Published in final edited form as:

Otol Neurotol. 2014 April ; 35(4): 649–655. doi:10.1097/MAO.0000000000000328.

Minimally-Invasive Image-Guided Access for Drainage of Petrous Apex Lesions: A Case Report

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Abstract

Objective—In this case report, we present a novel, minimally-invasive image-guided approach to drainage of a petrous apex lesion.

Patient(s)—A 34-year-old man diagnosed with a petrous apex lesion consistent with cholesterol granuloma. The granuloma was large and caused mild compression of the brainstem with associated neurologic symptoms and seizure-like activity.

Interventions—Based on the anatomical location of the lesion, it was determined that the treatment plan would be to surgically drain the lesion via two linear paths—one following an infralabyrinthine approach and the other a subarcuate approach. Customized microstereotactic frames that mount on bone-implanted markers and constrain the drill along the desired path were utilized to accurately drill these desired paths and avoid damage to surrounding critical structures. After a simple mastoidectomy, the petrous apex was successfully reached without damage to vital adjacent structures by drilling the two linear channels using two custom microstereotactic frames.

Main Outcome Measures—Viscous brown liquid and debris was recovered by irrigating through one of the channels and suctioning through the other.

Results—Drainage of the petrous apex was successfully performed via two linear channels without any complications. Custom microstereotactic frames were used to accurately drill those linear channels. Post-operative CT ensured no complications. Post-operative course of the patient was remarkable with normal hearing and normal facial nerve function.

Conclusion—We presented a successful implementation of an image-guided approach to drain petrous apex.

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Conflicts of interest: Drs. Labadie, Dawant, and Noble have pending patent applications on various components of the technology, which was used to perform the surgery described.

Keywords

Petrous apex drainage; cholesterol granuloma; image-guided surgery; minimally-invasive surgery; stereotactic frame

Cholesterol granulomas are the most common cystic lesions of the petrous apex. Unlike cholesteatomas, the cyst wall of a cholesterol granuloma is composed of fibrous tissue without keratinizing squamous epithelium. Therefore, drainage rather than total excision is generally considered adequate treatment for symptomatic lesions. Surgical access to this region is technically challenging, due to its proximity to numerous critical structures including the carotid artery and cranial nerves V through XI (1). Traditional approaches to petrous apex for normal hearing patients include the infralabyrinthine, infracochlear, subarcuate, transnasal, and retrolabyrinthine approaches. In patients without useful hearing, the translabyrinthine approach, offers direct visualization from the carotid to the sigmoid sinus and the middle fossa dura to the hypotympanum. Regardless of approach recurrence rates are between 14% and 16%, the most common cause being obstruction of the drainage ports by fibrous tissue (2,3).

Herein, we present the first reported case of petrous apex drainage via linear channels drilled using image-guidance techniques involving the use of custom microstereotactic frames as drill guides. Similar technology is approved by the Food and Drug Administration for accessing deep-brain nuclei during deep brain stimulation surgery in patients with Parkinson's disease and essential tremor. This technology is in clinical trials for minimally-invasive access to the cochlea for cochlear implantation (4,5), which involves drilling a linear path from the lateral skull to the cochlea through the facial recess avoiding damage to facial nerve and chorda tympani. Accurate drilling is achieved by determining a patient-specific safe trajectory in preoperative images and using a patient-specific microstereotactic frame that mounts on bone-implanted markers and achieves the desired trajectory (6,7). In our previous studies, we have shown that the accuracy of drilling to cochlea using such bone-mounted custom microstereotactic frame is 0.31 ± 0.10 mm (6).

CASE REPORT

A 34-year-old male with a history of progressive mental decline presented to the emergency room after a syncopal episode with associated seizure-like movements. He denied tinnitus, hearing loss, or dizziness. On presentation, the family reported a vague history of intermittent gait instability over the prior year. Additionally, in the 10 years prior to presentation, he developed progressive deficits in speech, balance, motor function, verbal expressiveness, and cognitive abilities. Past medical history was notable for a well-treated mood disorder. Social history was remarkable for isolative behavior beginning in middle school; however, he graduated from high school and maintained gainful employment.

