograft**

Received January 5, 2000; accepted April 27, 2000.

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INTRODUCTION

Unilateral glottal cancer with significant subglottal extension is most often treated by total laryngectomy. In contrast, the clinicians involved in this research developed a conservation procedure[1-6] consisting of a hemicricolaryngectomy and a subsequent reconstruction of the laryngeal defect with a transferable patch of revascularized cervical trachea. The advantages of this technique over the formerly performed total laryngectomy are the absence of a permanent tracheostoma and the preservation of the voice, obviating the need for a voice prosthesis and its accompanying inconveniences. In this new conservation procedure, the position of the patch at the glottal level is pivotal in determining its functional result with regard to airway patency, speech, and swallowing. As a working hypothesis, the clinicians involved proposed that the ideal patch position for providing the three crucial larynx functions is the so-called paramedian position (explained in Figure 1). Moreover, they stated that deformation of the tracheal patch can be ignored in an initial approximation.

To envisage all the consequences of the working hypothesis, an image-based laryngectomy simulator specific for the proposed resection and reconstruction technique was developed. A cadaver study was set up to determine whether the results of the simulator could be accurately transferred to the operating room. In one patient study it was investigated whether satisfactory laryngeal functions were obtained when the surgery was performed according to the planning. A retrospective patient study then addressed the final question as to whether the working hypothesis is necessary for obtaining good functional results.

MATERIALS AND METHODS

An image-based surgery simulation environment was developed.[9] At its core is the notion of representing the three-dimensional (3D) space covered by medical image data volume(s) as a 3D scene. In that scene, multi-planar reslices are co-presented with image-derived 3D surface triangle mesh representations of the anatomical structures of interest.

From the routinely made spiral CT images, 3D surfaces of the larynx and trachea are derived.[8] For real patients, the vicinity of other structures and the large differences in degree of calcification of the larynx necessitate manual segmentation.[7] Structures like the arytenoids, which are hard to see on CT, need extra attention. However, for the cadaver larynges, all segmentation was done by thresholding.

Constraints typical for success in this new laryngeal reconstruction technique are incorporated in the surgical simulator. The paramedian position is the constraint defining the desirable morphological result. Other constraints define the cutting planes, including the position of the radial forearm fascial flap revascularizing the cervical trachea segment, the middle of the cartilago thyroidea, and others. In this way, various important surgical parameters are determined (e.g., the distance between the upper border of the arytenoid and the lower border of the cricoid determines the cranio-caudal length of the tracheal patch). Such constraints are visualized as geometric entities (points, planes, axes, allowable transformations), and can be attached as annotations to particular locations of the 3D scene. Based on these constraints, the repositioning of the tracheal patch is determined.

Basic software tools (e.g., cutting of 3D surfaces, annotation tools, etc.) alone are insufficient for this procedure. To supply extra guidance, a menu-based approach guides the surgeon through a number of sub-tasks to complete the virtual operation. Such sub-tasks require the surgeon to instantiate the constraints on the individual anatomy of the patient. Based on his/her expertise, he/she indicates a possible resection and reconstruction configuration on the CT-image volume or on the derived 3D surface representations. During such sub-tasks, software cutting and repositioning actions are performed, whenever necessary, in an iterative way. Figure 1 shows details of a typical simulation.

Once an optimal reconstruction configuration is obtained, a set of measurements that are easily reproducible during the actual operation is derived (see Figure 2). Tracheal patch-related data include the cranio-caudal length of the patch and its upper and lower internal horizontal perimeters. Resection-related data include upper and lower section margins on the thyroid and cricoid cartilage as measured from the anterior midline. These data were used to reconstruct the virtual operation during the actual surgery. Measurement tools are available resembling those commonly used by the surgeon in the operating theater, e.g., (flexi)rulers.

