

Original Article

Comparison of the Surgical Techniques and Robotic Techniques for Cochlear Implantation in Terms of the Trajectories Toward the Inner Ear

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OBJECTIVES: The ideal outcome of cochlear implant surgery involves the insertion of the array inside the scala tympani of the cochlea with the least mechanical trauma. Recently, round window insertion and the direction in which the cochlea is approached have gained attention in this respect. The Angles of Cochlear Approach (ACA) can be defined with a plane in the plane of the basal turn, termed the in-plane angle, and the plane orthogonal to this plane, termed the out-plane angle. The aim of this study was to compare the trajectory angles for different surgical techniques of Veria, suprameatal, pericanal, and multiple posterior tympanotomy (PT) approaches, including an optimal trajectory that is simulated for robotic surgery.

MATERIALS and METHODS: The trajectories of these surgical techniques were simulated on the same high-resolution computed tomography scan. The simulated trajectory angles were analyzed with dedicated software for medical images, defining the ACA and distances to critical otological structures.

RESULTS: The ACA are the smallest for surgical techniques that pass through the PT. However, performing a surgical PT can include variability in the ACA, ranging from almost 0° to 20.8° in an out-plane angle, depending on how close a surgeon would approach the facial nerve. The Veria, Suprameatal approach (SMA), and peri-canal approaches have larger ACA and minimal distances to the ossicular chain and the ear canal. The maximum distance to the facial nerve and the widest out-plane angle is observed with a pericanal approach. The optimal PT approach refers to the trajectory without collisions and with the best possible ACA that can be planned.

CONCLUSION: Different surgical approaches yield important differences in the ACA. PT allows better ACA with maximum distances to the critical structures. However, the optimal PT trajectory simulated for robotic keyhole surgery is a further improvement on the trajectories through the facial recess.

KEYWORDS: Sensorineural hearing loss, cochlear implant, surgical technique, robotic otology

INTRODUCTION

The golden standard for cochlear implantation surgery is probably a large cortical mastoidectomy and a wide posterior tympanotomy (PT) ^[1-3]. High-speed drill enables a safer mastoidectomy than the previously used chisel; however, a PT requires more training to enable safe identification and prevent harm to the facial nerve. A previous study has reported the incidence of facial nerve palsy as 0.5%-2% ^[4]. This might have been an underestimation because reports on complications are always rare. Meanwhile, facial nerve monitoring has been popularized in cochlear implant surgeries in developed countries. However, after a complete mastoidectomy, a PT can be performed safely with special attention to the facial nerve and the chorda tympani, even without a facial nerve monitor by a well-trained otological surgeon. Through a wide PT, a cochleostomy or a round window, or even a so-called enlarged round window approach, can give access to the inner ear for electrode insertion. The earlier debate between a cochleostomy and

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round window approach appears to have been settled in the favor of a tissue-preserving round window approach. However, cochleostomy is still performed and may be necessary technique in ossified cases. Like every type of surgery, cochlear implant surgery has evolved over the years. Today, it might seem unlikely; however, previously, cochlear implantation only comprised the insertion of electrodes in the cochlea; further, studies were performed on the correlations between the number of electrodes in the cochlea and hearing outcomes [5]. Complications concerning the facial nerve can occur owing to the drilling or heating of the facial nerve during PT [6, 7]. The PT, as a classic technique, has proven sufficient in the vast majority of cochlear implantations. However, owing to the risk of facial nerve palsy, challenging patient anatomy, or timesaving, faster alternative techniques were advocated. To avoid temporary or permanent injury to the facial nerve, Kronenberg et al. [8], Kiratzidis [9], and later Hausler [10] designed different approaches that were further away from the facial nerve and excluded mastoidectomy to create the trajectory toward a cochleostomy. These “newer” or “alternative” cochlear implantation techniques without a mastoidectomy and PT were reportedly safe and effective [8-10].

The first author has experience with an alternative suprameatal approach (SMA) as described by Tange et al. in 2004 [11]. Although a systematic review did not reveal any differences in the complication rates between SMA and PT [12], are reported more complications with SMA [13]. Several colleagues were concerned about using the SMA in terms of the angle at which the SMA was used to enter the cochlea and how that could affect hearing outcomes. Figure 1 demonstrates the difference in the trajectories between mastoidectomy PT approach (MPTA) and the SMA. Today, cochlear implantation surgery has improved so much that even the angle of cochlear approach (ACA) in the classic PT technique is considered important these days.

The aim of this study was to analyze this angle of approach for the majority of surgical techniques used in cochlear implantation and compare them to the trajectory used in imaging-based robotic keyhole cochlear implantation. As the secondary outcome, the distances between the trajectory and critical anatomical structures were measured.

