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Image-guided otologic surgery

R.F. Labadie[a,*], M. Fenlon[b], H Cevikalp[a], S. Harris[a], R. Galloway[a], J.M. Fitzpatrick[a]

[a] *Department of Otolaryngology—Head and Neck Surgery, Vanderbilt University (Nashville) Medical Center, S-2100 Medical Center North, Nashville, TN 37232-2559, USA*
[b] *King's College, London, UK*

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Abstract

Application of image-guided surgical systems to otologic surgery has been limited by the need for submillimeter accuracy via a fiducial system that is easily useable (i.e. noninvasive and nonobstructive). To overcome these limitations and demonstrate the feasibility of image-guided otologic surgery, a novel fiducial marker system was constructed which attaches to a dental bite-block and has fiducial markers surrounding the surgical field of interest (the ears/temporal bones). Accuracy was tested by fitting the device to a cadaveric skull and embedding targets near anatomically important locations. High-resolution CT scanning (thickness = 0.5 mm) was then performed. Marker and target locations were measured in physical space using an infrared, image-acquisition system. These measurements were used in calculating target registration error—the error associated with identification of the surgical targets. This error was minimized when the maximum number of fiducial markers was used (nine fiducials surrounding each ear). Submillimeter target registration error was repeatedly achieved with five markers surrounding the ear of interest and one marker centrally located on the contralateral side.

Keywords: Image-guided surgery; Registration error; Fiducial markers; Otology; Mastoidectomy

1. Introduction

Otologic surgery is undertaken to treat a number of ear disorders including otitis media (treated via pressure equalization tube placement), conductive hearing loss

Abbreviations: TRE, target registration error; LADS, locking acrylic dental stent; CSOM, chronic serous otitis media.

* Corresponding author. Tel.: +1-615-343-6166; fax: +1-615-343-7604.
E-mail address: robert.labadie@vanderbilt.edu (R.F. Labadie).

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(treated via middle ear exploration and ossicular chain reconstruction), vertigo (treated via endolymphatic sac decompression, vestibular nerve section, or labyrinthectomy), and sensorineural hearing loss (treated via cochlear implantation). After tube placement for otitis media, which is the most commonly performed surgical intervention in the western world, the most common ear disorders requiring surgical intervention are chronic serous otitis media (CSOM) and cholesteatoma. Chronic serous otitis media is characterized by inflammation of the mucous membrane lining the middle ear which does not respond to medical therapy. Cholesteatoma consists of keratinizing squamous epithelium (skin) trapped within the middle ear cavity where it is locally destructive leading to chronic infection, hearing loss, facial nerve paralysis, and vertigo. Both CSOM and cholesteatoma are ultimately managed by surgical intervention consisting of mastoidectomy (described below). The incidence of these disease processes varies by population and age. Overall, annual incidence approaches 100/100,000 [1,2], approximately the same incidence as appendicitis. Despite its relative common presentation, it is poorly understood among individuals outside otolaryngology.

Surgery, performed via a tympanomastoidectomy, consists of removing the diseased tissue by surgically drilling away select portions of the temporal bone, the bone that encases the ear. Also encased within the temporal bone, and at risk during surgical intervention, are the facial nerve (injury results in paralysis of the face), the inner ear (injury results in permanent hearing loss and vertigo), the floor of the cranial vault (injury results in leakage of cerebrospinal fluid), and the internal jugular vein and carotid artery (injury results in blood loss which may be life threatening). Surgical intervention proceeds after radiographic imaging studies are obtained (i.e. CT scans), which can be used to prepare for surgery and which may be referenced during surgery. During surgery, which is performed using an operating microscope and surgical drill, visual feedback and surgical experience are the safeguards used to ensure accurate dissection.

Otologic surgery, especially given its rigid tissue (the temporal bone), is ideally suited for image-guided surgical systems. Application of image-guided surgery to otologic applications has been limited by the need for submillimeter accuracies to prevent injury to adjacent structures (i.e. the facial nerve) via a fiducial system that is easily useable (e.g. noninvasive and nonobstructive). Our goal was to overcome these limitations and demonstrate the feasibility of image-guided otologic surgery using a custom-designed fiducial system.

2. Methods

To satisfy the goal of an easily useable, noninvasive fiducial system, the Locking Acrylic Dental Stent (LADS) was utilized [3]. This device consists of a modified dental bite-block which is custom molded for individual maxillary dental patterns. For fitting purposes, the LADS is broken down into a central portion which imprints the lingual and occlusal surfaces of the maxillary teeth as well as a right and left piece which imprint the buccal surfaces and attach to the central portion locking the mouthpiece onto the maxilla. An extension from the central piece allows mounting of external hardware. The LADS, in conjunction an attached frame, has been shown to be effective for microscope-guided interventions [4]. For the current study, a new fiducial frame was designed and built to surround the surgical field of interest, the ears/temporal bones. As in Ref. [4], the frame was initially constructed such that fiducial markers could be placed in numerous configurations to determine an optimized fiducial placement pattern that minimized both fiducial maker number as well as registration error.