After the actual surgery, post-operative CT-imaging of the resected larynges makes it possible to compare the planned and actual results. The post-to-pre-registration was done by least-squares point-based matching of the fiducial markers and

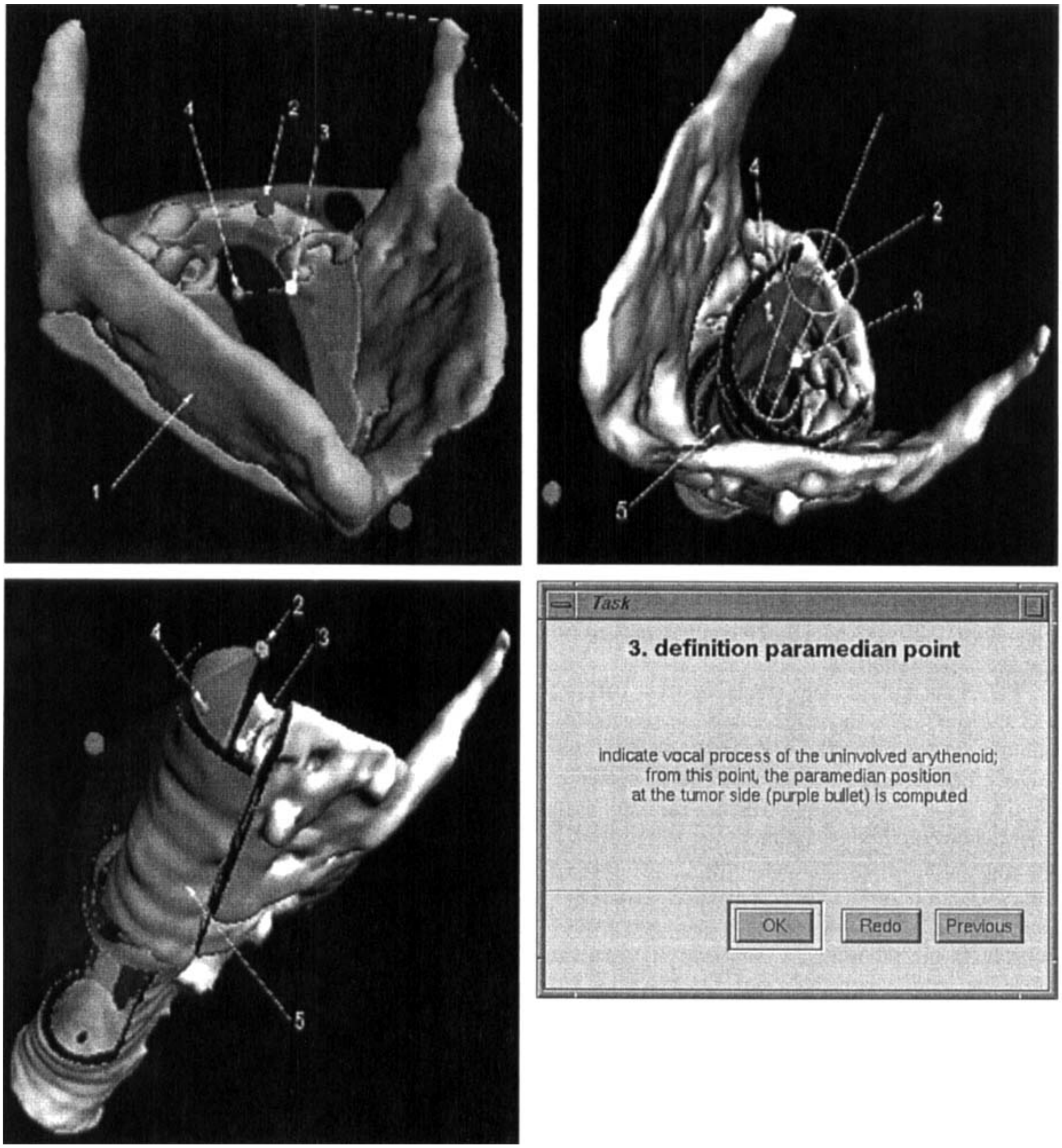

Figure 1. The laryngectomy simulation applied to a cadaver larynx. At top left, an axial CT slice at subglottal level and a surface model of the larynx (1) are partially shown. (2) is one of the 3D points defining the symmetry plane of the larynx. (3) is a 3D point added by the surgeon on an anatomical landmark on the CT slice at glottal level. From this point and from the position of the symmetry plane, the simulator calculates point (4). This point is at the paramedian position. At top right, the same structures are labeled and the tracheal patch (5) has already been cut and translated to an axis in the symmetry plane through point (2). A manipulator is attached to the patch in order to let the surgeon rotate it towards the paramedian position (4). This result is shown at bottom left, where the patch (5) is rotated in such a way that it makes contact with point (4). At that moment, the patch and the larynx are resected as shown. At bottom right, a typical example of a menu is shown. This particular menu asks the surgeon to indicate the cartilago arytenoidea (3).

