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Review

Techniques for otosclerosis surgery: Ear surgery from the microscope to the endoscope - A literature review

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ABSTRACT

Stapes surgery is the gold standard for managing otosclerosis. It has become increasingly appreciated to perform endoscopic ear surgery worldwide as the field of endoscopy expands. In basic terms, a stapes surgery intends to restore ossicular mobility and therefore improve sound energy transduction into the inner ear, thereby improving communication and sound amplification and bringing hearing levels back to acceptable levels. The aim of the study is to analyze surgical techniques comparing microscopic and endoscopic approaches for stapes surgery. The perspectives of Surgical Pioneers in Early Stapes Surgery and the contemporary development of surgical technology will be explored as well. Specifically, this study compiles well-documented, reliable information concerning the surgical outcomes for the endoscopic approach to stapes surgery and the results of recent studies.

1. Introduction

Otosclerosis is a disease characterized by abnormal bone growth in the structures od the middle ear and the inner ear capsule (Gurgel and Harnsberger, 2018). The physiopathological process is characterized by two major phases: the 1st phase of active bone resorption (***spongiosis***) and the 2nd phase of remission (***sclerosis***), which involves disordered resorption and deposition of bone, particularly along the enchondral portion of the otic capsule. There are four features of an otosclerotic focal lesion: resorption of bone, formation of new bone, vascular proliferation, and modification of connective tissue stroma (Batson and Rizzolo, 2017). The onset age can vary from 10 to 50, with ***30 years*** being the most common (B. L. Koch et al., 2017). There is a strong ***family history*** of otosclerosis, with over half of all affected people coming from families with similar symptoms (Reinshagen et al., 2019). In addition to elucidating the causal factors of the disorder, investigating the structural and functional aspects of OTSC4 could lead to new avenues in diagnosing, treating, and preventing otosclerosis (Brownstein et al., 2006) (see Fig. 1)

The disease can occur in familial and non-familial variants. A familial version of the disease, a quarter to a half of all cases, exhibits an autosomal dominant inheritance pattern associated with incomplete penetrance (Morrison, 1967). Genetic mapping in families revealed eight different genetic loci. However, it is pertinent to note that no causal gene has yet been identified within these loci (Ealy and Smith, 2010). In the presence of incomplete penetrance, linkage studies are likely to be less powerful. An analysis of the whole exome sequencing of SERPINF1 in a cohort of familial patients has identified multiple individuals who were found to have rare mutations in the gene (Ziff et al., 2016). These mutations appear to influence the expression of an alternatively spliced transcript that is commonly found to have high expression in the bony tissue of the stapes.

Research indicates non-familial otosclerosis involves complex genetic and environmental factors (Ealy and Smith, 2010). A common pathway is currently unknown when mutations within the same genes are linked to familial and non-familial diseases.

Based on the results of a study conducted by Mowat et al., 2018 in the British population, a functional variant in the TGFB1 gene was associated with clinically confirmed otosclerosis. According to this study, there is a significant relationship between SNPs within RELN and inherited otosclerosis, in pregnant women whose deafness does not progress during pregnancy (Mowat et al., 2018).

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Based on the other perspective, there is a potential role for the measles virus in the pathogenesis of otosclerosis (Karosi et al., 2005). In otosclerotic stapes footplates associated with measles virus infection, TNF-alpha mRNA is detected, indicating stimulation of osteoclast functions and inflammatory responses (Karosi et al., 2006).

Autoimmunity, hormonal factors, and the environment may also contribute to the pathological process of otosclerosis. A systemic prospective study utilizing comprehensive histopathological and molecular biological studies is necessary to obtain additional data about the background of otosclerosis because the diagnosis of otosclerosis is still established on histopathological analysis of the resected stapes footplate (Karosi et al., 2009). Hearing loss is the most common otosclerosis symptom, and in most cases, hearing loss is conductive, but it can also be sensorineural or mixed and is often bilateral (Quesnel et al., 2018).

Clinically, the disease progresses slowly, but pregnancy may aggravate hearing loss. The otoscopy usually shows no findings unless there is severe cochlear involvement, in which case hyperemia of the cochlear promontory may occur (Schwartze sign) (Foster and Backous, 2018).

An otosclerotic lesion causes an increase in blood flow to the promontory, resulting in discoloration. This phenomenon is observed in up to 10% of patients with otosclerosis cases (Peng and House, 2018).

Pure-tone audiometry may show a specific decrease in bone conduction around 2000 Hz (Carhart notch) (Quaranta et al., 2018).

There are two subtypes: fenestral (stapedial): ~80% and retrofenestral (cochlear): ~20%. *Fenestral* otosclerosis affects the oval window and the footplate, resulting in conductive hearing loss due to stapes immobility and thickening process (Karosi and Sziklai, 2010). Cochlear otosclerosis is defined as the loss of mineralization process of the cochlear capsule, and hearing loss is most of the time sensorineural, but the physiopathology is still unclear (Fang et al., 2021).

2. Diagnosing and screening for otosclerosis with audiological testing

It is of particular concern in otosclerosis research that it is difficult to consistently differentiate this disease from other disorders affecting the ossicular chain. Hearing concerns associated with a positive family history, tinnitus, and specific audiometric features are indicators of otosclerosis (Lima et al., 2022). However, these indicators are only sometimes reliable since they can also be present in other diseases. Additionally, a diagnostic assessment of otosclerosis is often delayed due to the difficulty distinguishing this disorder from other middle ear pathologies (Fisher and Fishman, 2020). Therefore, an accurate diagnosis of otosclerosis requires careful evaluation by an otolaryngologist. MRIs or CT scans may be used to confirm the diagnosis (Prasad et al., 2022).