His otologic exam was normal as was his audiogram. Subsequent work-up included a normal electroencephalogram (EEG). Magnetic resonance imaging (MRI) revealed an expansile mass in the right petrous apex region with brainstem compression. It measured $18 \times 25 \times 25$ mm with signal characteristics consistent with a large cholesterol granuloma

(Figure 1). The computed tomography (CT) scan showed a tiny area of apparent bony dehiscence adjacent to the carotid canal. After consultation with our neurosurgical colleagues, operative drainage was recommended given the appearance of brainstem compression and decreasing cognitive functioning.

Preoperative Planning

To minimize the chance of cyst recurrence, it was decided that a double-barrel stenting approach suggested by Shoman et al (8) would be utilized. This approach required drilling two tracts to the lesion. Given that the patient has normal hearing, only hearing preservative techniques were considered. His CT revealed prominent horizontal carotid arteries and thick clival bone preventing a transnasal transphenoidal approach (Figure 2 (a)), small infracochlear air cell tract preventing an infracochlear approach (Figure 2 (b) and (c)), and a posteriorly located labyrinth preventing a retrolabyrinthine approach (Figure 2 (d)). In order to reach and successfully drain the lesion with two tracts, subarcuate and infralabyrinthine approaches were hence chosen. While the subarcuate approach could be performed using standard surgical techniques, the angle of the infralabyrinthine approach made this drilling “blind”. The superior location of the cyst required a nearly vertical infralabyrinthine approach. Given the valuable surrounding structures including the inner ear and facial nerve, accurate drilling along the desired path was necessary and blind drilling was considered risky. The patient's large stature limited direct line of sight into the area and lowered safety as well. Hence, we chose to employ bone-implanted customized microstereotactic frames given its accuracy to guide the drilling along the desired paths (6).

The patient consented to participate in an Institutional Review Board approved study that involved drilling linear paths in the temporal bone using customized microstereotactic frames. A custom software identified critical structures of the ear including the labyrinth, facial nerve, chorda tympani, ossicles, and external auditory canal (EAC) (9,10) and outlined each of those structures in the three-dimensional preoperative CT scan (Figure 3). Trajectories were then planned around vital structures using three dimensional technology. The trajectories were created to avoid inner ear structures and the facial nerve by > 0.5 mm, almost two times the error rate using this technology. The two paths were chosen to allow for optimal fluid egress by equalizing pressure across the cavity. As mentioned above, the only viable, non-destructive trajectories were the infralabyrinthine and the subarcuate drill paths (Figure 3).

Surgery

After planning the paths preoperatively, the following steps were performed in the operating room to accurately drill along the desired path (Figure 4).

Skin incision—A standard post-auricular incision was made, followed by a c-shaped periosteal incision and elevation of the periosteum.

Implantation of fiducial markers—Three anchors were screwed in the temporal bone region surrounding the target. Extenders with spherical ends were attached to each anchor (Figure 5 (a)).

Acquisition of intraoperative CT scan—A CT scan was acquired using an intraoperative CT scanner (xCAT ENT, Xoran Technologies, Ann Arbor, Michigan, USA).

Intraoperative path planning—The planning software was used to register this intraoperative CT scan to the preoperative CT, which had the segmentations of critical structures and the trajectories planned for the surgery, using standard mutual-information based rigid registration technique (11). The planned trajectories were transformed from the preoperative CT to the intraoperative CT using the registration transformation.

Design and fabrication of custom microstereotactic frames—Two custom microstereotactic frames (one for each planned trajectory) were then designed using custom software such that each frame would mount on the three spheres on the extenders and constrain the drill attached to the frame along the desired path. The frames were then fabricated using a standard computer-numeric-control (CNC) milling machine within ten minutes (7). The frame consists of a tabletop with three leg holes and a target hole. The leg holes allow attachment of legs of specific lengths to the tabletop such that the frame would mount on the three spheres and the tabletop would be perpendicular to the trajectory (Figure 5 (b)). The target hole allows attachment of a drill to the frame and constrains the drill along the desired path (Figure 5 (c)).

Sterilization of the microstereotactic frames—The two frames were transported to the operating room for sterilization. The sterilized frames were then made available to the surgeon.

Time required from intraoperative scanning to presentation of sterilized microstereotactic frames in the operating room was less than 40 minutes. During this time a simple mastoidectomy was performed to the level of Körner's septum to adequately seat the microstereotactic frames, to enable visualization of the drainage, and to place stents at the end of the surgery.