MATERIALS AND METHODS

The two alternative approaches of Veria Technique and the SMA have similar surgical trajectories and are evaluated together. For further details of the Veria and SMA techniques, we referred to the original papers of Kiratzidis and Kronenberg, respectively [8, 9]. The pericanal technique is considered separately because the surgical trajectory passes through the ear canal; we referred to the original paper for the details of this technique published by Hausler [10]. All three alternative techniques tend to require a classic cochleostomy because their exposure does not always allow a round window access. Nevertheless, their trajectory targets were set as per the round window approach in the planning software. The facial recess approaches comprise firstly the PT in its most optimal possibility Po_p which is with the largest possible distance to all critical structures and then other approaches through the recess are considered in its extremities by allowing zero distance to the bordering critical structures. This will provide a range of ACA to the surgeon

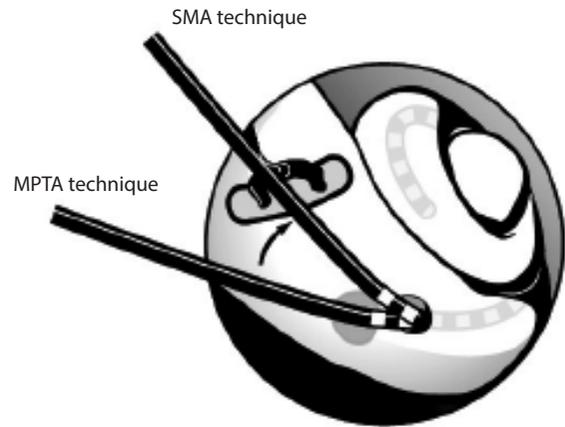


Figure 1. Trajectories of the MPTA and SMA for reaching the basal turn of the cochlea for cochlear implantation.

who we assume is able to perform a complete PT meaning as large as the anatomy of the patient will allow. The maximum limits would have to respect facial nerve, chorda tympani and other anatomical structures like the stapes supra structures at almost zero distance. The ideal insertion trajectory aligns with the centerline of the scala tympany (ST) at the level of the round window membrane in order to prevent damage to the basilar membrane, the modiolus, or the spiral ligament during insertion. In order to depict the trajectories from different surgical approaches, the same high-resolution clinical CT scan was uploaded in the commercially available medical image planning software: OTOPLAN® (version 1.3.1, Copyright 2019 CAscination AG, Switzerland). Although a clinical CT does not provide the necessary imaging resolution to detect the ST, the round window (RW) is visible. We assume that placing the target at the center of the RW and delineating a trajectory that will continue alongside the lateral wall of the basal turn will represent an ideal ST insertion trajectory. Wimmer et al. [14] used a method to depict deviations from this ideal trajectory in two planes. The so-called in-plane angle is the offset between the planned trajectory and the ideal trajectory with respect to the basal turn of the cochlea for a given target: here the RW. Consistently, the so-called out-plane angle is the offset between the planned and the computed ideal trajectory in the basal turn in an orthogonal plane. The best ACA are defined with both angles at 0°; however, this ideal trajectory would have to go through the facial nerve when it is in its most common normal anatomical position (Figure 2). Thus, the optimal trajectory already has to make some concessions in terms of ACA. The best ACA is defined by the lowest degrees of in- and out-plane angles, respecting all critical structures. In order to study the variation in ACA, three separate PT extremities are simulated. The PT_{extl} is when a skilled surgeon can execute a PT with zero distance to the facial nerve allowing, a trajectory millimetrically over the facial nerve corresponding with an out-plane angle of zero. Similarly, the ACA are calculated when PT_{extl} is simulated at 0 in-plane angle and PT_{extll} at 0 distance to chorda tympani. The dedicated software Otoplan is designed for robotic keyhole surgery; therefore, it is programmed to account for safety margins for the facial nerve in robotic drilling at a distance of minimum 0.4 mm and minimum 0.3 mm from the chorda tympani and accounts for a drill with a 1.8-mm diameter [15].

Table 1. Simulations of different surgical trajectories compared to a robotic keyhole trajectory

	S (mm)	I&M (mm)	EAC (mm)	FN (mm)	ChT (mm)	In-plane (°)	Out-Plane (°)
PT _{extl}	1.53	2.52	3.44	0	1.87	-3.0	0
PT _{exll}	0.20	1.78	1.64	0.31	0.56	0	13.2
PT _{exlll}	0.46	1.42	0.38	1.03	0	-3.3	20.8
SMA/Veria	0	0	0.24	0.66	0	21.5	30.1
Pericanal	0	0.06	1.33	2.17	0.64	-7.0	46.1
PT _{opt}	0.63	1.86	1.53	0.45	0.38	-3.0	13.2

EAC: external auditory canal; FN: facial nerve; PT: posterior tympanotomy; SMA: suprameatal approach