anatomical landmarks. After registration, the post-operative images were resampled on the grid of the pre-operative image volume to generate comparable measurements. To apply adequate measurements, magnitudes presumed to be related to the functional results of the operation were chosen.[1]

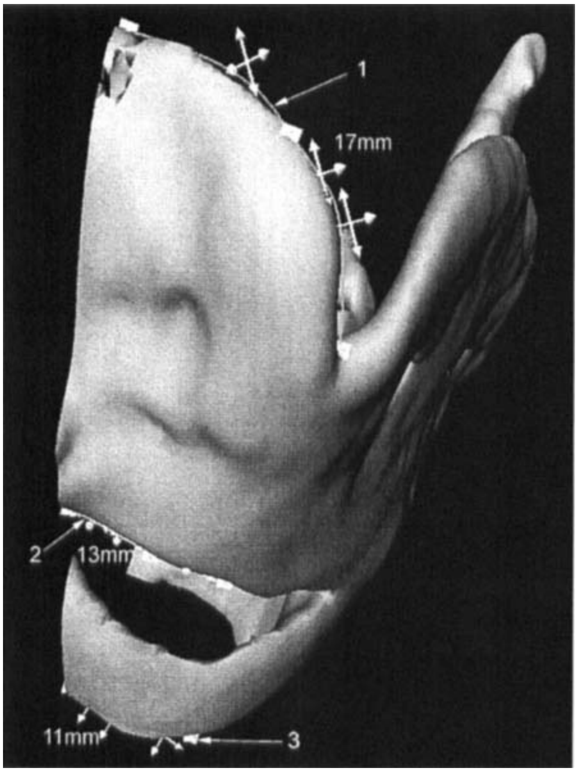

Figure 2. Measurements on the part of the larynx that will be resected. All measurements start from the middle of the larynx, a landmark that can easily be determined intraoperatively. (1) and (2) indicate distances on the cartilago thyroidea, (3) indicates a distance on the arcus cartilago cricoidea. The measurement tool is a flexiruler (i.e., a planar but curved distance).

RESULTS

Cadaver Study

On seven cadaver larynges, we tested whether the simulated operation (i.e., the optimal one according to the hypothesis of the surgeons) could be advantageously transferred to the actual operation in order to achieve the planned morphological results.

For each cadaver larynx, pre-operative CT-imaging was used to plan the operation. The surgeon repeated and adapted the planning until an optimal configuration was reached. Based on this configuration, reproducible distances essential for reconstruction of the virtual operation during the actual surgery were measured.

Based on the seven test cases, a few trends became clear. First of all, the major goal of the planning, i.e., assuring that the patch attains the paramedian position, was achieved. All the tracheal patches were positioned close to this position. However, concerning the anterior-posterior glottal diameter and the airway lumen areas (at the glottal and subglottal level), there were fairly small differences (see Table 1). The fact that there was a slight variation in the stitches used to fix each patch to the cricoidal remnant posteriorly and to the thyroid cartilage and vocal cord remnant anteriorly can explain these divergences from the planned configuration. Also interesting is the observation that, in some cases, the tracheal patch is stretched in the sagittal direction, thus deviating from the planning, which hinges on the assumption of a rigid, non-stretchable tracheal patch. Nonetheless, we can conclude that the pre-surgical planning is accurately transferred to the actual surgery.

Patient Case Study

In order to test whether the hypothesis leads to satisfactory functional results, a case study with a patient was set up.

Surgery was planned with the assumption that the tracheal patch was rigid and that the functional optimum of the surgery is reached when the patch is at the paramedian position (see Figure 4). Subsequently, after obtaining informed consent, the tumor resection and reconstruction using the tracheal autograft were carried out according to the data obtained from the simulation. Table 2 summa-

Table 1 Measurements on Seven Test Larynges

Larynx	AP plan (mm)	AP post (mm)	GL plan (mm^2)	GL post (mm^2)	SG plan (mm^2)	SG post (mm^2)	ΔPM (mm)
1	15	17	104	90	125	110	−1
2	20	17	126	111	170	129	0
3	13	16	52	53	178	213	0
4	21	21	95	55	191	121	−2
5	17	20	77	116	89	143	1
6	20	22	80	109	149	157	0
7	19	14	64	45	105	115	0

AP = Anterior-posterior diameter at glottal level; GL = Area of airway lumen at glottal level; SG = Area of airway lumen at subglottal level; ΔPM = Difference between simulated paramedian distance and post-operative patch position (negative distance means that the patch is more medially located).