This device was fitted to a cadaveric skull using a LADS customized to the skull's dentition (Fig. 1). Commercially available markers (Acustar™, Z-Kat, Hollywood, FL, USA) were mounted on the fiducial frame. Nine markers were placed surrounding each external ear. These 18 markers were used as fiducial markers for the purposes of registration. In addition, markers were placed at surgically significant anatomic locations: the internal auditory canal and stylomastoid foramen. These two markers served as surgical targets for the purpose of estimating target registration error (TRE). Radiographic markers, which are imaged during radiographic studies, are replaced by physical markers, which are used in identifying coordinates in the laboratory. As shown in Fig. 2, the radiographic markers and physical markers mount on the same post and are designed such that it is possible to localize the same point in both radiographic space and physical space [5]. The centroid of the radiographic marker (a) and the center of a hemispherical divot in the physical marker (b) are in the same position relative to the post. As shown in (c), a spherical probe tip placed into the hemispherical divot localizes the center of the divot.

CT scanning was then performed using a clinically applicable, temporal bone acquisition protocol (scan thickness of 0.5 mm). The center of each radiographic marker was then identified in CT space using a previously described algorithm [6]. The skull was then transported to our laboratory where the radiographic markers were replaced by

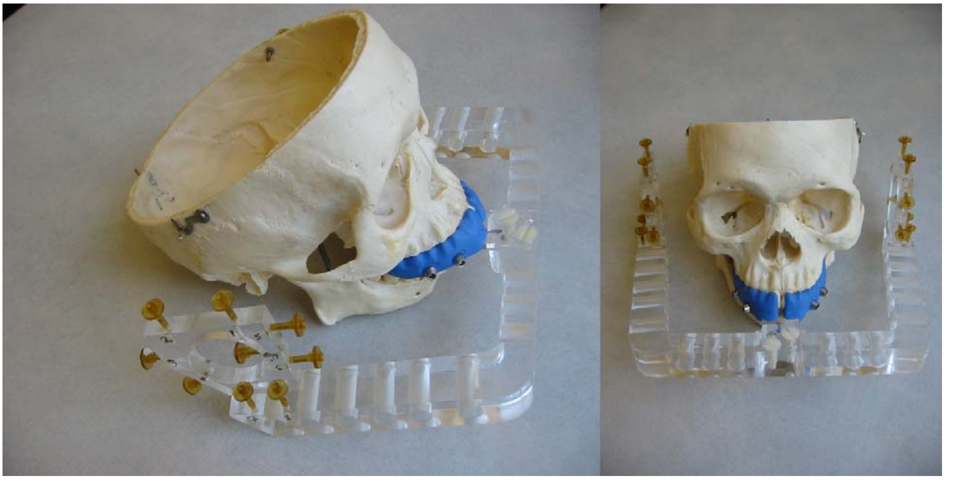

Fig. 1. Fiducial frame (constructed of plexiglass) mounted to cadaveric dentition using LADS. Fiducial markers are shown surrounding each temporal bone.

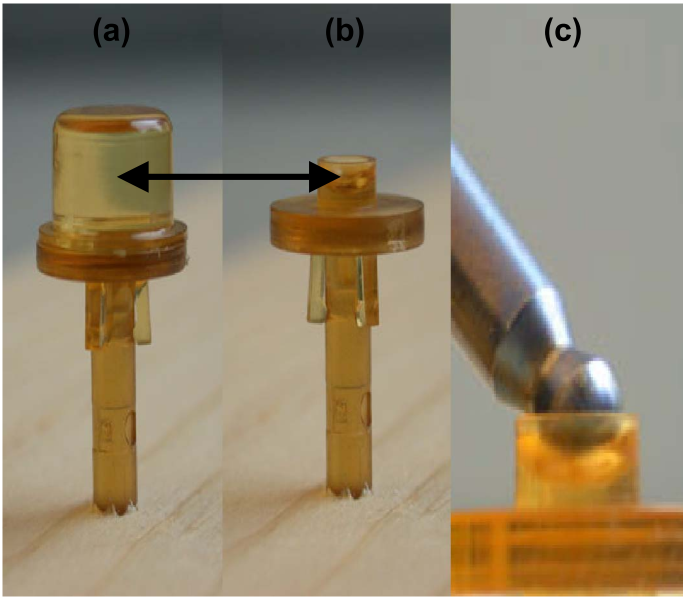

Fig. 2. Radiographic marker (a) and physical marker (b), each mounted on the same post. In (c), the spherical tip of a tracked probe is shown in contact with the hemispherical divot of the marker in (b). The arrows point to the centroid of the radiographic marker and the center of the divot in the physical marker.

the physical markers. The physical markers were localized using a commercially available infrared optical tracking system (Polaris®, Northern Digital, Waterloo, Ontario, Canada).

