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Coregistration of Preoperative Computed Tomography and Intraoperative Three-Dimensional Rotational X-Ray Images for Cochlear Implant Surgical Evaluation

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Objective: A registration procedure of intraoperative three-dimensional rotational x-ray (3DRX) imaging and preoperative computed tomography (CT) imaging so that intraoperative CT quality imaging is available during cochlear implant surgery, providing detailed information concerning electrode position in the cochlea and its relation to surrounding bony structures.

Study Design: Retrospective case series

Setting: Tertiary referral center

Data: The imaging of five patients who had undergone cochlear implant surgery is used to develop a semiautomatic registration procedure to integrate intraoperative 3DRX and preoperative CT. The method is implemented in advanced medical imaging software to compute the transformations. The electrode is segmented from the registered 3DRX images using a semiautomated approach. The segmented electrode is superimposed onto the CT data. The methods are quantitatively validated based on expert-labeled anatomical landmarks. These landmarks are identified in the CT and 3DRX images by an expert.

Main Outcome Measure: Mean error of the registration procedure for five anatomical landmarks in millimeters.

Results: Quantitative analysis showed a mean error of between 0.5 and 1 mm for all anatomical landmarks, suggesting that the results are trustworthy.

Conclusion: We developed a reliable procedure for the registration of intraoperative 3DRX imaging and preoperative CT imaging for cochlear implant surgery. This registration procedure provides the ENT surgeon intraoperative high-quality CT imaging during cochlear implant surgery. Key Words: 3DRX—Cochlear implant—Deafness—Hearing loss—Intraoperative imaging—Surgery.


At the time of the introduction of cochlear implantation, the cochlear implants were only available for patients afflicted with congenital deafness. Nowadays, the indication extends also to people with only high-frequency sensorineural hearing loss with residual hearing of the lower frequencies (1–3). Implanting people with residual hearing makes hearing preservation surgical techniques during cochlear implant surgery extremely important. There are many factors influencing effective hearing preservation during cochlear implant surgery.

The position of the electrode is an important factor in the functional outcome of cochlear implantation. Shepherd et al. (4) determined significant threshold reductions when the electrode is located in the scala tympani, close to the modiolus. Aschendorff et al. (5) reported better speech performance in scala tympani insertions. Speech performance was poorer when dislocation of the electrode, from the scala tympani into the scala vestibule, occurs. The poorest speech performance occurs in scala vestibuli implantation. Skinner et al. (6) detected a negative correlation between scala vestibule insertions and word tests. Finley et al. (7) reported a negative correlation between scala vestibule insertions and word recognition scores. Correct insertion of the electrode in the scala tympani close to the modiolus improves functional outcome.
Others reported a correlation between insertion depth and speech performance (7–12).

Lehnhardt (13) described the soft surgery procedure to reduce intracochlear damage during insertion. Meshik et al. (14) determined that insertion inferior or anteroinferior to the round window may facilitate atraumatic insertion. Postelmans et al. (15) compared the suprameatal approach and a mastoidectomy and posttympanic approach for cochlear implantation. There has been no significant reported difference in functional outcome between the methods. There is no difference between a cochleostomy and a round window insertion regarding hearing preservation (16).

When intracochlear damage caused by electrode insertion occurs, it ranges from minor trauma to severe disruption of the organ of Corti. Several electrodes have been specifically developed to reduce insertion trauma. Briggs et al. (17) reported that narrow flexible straight arrays are the least traumatic. Curved or stiffer electrodes are correlated with basilar membrane perforation. Roland et al. (18) analyzed the effect of a modiolar hugging electrode. They found cochlear damage caused by the electrode. Briggs et al. (19) evaluated the modiolar research array, a very thin precurved perimodiolar prototype electrode array that is held straight by a sheath. The sheath is helpful during the insertion and does not cause additional intracochlear damage. The sheath could be safely removed after insertion of the electrode.

To achieve hearing preservation during cochlear implantation, it is important for the surgeon to monitor the position of the electrode. Imaging has become a critical tool for monitoring electrode position. Carelsen et al. (20) described the value of intraoperative three-dimensional rotational x-rays (3DRX) for monitoring the localization of the electrode in cochlear implant surgery. With 3DRX, you can observe misdirection, or foldovers, of the electrode (21–23). Intraoperative imaging is a valuable tool.
especially in cases of postmeningitis or otosclerosis where insertion can be difficult (24,25). Intraoperative imaging is advantageous because, in the case of suboptimal insertion, revisions can be made during the same procedure. The main limitation of intraoperative 3DRX imaging is its relatively low resolution; scala tympani and scala vestibule insertions cannot be clearly resolved nor can the position of the electrode in relation to the modiolus be recovered. The aim of this article is to register intraoperative 3DRX imaging and preoperative computed tomography (CT) imaging so that intraoperative CT quality imaging is available during cochlear implant surgery, providing detailed information concerning electrode position in the cochlea and the position of surrounding bony structures.