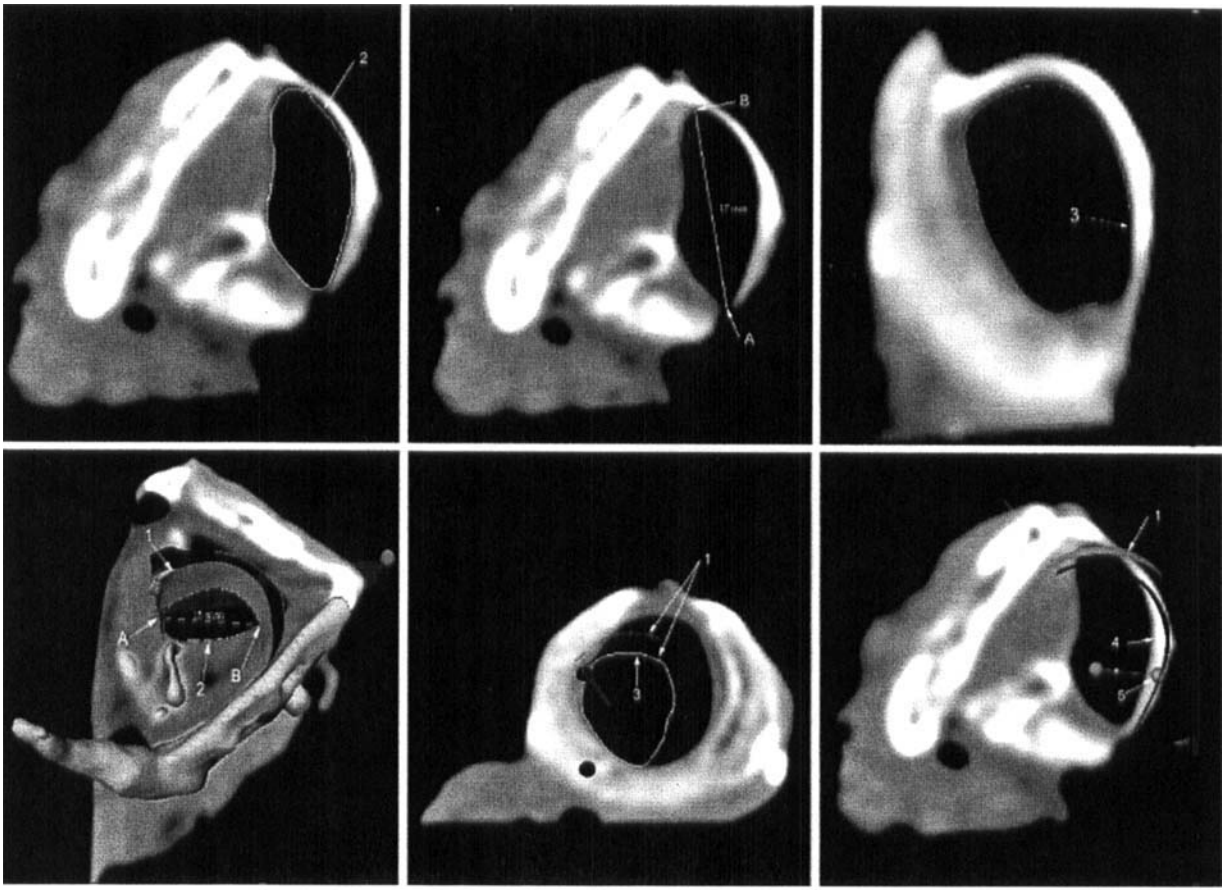

Figure 3. Quantitative measures of larynx 1 as used in Table 1. The upper row shows three slices through the post-operative CT volume. The lower row shows two slices (left and center) through the pre-operative and one (right) through the post-operative CT volume, in combination with simulation data. (1) is the planned tracheal patch; Line AB is the anterior-posterior glottal diameter; (2) is the area of the airway lumen at glottal level; (3) is the area of the airway lumen at subglottal level; (4) is the actual tracheal patch; (5) is the paramedian position. This position is shared by both the planned and actual patches.

rizes the pre-operative findings, the planning result, and the post-operative results for this patient.