Drilling using the microstereotactic frames—The two microstereotactic frames were used to drill the two desired linear paths (Figure 5). The drilling technique involved drilling laterally with a 3.8 mm diameter twist drill followed medially with a 1.6 mm diameter twist drill bit (6). Given the high cost of potential injury to surrounding structures, a safety CT was done between lateral and medial drilling to ensure that the drilling is being performed along the desired path. The lateral hole allows placement of a bushing for guiding the medial drilling along the desired path and the ability to irrigate during deeper drilling.

Each microstereotactic frame was mounted on the fiducial markers one at a time and the two lateral wider holes were drilled. After confirmation using the safety CT that the drilling is along the desired path, the microstereotactic frames were remounted on the markers one at a time and medial drilling was done using the thinner drill bit.

With completion of drilling, egress of murky fluid through both drilled paths was consistent with the suspected diagnosis of petrous apex cholesterol granuloma. A 1.3 mm flexible

endoscope (Karl Storz, Tuttlingen, Germany) was used to visualize the cavity through the drilled paths and confirm entry into the cyst.

Drainage of the cyst—The cavity was copiously irrigated through the infralabyrinthine tract to flush out the contents of the cyst through the subarcuate tract.

A third CT was performed to ensure proper tract trajectory and no complications. Both the tracts were wicked open with 20 Gauge angiocatheters to avoid recurrence of the symptoms after the surgery. A small amount of pneumocephalus was noted at the site of bony dehiscence seen on preoperative CT.

Removal of fiducial markers and skin closure—The bone-implanted markers were removed. Then the mastoid periosteum and skin were closed in the normal fashion.

The patient has had an uneventful postoperative course and during his last post one-year follow-up examination was noted to have normal hearing. Though no specific measurements were performed, the patient appeared to have had an immense improvement in cognitive function and functional daily activities. He is now not dependent on his mother and able to maintain a normal conversation, live on his own, and maintain gainful employment.

DISCUSSION

Surgery to access the petrous apex is challenging because of the critical structures surrounding it including the cochlea, facial nerve, internal jugular vein, inner ear, and carotid artery. The traditional approaches for hearing preservation to symptomatic cholesterol granuloma, the most common benign pathologic lesion of the petrous apex, have historically been middle fossa, transnasal, retrolabyrinthine or infralabyrinthine approaches. The specific approach to drain the cyst must minimize risk to the inner ear, the need for brain retraction, and create a natural drainage pathway after marsupialization of the granuloma. Occasionally, as in this patient, the transnasal, infracochlear, and retrolabyrinthine approaches are impossible due to the physical constraints of the patient's anatomy. To minimize blind drilling and reduce risk of damage to surrounding structures, a guidance system with submillimetric accuracy is often required.

A review of the literature reveals no prior use of framed stereotactic guidance for drainage of petrous apex lesions. The use of image-guided surgical navigation systems during complex surgeries has the potential to improve surgical outcome as it provides a real-time display of patient anatomy and pathology which has been reported to decrease morbidity (12, 13). However, navigation systems that are currently commercially-available depend on the hand-eye coordination of the surgeon to constantly look at the navigation system and move the surgical tools as desired and does not provide the required submillimetric accuracy (14,15). Van Havenbergh et al (15) studied the potential use of Stealth (Medtronic, Miami, Florida, USA) to access the petrous apex cholesterol granulomas via an epidural middle fossa approach on two patients and reported achieving accuracy <2.0 mm. In the case of petrous apex lesions, 2 mm of error can mean the difference between successful surgery and injury to vital surrounding structures.

To achieve submillimetric accuracy, we used bone-implanted markers and microstereotactic frames that are custom designed and fabricated to mount on these markers and constrain the drill along the desired path. The initial groundwork for our study was laid in an *in vitro* study conducted by Wanna et al (16). On 10 cadaveric specimens, the authors demonstrated the feasibility of linear access to the petrous apex using these customized, bone-mounted, microstereotactic frames. The frames were designed to allow a straight transmastoid infralabyrinthine trajectory from the mastoid surface to the petrous apex without violating vital structures. In all 10 specimens, the drilled trajectory targeted the petrous apex region with adequate clearance from the cochlea, facial nerve, carotid artery, and jugular vein. The targeting error was measured as 1.02 ± 0.39 mm and was considered slightly higher than desired. On analysis, it was found that this high targeting error was due to the design of the drilling mechanism. With modified design of the drill press system, which is used to smoothly move the drill along the desired path and which was used for the presented study, we have shown in an *in vitro* study that the accuracy of drilling to the cochlea is 0.31 ± 0.10 mm (6). This level of accuracy, which ensures a low risk of damage to vital structures that lie near the surgical path, can only be achieved with bone-mounted, custom microstereotactic frames such as the ones used in this study.