MATERIALS AND METHODS

We present a registration pipeline designed to accurately register intraoperative 3DRX to preoperative CT. Aside from a simple preprocessing stage, explained in the following sections, the method is fully automated. Furthermore, we use a semiautomated method to segment the implanted multielectrode array from the 3DRX image and then overlay the array in the CT image. Figure 1 provides an overview of our entire approach.

Registration Pipeline

The registration algorithm used in this work seeks to align the images based on matching intensities in the regions containing bone in each image. The output of the algorithm is a transformation that warps the 3DRX image into the CT image domain.

Before registration, the following preprocessing steps are performed:
1. CT ROI Selection: A region of interest (ROI) containing slightly more than all of the anatomical information in the 3DRX image is manually delineated in the CT image.
2. Bone Segmentation: Simple intensity thresholding is used to segment the bone from the CT and 3DRX images.
3. Masks: Segmentations are used as bone masks on original image pairs. Figure 2 contains example slices from the 3DRX and CT, before registration, and the ROI is chosen from the CT. Figure 3 contains the bone masks determined by thresholding these slices. Because the 3DRX image contains significantly more noise than the CT, its resultant bone mask is less accurate. Nonetheless, this mask is suitable for registration. A coarse rotation, determined empirically, is also applied to all 3DRX images as an initialization for the registration. Each 3DRX image is acquired with a reasonably similar field of view, and this rotation is largely uniform for all data sets.

Registration proceeds in two stages. First, a similarity transform (scale, translation, and rotation) is computed to roughly align the images. An affine transform (scale, translation, rotation, and shearing) is then determined to obtain the final result. Both stages seek to maximize, by means of registration, the normalized correlation between the intensities in each image. This measure is ideal for template-matching problems such as ours, where we expect similar intensity distributions but not necessarily similar contrast in the image pairs. Both stages compute a multiresolution registration, that is, the images are smoothed with a Gaussian kernel of decreasing width so that large structures are initially matched before fine details. The registration result is iteratively refined at each resolution. As an example, Figure 4 contains a registered 3DRX image overlaid on the corresponding CT.

FIG. 3. Sections of bone masks for 3DRX (A) and CT (B). These masks are produced by thresholding.

FIG. 4. Section of registered 3DRX image is overlaid on the corresponding CT slice.
Fusion

The multielectrode array is segmented from the registered 3DRX using a simple semiautomated approach. As an example, Figure 5 contains a 3-D rendering of the 3DRX image with the segmented array overlaid.

A user sequentially clicks on the electrode locations in the 3DRX image, and a smooth curve is fit through these points. This curve is then superimposed onto the CT data, where measurements can be made regarding its proximity to clinical landmarks. Renderings of the array in the CT are shown in Figure 6.

Experiments

The registration method is applied to five subjects who have undergone surgery to implant a multielectrode array at the University Medical Center Utrecht.

Data

Preoperative CT images are reconstructed with a resolution of 0.21 × 0.21 × 0.3 mm³. Three-dimensional rotational x-ray images of the implanted array and the surrounding structures are reconstructed with a resolution of 0.71 × 0.71 × 0.71 mm³ using a motorized C-arm.

Methods are implemented in advanced medical imaging software, and the elastix toolbox is used to compute the transformations (26). Registrations take, on average, 14 minutes on a 64-bit PC with eight 2.27-GHz processors and 16-GB RAM.

Quantitative Analysis

Table 1 contains the target registration errors for the five anatomical landmarks identified by an expert observer. The errors for each landmark along with the mean error are less than a voxel, suggesting that the results are trustworthy. It should be noted that the registration error is larger for some targets than others, suggesting that the registration results are poorer for these locations. Alternatively, these locations may have been more difficult to identify manually in the images. Furthermore, the large

Subjects

For this study, we used the imaging of five patients who underwent cochlear implant surgery. All patients were operated on using a suprameatal approach (27).

Validation

Methods are quantitatively validated using five expert-labeled anatomical landmarks identified by an ENT resident. These landmarks are identified in both the CT and 3DRX images. The transformations computed by the registration are then used to warp the points in the 3DRX image into the CT domain, where Euclidean distances are calculated by comparing these locations with their corresponding locations in the CT image. Furthermore, because one patient required a postoperative CT, the corresponding intraoperative 3DRX is registered to this image to provide additional validation. Electrode locations in the cochlea are identified in the warped 3DRX and the postoperative CT, and Euclidean distances are calculated between these points.