From a technical point of view, the planned measurements that could be realized satisfactorily (as determined by looking at the post-operative results in the actual patient) were the anterior-posterior diameter, the glottal area, and the paramedian position of the patch (see Table 2). These morphometric results are compatible with those post-operative functions of the patient that require a neolarynx that can be adequately closed, i.e., swallowing and voice function. The patient was able to recommence full oral feeding on the ninth post-operative day, and had a post-operative maximal voice intensity of 95 dB. However, a major deviation was observed between the planned subglottal area and that actually realized. This had a negative impact on the third laryngeal function, respiration, which requires a neolarynx that can be adequately opened. Thus, the post-operative subglottal stenosis resulted in an inability to decannulate the patient. A second intervention consisting of a tracheaplasty substantially widened the subglottal area and allowed us to decannulate the patient.

Two basic remarks arise from a critical appraisal of the surgery simulation in this case:

- A resection as large as that planned was not necessary from an oncological point of view.
- The surgery simulator predicted a larger subglottic area than the one that was actually obtained.

Retrospective Study

The necessity of the working hypothesis for achieving good functional results was tested by perform-

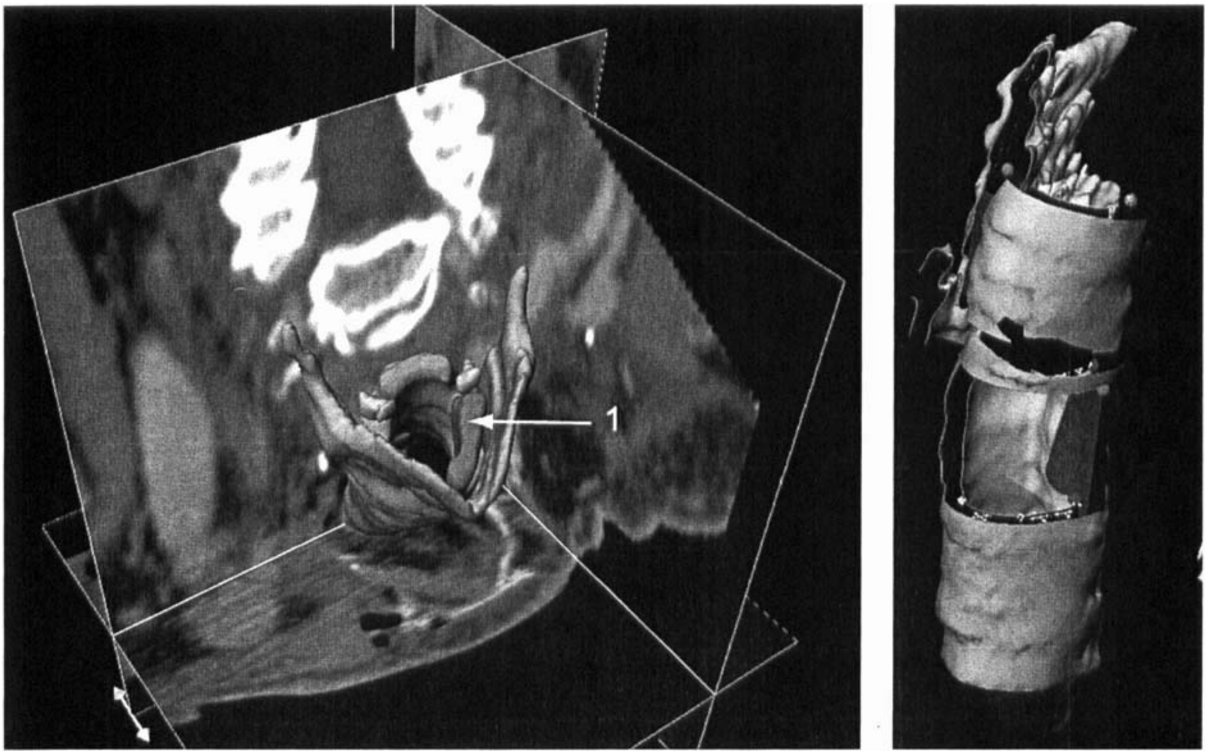

Figure 4. The simulator applied to a real patient. On the left is a 3D scene representation of a larynx containing a T3 glottal cancer with vocal fold fixation (1). On the right is the result of laryngeal resection and tracheal patch relocation.