Rigid registration between physical space and radiographic space was performed using various subsets of the fiducial markers with a closed-form algorithm (singular-value decomposition) [7]. Each resulting transformation was applied to each surgical target marker in physical space. The disparity between the transformed position and the measured position in the radiographic space served as a measure of registration error. We gather statistics on two types of registration error—"fiducial registration error" (FRE) and "target registration error" (TRE). The former is the root mean square of the distance between corresponding fiducial.

3. Results

The numbering system for the fiducial markers in shown in Fig. 3. TRE for various combinations of markers are given in Table 1. With all 18 fiducial markers used for registration, target registration errors (TRE) for the surgical sites (TRE1 = right internal auditory canal, TRE2 = right stylomastoid foramen) were 0.41 and 0.90 mm, respectively. Surrounding the ear of interest with markers (nine markers) and balancing this with a single, centrally placed marker on the contralateral side produced similar results with TRE1 = 0.52 and TRE2 = 0.90. Results for the inverse situation (markers sur-

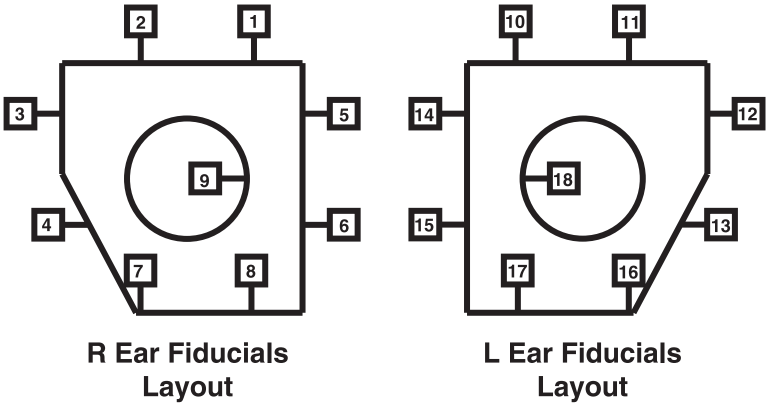

Fig. 3. The fiducial marker arrangements which surround each ear. The markers numbers are referenced in the table below which gives TRE for combinations of markers.

rounding the contralateral ear of interest with a single marker balancing the side of interest) produced worse results with TRE1 = 1.26 and TRE2 = 1.80. These were the largest errors noted in 17 combinations of fiducial markers. Acceptable errors (< 1 mm) were reproducible achievable using five markers surrounding the ear of interest balanced with a centrally located marker on the contralateral side for a critical number of six total fiducial markers.

Table 1
Surgical targets were placed on the right side of the skull at the internal auditory canal (TRE1) and the stylomastoid foramen (TRE2)

Scenario	Markers included	Number markers	FRE	TRE1	TRE2
All	1–18	18	0.49	0.41	0.90
R All	1–9	9	0.35	0.52	0.90
L All	10–18	9	0.48	1.26	1.80
R All + L Center	1–9, 18	10	0.34	0.47	0.83
L All + R Center	10–18, 9	10	0.49	0.51	1.10
R Mid + L Center	1, 2, 7–9, 18	6	0.32	0.54	0.80
L Mid + R Center	10, 11, 16–18, 9	6	0.37	0.48	1.18
R Mid + L Mid	1, 2, 7–11, 16–18	10	0.45	0.40	0.98
R Ant	3–8	6	0.31	0.40	0.71
L Ant	12–17	6	0.46	0.92	1.06
R Ant + L Ant	3–8, 12–17	12	0.44	0.46	0.84
R Lim Ant + L Center	1, 5, 6, 8, 9, 18	6	0.28	0.58	1.02
L Lim Ant + R Center	10, 14, 15, 17, 18	6	0.52	0.50	1.06
R Lim Ant + L Lim Ant	1, 5, 6, 8–10, 14, 15, 17, 18	8	0.48	0.52	1.02
R Ant, Sup + L Center	1, 5, 6, 9, 18	5	0.20	0.65	1.19
L Ant, Sup + R Center	9, 10, 14, 15, 18	5	0.44	0.35	0.97
R Ant, Sup + L Ant, Sup	1, 5, 6, 9, 10, 14, 15, 18	8	0.45	0.49	1.00

Scenario indicates the strategy, marker numbers refer back to Fig. 3, and FRE, TRE1, and TRE2 are given in millimeters (R = right, L = left, Mid = middle, Ant = anterior, Lim = limited, Sup = superior).

4. Conclusions

These early findings show that image-guided otologic surgery with submillimeter accuracy is achievable with a minimally invasive fiducial frame. Geometric arrangement of fiducial markers and their relation to target position affects error as expected from previous theoretical predictions [7,8]. Specifically, error is minimized with arrangement of the markers surrounding the surgical site of interest such that the centroid approximates the surgical site. In addition, accuracy improves with the number of markers but with diminishing returns over a critical number. This becomes important in high-resolution CT scanning when the scannable volume is finite, thus limiting the feasible number of markers. These results are being validated intraoperatively.

Acknowledgements

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