The most common cause of cyst recurrence is outflow obstruction of the drainage tracts by fibrous tissue. Shoman et al (8) described a double-barrel stenting approach to minimize the chance of outflow obstruction. We decided two ports through an infralabyrinthine and subarcuate tract were ideal for drainage into mastoid. We incorporated this technique to facilitate intraoperative drainage and to decrease the likelihood of fluid re-accumulation.

The subarcuate path used in the surgery provided direct access to the lesion, but it involved drilling through the center of the superior semicircular canal, which is about 4.7 mm wide. Drilled manually, the approach provides low visibility and has a high risk of injury to the inner ear. The high targeting accuracy of the microstereotactic frame reduced the overall risk. For the infralabyrinthine approach, the path required to enter the cyst required near vertical drilling. This essentially means a hidden, blind drilling behind the inner ear and posterior to the facial nerve. The preplanned and guided tracts allowed drilling along the desired path with high accuracy.

A simple mastoidectomy was performed for the presented surgical case to allow utilization of existing hardware available for this technology as the hardware used for this case was developed for cochlear implantation. Accessing the petrous apex required drilling deeper than that required for accessing the cochlea. The drilling technique required use of a bushing to guide the drill bit accurately along the desired path without any wobble effect. For accuracy, the bushing must be placed as close as possible to the target. A simple mastoidectomy was performed to allow placement of the bushing for the lateral drilling deeper into the skull, which would allow placement of the bushing for the medial drilling closer to the target. To perform the surgery in a completely minimally-invasive fashion only via the linear paths for future cases, the bushings would have to be modified to enable proper placement of the hardware without the need for a mastoidectomy.

Intraoperative CT scanners have been utilized to provide assistance with complex surgeries (17). The intraoperative CT scanner utilized in our study allowed placement of bone-implanted markers in the operating room after induction of general anesthesia and also the ability to perform a safety check during the surgery to ensure that the drilling is proceeding along the desired path. Mobile CT scanners such as the xCAT or rotating fluoroscopy units such as the Allura Xpert FD20 (Philips Medical Systems, Eindhoven, The Netherlands), which are usually available in Level I trauma centers, easily accommodate that need.

The intraoperative CT scans does increase the amount of radiation to which the patient is exposed. This risk-benefit has to be carefully analyzed before acquisition of the scans. Given the critical nature of the proposed approaches for the petrous apex drainage for this patient, it was vital that the drilling be performed with submillimetric accuracy. To achieve this level of accuracy, the use of bone-implanted markers was necessary. The patient provided consent to this additional radiation exposure prior to the surgery. A flat-panel cone-beam CT scanner that can acquire CT using low-dose protocols was used in this study. The patient was exposed to about 35 mrem per intraoperative CT scan (based on the measurements done using the machine) making the total to about 105 mrem for the three intraoperative scans compared to 100 mrem or more per traditional temporal bone CT scan.

The use of image guidance for this surgery decreased the surgery time versus that projected by the surgeon. The surgeon estimated that it would take 8 hours for the traditional approach based on historical times and the overlaying complexity of the case. With the image-guided technology presented, the surgery time was 5 hours. This time also included an approximately 1.5 hour delay due to unexpected technical difficulties with equipment not related to the microstereotactic frame approach. The presented approach, thus, has the potential to decrease the surgical time for critical cases.

The proposed approach resulted in accurate targeting of the petrous apex region, less tissue removal, and less surgery time for this patient. Even though these benefits could not be generalized with just one patient, based on our preliminary experience with clinical implementation of minimally-invasive image-guided cochlear implantation, we believe these benefits would be observed in future cases using the proposed approach. Based on our estimates from our clinical studies, we estimate that the variable cost per case would be less than \$500 for drilling two linear tunnels including the cost to make custom microstereotactic frames (~\$100 per frame), the cost for drill bits per case (~\$100), and the cost for the fiducial markers and drapes for CT scans (\$100). The use of the technology requires an intraoperative CT scanner, which costs about \$250,000, and a CNC milling machine, which costs about \$15,000. Even though the initial investment to acquire the scanner and milling machine would be high, their utilization for multiple surgeries would be capitalized over many cases reducing the fixed cost per case over time. With increasing access to portable CT scanners in critical care units (18) and operating rooms (e.g. biplane fluoroscopy units in interventional cardiology and neurosurgical suites), we believe that such scanners will be readily available in most hospitals in the near future. The potential benefits of the proposed approach may considerably reduce the risk of complex surgeries and operating time, which would result in considerable cost savings to the hospital potentially justifying the investment