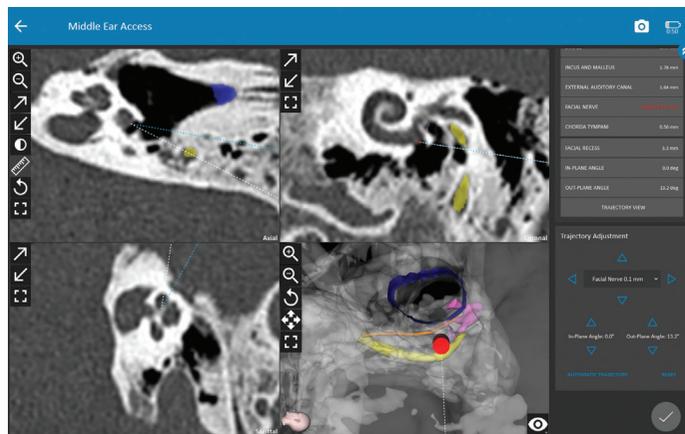


Figure 2. Simulation of a surgical trajectory PT_{exll}. Closest trajectory without collision (blue line) to the ideal trajectory (white line) with the in-plane angle set at 0° (right top coronal plane where the white line and blue line are the same) and an out-plane angle of 13.2° (left top; axial plane). Sagittal plane (left, under). Three-dimensional reconstruction (right, under). Red dot indicates the drill trajectory, yellow facial nerve, brown chorda tympani, purple ossicular chain, and blue is external ear canal.

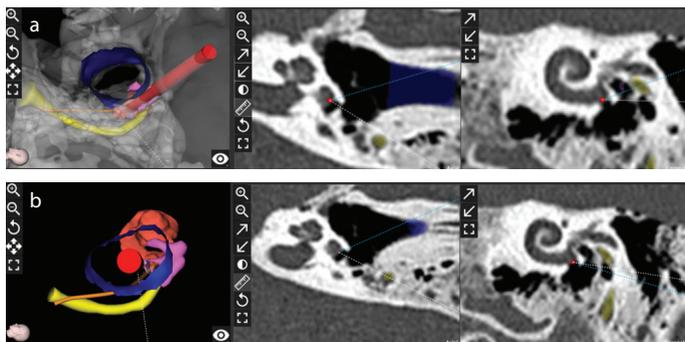


Figure 3. a, b. a) The SMA suprameatal and Veria approach (left panel) with an out-plane angle of 30.1° (middle panel) and in-plane angle of 21.5° (left panel). b) The pericanal approach with an out-plane angle of 46.1° and in-plane angle of 7.0°.

RESULTS

The random clinical scan used to plan the trajectories of all separate techniques had a facial recess size of 3.3 mm and common anatomical landmarks that could easily be depicted. The closest surgical trajectory to the ideal trajectory in terms of the ACA is PT_{extl} with a hypothetical out-plane angle of 0° and thus no distance to the facial nerve (FN). PT_{extl} has an in-plane angle of -3.0°. When the in-plane angle is improved to 0°, the out-plane angle is increased to 13.2° in the trajectory PT_{exll}. This also increases the distance to the FN to 0.31 mm.

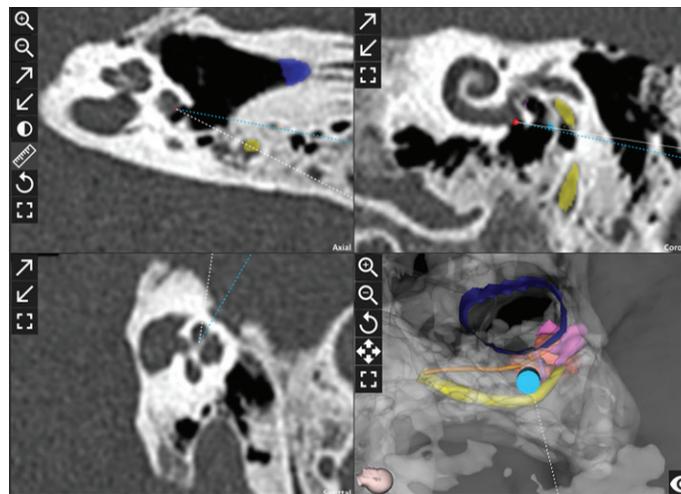


Figure 4. The simulated optimal robotic trajectory with minimal ACA.

As mentioned before, the SMA and Veria Technique are depicted together in figure 4A because of their similar trajectories. The pericanal approach is depicted separately in figure 4B.

The so-called alternative surgical techniques that do not involve a PT have the highest ACA. The pericanal approach has the highest overall out-plane angle of 46.1°, but also has the farthest distance of 2.17 mm to FN. While the SMA/Veria approaches are at a distance of 1.33 mm of the FN, they have the ossicular chain (I&M) in between their surgical trajectory and the FN, at a distance of 0 mm.