ing retrospective planning on the pre-operative CT data of patients who were treated using our described surgical technique without the use of the surgery simulator. Three patients with good functional results were selected, and the morphometric data of the actual surgery were compared with those obtained from the retrospective planning. Results are shown in Table 3 and Figure 6. The major findings from this analysis are as follows:

- Currently in the surgery simulator, the anterior resection margin in the laryngeal remnant is determined by the tangent plane of the resected rigid tracheal patch and the thyroid cartilage of the laryngeal remnant. This situation seems perfectly justified in patients requiring a maximal resection due to a large tumor crossing the anterior commisure (as in Patient 1). However, as the majority of patients (like Patients 2 and 3) have smaller tumors that do not need this large resection, a more conservative resection is mandated, and the reconstruction of the resulting defect requires a stretched tracheal patch.
- The constraint "paramedian position at the glottal level" is not essential for obtaining a good post-operative result, as well-functioning patients are observed which do not have their patches in that position. Furthermore, the exactness of the determination of the paramedian position is questionable because it assumes that the arytenoid cartilage can be clearly seen on CT during normal breathing by the patient. However, the arytenoid cartilage is often hard to distinguish on CT and the breathing pattern is often abnormal due to the glottic cancer.
- Patients that do well have a larger subglottic lumen than the one resulting from our simu-

Table 2 Results of Case-Study on Real Patient

AP pre (mm)	AP plan (mm)	AP post (mm)	GL pre (mm^2)	GL plan (mm^2)	GL post (mm^2)	SG pre (mm^2)	SG plan (mm^2)	SG post (mm^2)	ΔPM (mm)
19	15	15	113	94	79	206	128	45	0

See Table 1 for explanation of abbreviations.

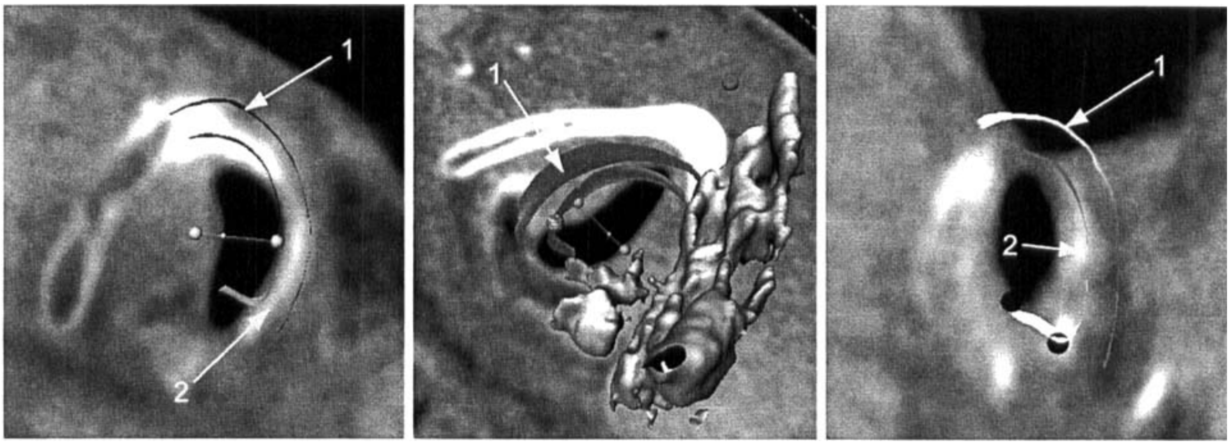

Figure 5. The case-study on a real patient. The left image, comparing the planned (1) and actual (2) postoperative patch shows good correspondence at glottal level. The same differences as in the cadaver study can be noted. In the center, the global change in shape due to the surgery is shown. The CT slice corresponds with the pre-operative geometry, whereas the 3D surface model shows the planning results. Finally, the right image shows the difference in subglottal lumen between the planned and post-operative situations. As the planned situation already implied a significant reduction of subglottal lumen, this post-operative result, reducing the subglottal area even more, is highly undesirable.

lation. The subglottic length of the patch in our simulator is determined by the tangent plane of an assumed rigid patch with the cricoid remnant. This does not seem to be a realistic option.