RESULTS

Note in the overlay images in Figure 4 that the 3DRX overlay visually corresponds with the CT image. There is no obvious misalignment. Nonetheless, the results are limited by the resolution of the images, and the regions registered in this project contain small anatomies of clinical interest. For this reason, the quantitative figures are more illuminating.
TABLE 1. Target registration errors

<table>
<thead>
<tr>
<th>Vestibulocochlear nerve</th>
<th>Facial nerve</th>
<th>Vestibular aqueduct</th>
<th>Sigmoid sinus</th>
<th>Horizontal canal</th>
<th>Mean</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.592 ± 0.283</td>
<td>0.983 ± 0.172</td>
<td>0.720 ± 0.141</td>
<td>0.499 ± 0.140</td>
<td>0.887 ± 0.338</td>
<td>0.736 ± 0.201</td>
</tr>
</tbody>
</table>

Five landmarks are identified in each image by a trained expert, and distance after registration is calculated between the registration target and the transformed point in the three-dimensional rotational x-rays. Values are given in millimeters.

variance associated with several of the measures can be attributed to large differences in the field of view between 3DRX scans, making landmark identification in some images more difficult than others.

Figure 7 contains the multielectrode array from the postoperative CT image segmented and overlaid on 3DRX image. Note that the overlay corresponds with the array locations in the 3DRX image. The first five electrode locations are quantitatively compared in Table 2.

DISCUSSION

We described the registration of intraoperative 3DRX imaging to preoperative CT imaging. With this registration, we can place the electrode array in the preoperative CT scan, which allows us to relate the position of the electrode to its surrounding bony cochlea with the advantage of a better quality and higher-resolution CT scan images.

Hearing preservation becomes more important during cochlear implant surgery, so do the position of the electrode. The electrode should be placed in the scala tympani close to the modiolus. With this registration tool, it’s a first step to detailed high-quality intraoperative imaging during cochlear implant surgery.

The registration is still time-consuming, it takes approximately 10 minutes to make the 3DRX imaging and it takes another 15 minutes for the registration. But in patients with residual hearing, postmeningitis, or otosclerosis, we are convinced that it is justified to do the registration to monitor the exact location. Registration offers the surgeon a chance to improve the position or to do an electrode array reinsertion during the same procedure.

In the future, for other indications, intraoperative 3DRX imaging may prove useful. For example, in case of middle ear implantations like a sound bridge of a bone bridge and even for a mastoidectomy or radicalization, these registration tools allow for intraoperative monitoring of surgery.

Schipper et al. (28) described the use of computer-assisted cochlear implant surgery using a navigation system. They reported a deviation of 1.6 mm around the cochleostomy site. Matsumoto et al. (29) developed a noninvasive image guidance for cochlear implant surgery using the STAMP method and navigation software. They reported an average registration error of 2.4 mm. It gives the surgeon feedback of his performance during cochlear implant surgery. Stelter et al. (30) used an intraoperative CT scan for image-guided cochlear implantation. It gives a detailed view of anatomical landmarks in the mastoid. The average deviation was between 0.9 and 1.01 mm and is quite precise. Drawbacks of this navigation are the costs and the time needed for preparing the navigation. Therefore, interdisciplinary use by neurosurgeons, maxillofacial surgeons, and orthopedic surgeons is required to make it cost-effective.

Compared with these navigation tools, our registration is more accurate with a standard error between 0.5 and 1 mm. Our method is more economic. It cannot help us while we are performing the insertion, but we have a check immediately after insertion in the same session.

In the future, minimally invasive cochlear implant surgery will grow in popularity. Majdani et al. (31,32) and Reda et al. (31,32) described a registration procedure for surgical navigation using intraoperative flat-panel volume computed tomography. Their registration procedure is reported to have an accuracy of less than 0.2 mm. Their registration procedure allows the ENT surgeon to drill a straight tunnel to the cochlea and perform a cochleostomy using a minimally invasive technique. Their method is more precise than ours, but their patients were exposed to relative high doses of x-rays by using flat-panel volume computed tomography compared with using 3DRX and preoperative CT scan.

CONCLUSION

We developed a reliable semiautomatic procedure for the registration of intraoperative 3DRX imaging and preoperative CT imaging for cochlear implant surgery. This registration procedure provides the ENT surgeon intraoperative high-quality CT imaging with the intraoperatively made 3DRX images fused with it. The intraoperative 3DRX scanning causes low-dose radiation exposure. The next step to help improve the clinically relevant images available to the surgeon is by fusing intraoperative acquired images with preoperative high-resolution magnetic resonance images—the obvious advantage being a more detailed overview of the soft tissues surrounding the electrode array. This registration procedure can be a next helpful step to a new method.

TABLE 2. Quantitative comparison between transformed electrode array in three-dimensional rotational x-rays with array in postoperative computed tomography

<table>
<thead>
<tr>
<th>Electrode</th>
<th>Distance</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0.208</td>
</tr>
<tr>
<td>2</td>
<td>0.295</td>
</tr>
<tr>
<td>3</td>
<td>0.466</td>
</tr>
<tr>
<td>4</td>
<td>0.499</td>
</tr>
<tr>
<td>5</td>
<td>0.742</td>
</tr>
<tr>
<td>Mean</td>
<td>0.442 ± 0.206</td>
</tr>
</tbody>
</table>

Values are given in millimeters.
for intraoperative navigation during minimally invasive cochlear implant surgery.

REFERENCES