Table 1 summarizes all the simulated trajectories and distances to the critical anatomical structures. In yellow, the preset margins at no distance are extra highlighted with yellow background. The PT extremities show variations in the ACA for out-plane angles ranging from 0°-20.8° and for in-plane angles ranging from -3.3° to 0°. The pericanal, SMA, and Veria approaches demonstrate 0 mm distance to the critical structures, indicating collisions. Two PT trajectories could be simulated without collisions. The first was PT_{exll} as demonstrated in figure 2, and the second was PT_{opt} as shown in figure 4. The dedicated software optimized these ACA with a preset safety margin to FN (minimum 0.4 mm) and ChT (minimum 0.3 mm). These minima were not reached, indicating that the PT_{opt} in-plane angle of -3° and out-plane of 13.2° are the ideal ACA for a facial recess of 3.3 mm in this patient's anatomy. Figure 4 shows the planned trajectory for this case for robotic cochlear implant surgery. The dedicated software shows the drill trajectory in blue (safe) instead of red (unsafe) because it is within the preset safety margins.

DISCUSSION

This study compares the different surgical approaches to the inner ear for CI. In 1993, the principles of soft surgery have led the way for CI approaches [16]. In particular, with the popularization of hybrid electro acoustic stimulation, most surgeons attempt the preservation of residual hearing with tissue-preserving approaches. In this respect, the ACA are determining factors of friction or collision of an array, regardless of the rigidity or stiffness, in the lateral wall of the basal turn. Torres et al. [17] report on the variability of ACA and report the presence of an "optimal scala tympani axis". In the context of ACA, this study compared the vast majority of surgical trajectories currently used with a trajectory in upcoming robotic CI surgery [18]. A comparison of the facial recess approaches with alternative techniques clearly favors the PT. Other surgical aspects, such as implant and array management in the pericanal or suprameatal approaches, are not even considered although it is known these also prompt challenges for the surgeon. In the suprameatal approaches, the electrode array is by definition in contact with the ossicular chain and cannot be proposed as a hearing-preserving technique because it would cause conductive hearing loss. These techniques would also require the opening of the middle ear by raising of the eardrum, increasing the risk of harming it. At the time, the SMA and Veria were proposed as the safest approaches to FN; however, our analyses show that the safest approach for the facial nerve would be the pericanal approach with a distance of 2.17 mm. Nevertheless, this approach has the worst out-plane angle, and its array handling through the ear channel warrants consideration.

A restriction of this study is that the dedicated software is programmed to simulate a trajectory with a 1.8 mm diameter. A consequence is that the software is designed to calculate safe trajectories and does not show negative distances that would reflect on how far the simulated trajectory would harm the FN. Table 1 shows why the distance to the stapes is 0 mm and that to the incus and malleus is 0.06 mm. With a 1-mm drill, these critical structures would be safe at a minimum distance of an extra 0.8 mm.

This study confirms that facial recess approaches are the golden standard; second, it demonstrates the variability in the ACA in PT approaches. A well-trained otological surgeon can expose the ChT and FN to probably a distance close to 0 mm without harming them. This will give him a choice in the ACA that varies in out-plane angles ranging from 0° to 20.8° and in-plane angles ranging from -3.3° to 0°. Further, it is likely that a less experienced otologist would tend to go toward ChT and even opt for a PT_{exill} trajectory, automatically enlarging the out-plane angle up to 20.8°.

Surgical skills are needed to open the PT at its maximum limits; moreover, it depends on the surgeon's experience as to how he/she decides which ACA he should direct the array during insertion. There are no surgical landmarks in an exposition of a PT beyond the RW and the lateral inferior wall of the cochlea. Torres et al. [19] reported on the mental representation of the insertion axis to the scala tympani that needs to be estimated by the surgeon. The insertion axis in their study varied considerably with 7° variations for experts and 14° for residents performing CI [19].

When a direct cochlear access keyhole trajectory is applied with the ideal ACA for that individual patient with a robot arm, the level of

deviation change to microns. Optimizing such sub-millimetric details of CI requires extreme human dexterity. Therefore, it has led research groups to explore robotized CI surgery [20, 21]. PT is considered to be the gold standard; therefore, such a robotic approach requires high accuracy to pass through the facial recess. In 2017, Weber et al. [22] developed an image-navigated robotic arm that had demonstrated this precision and had performed keyhole PT in 6 patients. The system is improving and allows superior control of the ACA [18].

CONCLUSION

Posterior tympanotomy approaches allow much smaller ACA than those for SMA/Veria and pericanal approaches. Within different PT modalities, mathematically calculated approaches for robotic assisted surgery provide the most optimal ACA in a collision-free trajectory that allows easy access to an array and surgeon.

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