DISCUSSION AND CONCLUSION

In this paper, a method is discussed for reconstructing laryngeal defects after hemicricolaryngectomy using an autotransplanted tracheal patch. To support this method, an image-based planning system was developed based on the hypothesis that the optimal shape and position of the patch (in the sense of optimizing the three laryngeal functions) are determined by rigidly applying the patch at the so-called paramedian position at the glottal level. The need for simulation in this field has been demonstrated, and the basic hypothesis was tested by assessing the results of the tryout of our surgery simulator.

During the course of the design of our "resection and reconstruction" system and its employment in cadaver experiments, the surgeons reported gaining insight with respect to refinement of their technique. They felt more comfortable when operating on cadaver larynges, mainly because of a higher pre-operative certainty of reaching the paramedian position. They also reported obtaining better insight into the specific anatomy, and even into sometimes-competing constraints that they were only implicitly aware of (e.g., attaining the paramedian position at glottal level versus minimally decreasing the airway lumen area at subglottal level). Validation results concerning planning transfer suggested that the actual surgery agrees fairly well with the planning. In this sense, our image-based system has reached its goal.

In spite of only performing one case-study on a patient, and the occurrence of an important deviation from the planning at the subglottal level, the expected functional results were obtained. This indicates that the hypothesis regarding the shape and position of the patch is a sufficient condition for obtaining good functional results. However, based

Table 3 Morphometric Data from Actual Surgery Compared with those from Retrospective Planning

Patient	AP pre (mm)	AP plan (mm)	AP post (mm)	GL pre (mm^2)	GL plan (mm^2	GL post (mm^2)	SG pre (mm^2)	SG plan (mm^2)	SG post (mm^2)	ΔPM (mm)
1	14	17	22	93	105	167	237	132	265	2
2	16	11	18	91	40	156	240	85	185	—
3	28	21	20	233	136	151	365	226	358	—

See Table 1 for explanation of abbreviations.

