Surgical Workflow Considerations for Mastoidectomy using a Bone-Attached Robot

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I. Background / Motivation
Mastoidectomy required for many ear surgeries
- Removal of pocket of bone to gain access to middle and inner ear for a variety of procedures.
- Vital anatomical structures embedded in mastoid bone (e.g. facial nerve, chorda tympani)
- ~120,000 cases per year in U.S.

Image-guided robotic system has the potential to reduce the likelihood of damage to vital anatomy, require the removal of less bone, and decrease operation time.

II. Robotic Approach
1. Robot performs bulk removal of bone
2. Surgeon completes surgery as necessary (e.g. removal of acoustic neuroma, electrode insertion)

Bone-attached robot
- Three incisions / screws required for fixation
- Rigid, accurate registration between robot and patient
- Eliminates need for external tracking system
- 4 degrees-of-freedom: 3 linear joints and one rotational joint (enables access to overhung bone)
- Standard surgical drill mounts to robot

III. Surgical Workflow

1. Acquire pre-operative CT scan.
   - Automatically segment vital anatomy (facial nerve, chorda tympani, etc.).
   - Surgeon outlines bone to be removed by robot.
   - Segmentation converted to 3D target volume.

2. In the operating room, attach pre-positioning frame (PPF) to patient’s skull.
   - PPF attaches to skull via 3 small screws; contains spheres for robot attachment and image-to-OR registration.

3. Register intra-op CT to pre-op CT and transform segmentation data.
   - Localize fiducial markers.
   - Register robot to patient.
   - Plan safe milling path.
   - Convert to robot joint values (accounting for skull geometry, bone density, etc.)

4. Mount robot to patient, begin procedure.
   - Ball-socket “gripper” mechanisms on base of robot lock to PPF.

5. Robot performs bone removal, monitored by surgeon
   - Can adjust speed of robot, pause or abort procedure at any time.
   - Drill can be retracted to replace burr as needed.
   - Robot removed after milling is finished; surgeon completes surgery as necessary.

IV. Cadaver Experiments & Results

Table 1: Pre-Milling Time

<table>
<thead>
<tr>
<th>Task</th>
<th>Time (min)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Incision / PPF Attachment</td>
<td>8</td>
</tr>
<tr>
<td>Intra-operative CT scan</td>
<td>5</td>
</tr>
<tr>
<td>Image-processing and path planning</td>
<td>10</td>
</tr>
<tr>
<td>Robot attachment</td>
<td>4</td>
</tr>
<tr>
<td><strong>Total pre-milling time</strong></td>
<td><strong>27</strong></td>
</tr>
</tbody>
</table>

Mean 51.8 ± 20.7

Table 2: Milling Time

<table>
<thead>
<tr>
<th>Task</th>
<th>Specimen</th>
<th>Time (min)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Incision / PPF Attachment</td>
<td>1</td>
<td>54.4</td>
</tr>
<tr>
<td>Intra-operative CT scan</td>
<td>2</td>
<td>41.9</td>
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<tr>
<td>Image-processing and path planning</td>
<td>4</td>
<td>23.5</td>
</tr>
<tr>
<td>Robot attachment</td>
<td>5</td>
<td>78.8</td>
</tr>
<tr>
<td><strong>Total milling time</strong></td>
<td><strong>Mean</strong></td>
<td><strong>51.8 ± 20.7</strong></td>
</tr>
</tbody>
</table>

Total time: 78.8 ± 20.7 minutes

- Post-op examination revealed no damage to vital anatomy.
- Greater than 90% of originally segmented volume removed (note: some regions of segmented volume not targeted by robot due to geometry of segmentation and size of burr)

V. Conclusions & Future Work

- Robotic mastoidectomy is technically feasible with bone-attached robot; however, it currently takes more time than typically achieved by an experienced surgeon (~30-45 min for standard mastoidectomy).
- Accurate robotic system has potential to reduce risk of damage to critical structures and minimize invasiveness of the surgery.
- Success of robotic system will depend on improvement in operation time and demonstrated benefit over manual method.
- Currently performing experiments on full cadaver heads with wider surgical resection (e.g. labyrinthectomy for IAC access).

References & Acknowledgements


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