in a CNC milling machine and additional expenses (~\$500 per case) for CT scan(s), fiducial markers, fabrication of microstereotactic frame, and drill bits.

CONCLUSION

The petrous apex remains a technically challenging region to approach surgically. We presented a successful *in vivo* implementation of an image-guided approach for petrous apex drainage using custom microstereotactic frames. To our knowledge this is the first report of such an implementation. We believe this system may provide surgeons more options to access the petrous apex, including paths that were previously avoided due to increased risk.

Acknowledgments

Disclosure: The project described was supported by Award Number R01DC008408 from the National Institute on Deafness and Other Communication Disorders. The content is solely the responsibility of the authors and does not necessarily represent the official views of the National Institute on Deafness and Other Communication Disorders or the National Institutes of Health.

This award provided partial funding support for (1) the authors Ramya Balachandran, Jack H Noble, Benoit M Dawant, and Robert F Labadie and (2) some of the hardware used during the surgery for image-guidance.

REFERENCES

1. Gore MR, Zanation AM, Ebert CS, Senior BA. Cholesterol granuloma of the petrous apex. *Otolaryngol Clin North Am*. 2011; 44(5):1043–58. [PubMed: 21978895]
2. Fong BP, Brackmann DE, Telischi FF. The long-term follow-up of drainage procedures for petrous apex cholesterol granulomas. *Arch Otolaryngol Head Neck Surg*. 1995; 121:426–430. [PubMed: 7702817]
3. Mosnier I, Cyna-Gorse F, Grayeli AB, Fraysse B, Martic C, Robier A, et al. Management of cholesterol granulomas of the petrous apex based on clinical and radiologic evaluation. *Otol Neurotol*. 2002; 23:522–528. [PubMed: 12170156]
4. Labadie RF, Balachandran R, Mitchell J, Noble JH, Majdani O, Dawant B, et al. Clinical Validation Study of Percutaneous Cochlear Access Using Patient Customized Micro-Stereotactic Frames. *Otol Neurotol*. 2010; 31(1):94–9. [PubMed: 20019561]
5. Labadie RF, Noble JH, Dawant BM, Balachandran R, Majdani O, Fitzpatrick JM. Clinical validation of percutaneous cochlear implant surgery: initial report. *Laryngoscope*. 2008; 118(6): 1031–9. [PubMed: 18401279]
6. Balachandran R, Mitchell J, Blachon G, Noble JH, Dawant B, Fitzpatrick JM, et al. Percutaneous Cochlear Implant Drilling via Customized Frames: an in vitro study. *Otolaryngol Head Neck Surg*. 2010; 142(3):421–6. [PubMed: 20172392]
7. Labadie RF, Mitchell J, Balachandran R, Fitzpatrick JM. Customized, rapid-production microstereotactic table for surgical targeting: description of concept and in vitro validation. *Int J CARS*. 2009; 4:273–80.
8. Shoman NM, Samy RN, Pensak ML. Double-barrel stenting in infracochlear approach for drainage of petrous apex cholesterol granulomas. *The Laryngoscope*. 2011; 121:574–576. [PubMed: 21344437]
9. Noble JH, Dawant BM, Warren FM, Labadie RF. Automatic identification and 3D rendering of temporal bone anatomy. *Otol Neurotol*. 2009; 30(4):436–42. [PubMed: 19339909]
10. Noble JH, Warren FM, Labadie RF, Dawant BM. Automatic segmentation of the facial nerve and chorda tympani in CT images using spatially dependent feature values. *Med Phys*. 2008; 35(12): 5375–84. [PubMed: 19175097]
11. Maes F, Collignon A, Vandermeulen D, et al. Multimodality image registration by maximization of mutual information. *IEEE Trans Med Imaging*. 1997; 16:187–98. [PubMed: 9101328]