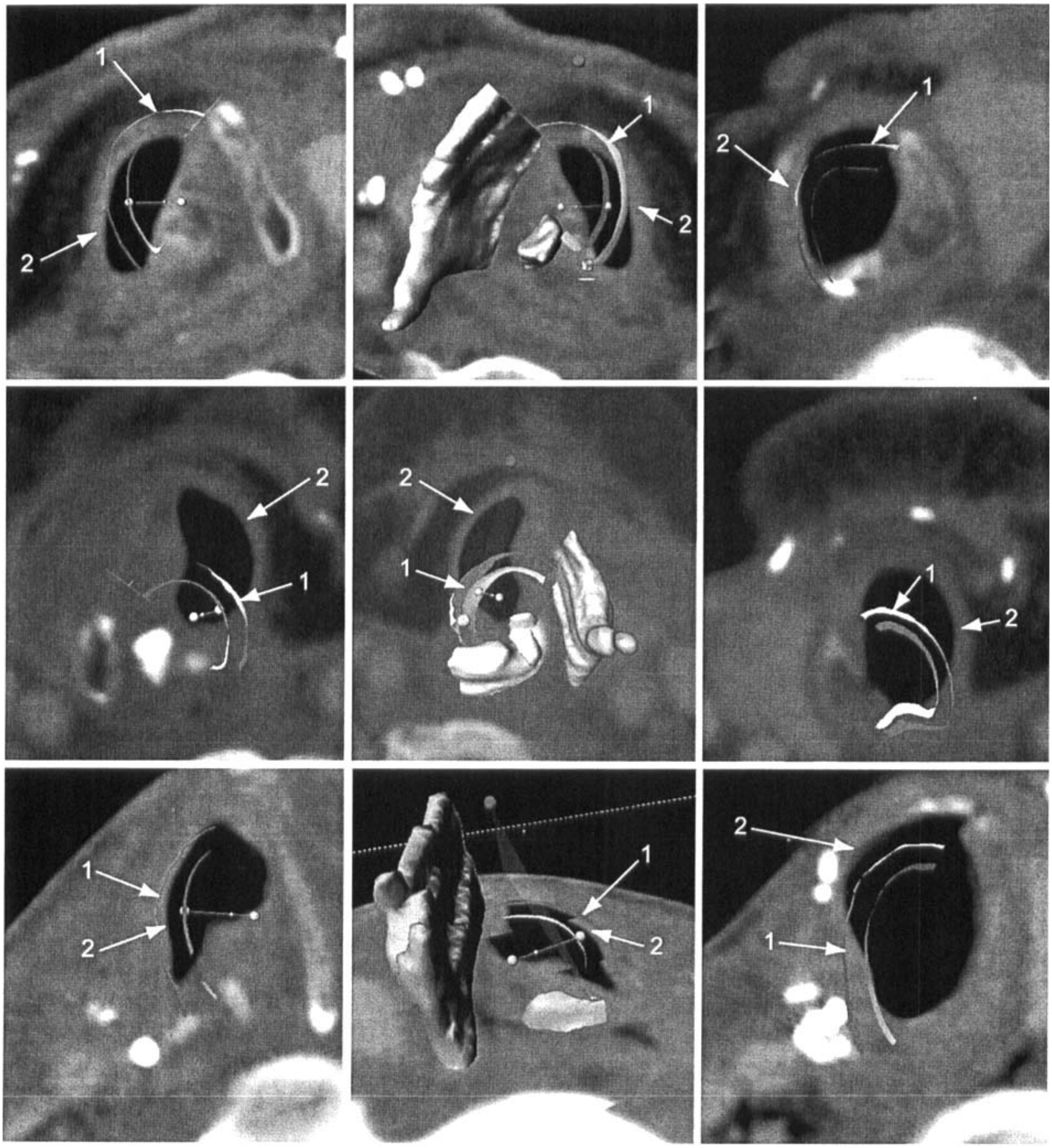

Figure 6. Differences between the retrospective planning results and the actual operational results for 3 patients. Each row corresponds to one patient. The first column compares the planned (1) and postoperative (2) patches at glottal level. The second shows the same situation together with the planned resected thyroid cartilage. Finally, the third column illustrates the comparison of the planned and post-operative patch at subglottal level. These figures illustrate that the hypothetical assumptions about the rigidity of the tracheal patch and the importance of the paramedian position are not necessary in order to obtain good functional results. Patient 1 (top row) corresponds to a group of patients where the tumor size compels a maximal resection. In such cases, quite a good correspondence with the retrospective planning can be observed. Patient 2 represents a group of patients where a rigid patch geometry defines too large a resection in contrast with what is needed from an oncological point of view. In this case, our hypothesis is undesirable. A larger part of the thyroid cartilage is kept, and the tracheal patch is highly deformed. Finally, Patient 3 is typical of the largest group of patients. The characteristics of the geometric construction vary between the extreme cases of Patients 1 and 2.

on the results of the retrospective study, it becomes obvious that the hypothesis is not always needed for good functional results. Indeed, the large resection of the thyroid cartilage is often unnecessary from an oncological point of view. To cope with this problem, our simulation environment should be extended towards flexible tracheal patches, as it is the rigid patch that causes the large resection. Based on clinical experience, a patch should be obtained which has the same length as the remnant vocal cord, and it should be positioned in a plane between the midline and a distance of 1 or 2 mm laterally.

This study revealed the need for two major changes to the planning environment. First, it is obvious that a flexible patch is needed in different clinical situations. However, modeling a flexible patch in a planning system has inherent difficulties: the biomechanical properties (elasticity modulus, Young modulus, etc.) of the cervical trachea are largely unknown. Moreover, significant variation between different patients occurs because of different degrees of calcification of the trachea. The second important change to this environment will be a reversal of the current planning methodology and its adaptation to the clinical reality of a resection dictated by the extent of the tumor and not by the reconstruction technique. Although the surgical procedure is currently performed without the simulation technique, it is believed that, if a planning environment including the flexible patch simulation can be created, the precision of the technique will be improved and the use of the planning environment will then be highly desirable.

ACKNOWLEDGMENTS

The work discussed here belongs partly to the Flemish government-funded IWT ITA-GBO202, TeleVisie project, partly to the grant GOA/99/05 (VHS+ Variability in Human Shape and Speech) of the K.U. Leuven Research Council, partly to the EU-funded Brite Euram III PISA project (nr. BRPR CT97 0378), and to a grant for research specialization from the Flemish Institute for the Promotion of Scientific-Technological Research in Industry (IWT) awarded to Filip Schutyser.

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