12. Dalgorf, Dustin M.; Sacks, Raymond; Wormald, Peter-John; Naidoo, Yuresh; Panizza, Ben; Uren, Brent; Brown, Chris; Curotta, John; Snidvongs, Kornkiat; Harvey, Richard J. Image-Guided Surgery Influences Perioperative Morbidity from Endoscopic Sinus Surgery: A Systematic Review and Meta-Analysis. *Otolaryngology -- Head and Neck Surgery*. 2013; 149:17–29. [PubMed: 23678278]
13. Kohan D, Jethanamest D. Image-guided surgical navigation in otology. *Laryngoscope*. Oct; 2012 122(10):2291–9. [PubMed: 22961537]
14. Balachandran R, Fitzpatrick JM, Labadie RF. Accuracy of Image-guided Surgical Systems at the Lateral Skull Base as Clinically Assessed Using Bone-Anchored Hearing Aid Posts as Surgical Targets. *Otology and Neurotology*. 2008; 29(8):1050–1055. [PubMed: 18836389]
15. Van Havenbergh T, Koekelkoren E, De Ridder D, Van De Heyning P, Verlooy J. Image guided surgery for petrous apex lesions. *Acta Neurochir (Wien)*. 2003; 145(9):737–42. discussion 742. [PubMed: 14505098]
16. Wanna GB, Balachandran R, Majdani O, Mitchell J, Labadie RF. Percutaneous access to the petrous apex in vitro using customized micro-stereotactic frames based on image-guided surgical technology. *Acta Oto-Laryngologica*. 2010; 130(4):458–463.
17. Conley DB, Tan B, Bendok BR, Batjer HH, Chandra R, Sidle D, Rahme RJ, Adel JG, Fishman AJ. Comparison of Intraoperative Portable CT Scanners in Skull Base and Endoscopic Sinus Surgery: Single Center Case Series. *Skull Base*. 2011; 21(4):261–270. [PubMed: 22470270]
18. Balachandran R, Schurzig D, Fitzpatrick JM, Labadie RF. Evaluation of portable CT scanners for otologic image-guided surgery. *International Journal of Computer Assisted Radiology and Surgery*. 2012; 7(2):315–321. [PubMed: 21779768]

Figure 1.

T1-weighted with contrast (left) and T2-weighted (right) MRI of petrous apex lesion consistent with a cholesterol granuloma. The T2 image demonstrates compression of the brainstem by this lesion.

Figure 2.

Traditional approaches to the petrous apex (PA) lesion. (a) Axial view of the CT scan showing a prominent horizontal carotid artery (CA) and thick clival bone preventing a transnasal transphenoidal approach. (b) and (c) show the coronal views of the CT scan indicating the posteriorly located carotid artery and a small infracochlear air cell tract (black arrows) preventing an infracochlear approach. (d) Axial view of the CT scan showing posteriorly located labyrinth (black straight arrows) and anterior endolymphatic duct (ELD) preventing a retrolabyrinthine approach. IAC – internal auditory canal.

Figure 3.

Trajectories manually picked by the surgeon are shown as white dotted lines along with the results of automatic segmentation. The boundaries of the 3.8 mm and 1.6 mm wide drilling are shown as white solid lines. (a) Infralabyrinthine approach. The tract is about 2.7 mm from the facial nerve, 1.4 mm from the posterior semicircular canal (PSSC), and 5 mm from the cochlea. Note a tiny area of apparent bony dehiscence adjacent to the carotid canal. (b) Subarcuate approach. The tract is about 3.7 mm from the facial nerve and 1.8 mm from the horizontal semicircular canal (HSCC). The path goes through the center of the superior semicircular canal (SSCC), which is about 4.7 mm wide with a clearance of 1.2 mm.

Figure 4.

Steps involved in performing the minimally-invasive, image-guided access to the petrous apex. The gray-filled box indicates that the step is performed prior to surgery.

Figure 5.

(a) Fiducial markers – Three anchors were bone-implanted surrounding the temporal bone region. Extenders with spherical ends were attached to each anchor. A simple mastoidectomy was performed to provide the required clearance to attach the microstereotactic frame and drill components. (b) Custom microstereotactic frame for the subarcuate linear path mounted on the spheres. (c) Drill press system attached to the microstereotactic frame. The microstereotactic frame defines the drill path and the drill press controls the linear movement of the drill to a predetermined depth.