Common characteristics include conductive hearing loss, a Carhart notch, normal or decreased tympanic mobility, and the absence of acoustic reflex. Hearing aids may be used to improve hearing in cases where surgery is inapplicable. In some cases, medications such as steroids may be used to reduce symptoms (Vîrzob et al., 2023).

In otosclerosis, for instance, air-bone gaps are often observed but can also appear in other conditions. In addition, the degree to which these traits manifest themselves also varies from case to case (Eggermont, 2017).

There is no definitive correlation between the Carhart notch and otosclerosis. Other middle-ear pathologies can alter the ossicular chain's typical resonance characteristics, resulting in minor air-bone gaps near 2000 Hz.

Therefore, the Carhart notch is not a reliable indicator of otosclerosis, and other tests must be performed to make a diagnosis.

If otosclerosis is suspected, patients are referred for further investigation, which may include tuning fork tests, a CT scan of the temporal bone, or even exploratory tympanotomy. Tympanometry may be a common practice, usually applied to the adult population based on compensated admittance at 226 Hz, but is not effective in distinguishing pathologies like otosclerosis, which are not directly related to tympanic lesions. As otosclerosis affects the ossicular chain and not the tympanic membrane (TM), the admittance values measured during clinical tympanometry are not affected. In comparison with ears that function normally, multifrequency tympanometry is more effective in identifying individuals with otosclerosis than 226 Hz tympanometry (Shahnaz et al., 2009).

It has been concluded that sweep frequency impedance testing is more adequate for measuring middle ear stiffness modifications associated with adult otosclerosis than 226-Hz tympanometry (Zhao et al., 2002). Furthermore, the test is more accurate, reproducible, and reliable. For determining whether ears are normal or otosclerotic, the diagnostic precision of this test has not been determined.

2.1. Acoustic stapedius muscle reflex responses

The first impedance bridge developed for measuring ASRs in normal auditory function ears was described by Metz (1946). The bridge measures the compliance changes in the middle ear induced by a reflexive contraction of the stapedius muscle. The bridge is still used today and has helped to advance the understanding of the physiology of the auditory system. The admittance magnitude of the ear measures the relative amount of sound energy entering the ear canal. By comparing

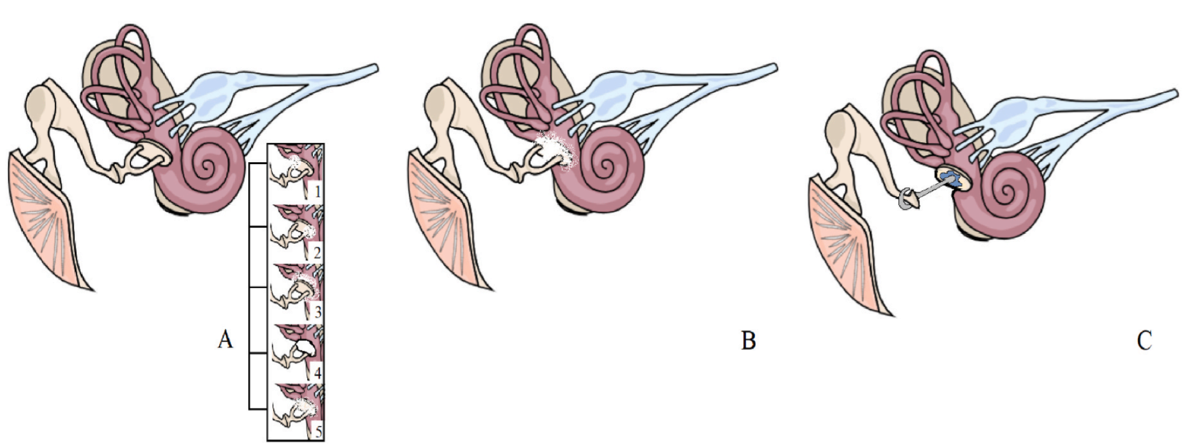

Fig. 1. A. Various types of stapedial otosclerosis can be distinguished, including 1. anterior focus (most common): anterior to oval window, 2. posterior focus: behind oval window, 3. circumferential: affecting only the footplate margin, 4. biscuit type: preserving the margins while affecting only the footplate, and 5. obliterative: obliterating the entire oval window.
B. Schematic coronal illustration of otosclerotic lesion
C. Surgical placement of the otosclerotic prosthesis.

the admittance magnitude in a quiet condition to one with an activator signal, the clinician can assess how the ear responds to different sound pressure levels.

When sound pressure levels drop below a certain level, the acoustic stapedius muscle reflex is triggered, which results in a significant amplitude shift in admittance. The acoustic stapedius reflex measures how sensitive the ear is to sound and is used to diagnose hearing problems. It is vital to measure the admittance magnitude in different sound environments and compare the results to assess how the ear responds to varying levels of sound pressure (Keefe et al., 2017).

3. Surgical Pioneers in Early Stapes Surgery

Valsalva described ankylosis of the stapes for the first time in 1741 (Canalis, 1990). Approximately 150 years later, Toynbee defined how the stapes were fixed to the oval window (Betlejewski and Betlejewski, 2009). Modern otosclerosis surgery has evolved through several eras. At first, in the mid-18th century, stapes were mobilized, then removed completely, leaving an oval window open.

Holmgren pioneered fenestration in the early 1900s, creating fistulas in the horizontal semicircular canal (Nazarian et al., 2018). During the 1950s and 1960s, ***Shea*** demonstrated that the oval window should be covered with a vein graft after stapes removal (Vincent et al., 2006). Using the Teflon that Shea had used to establish the sound-conducting mechanism, Harry Treace made the first biocompatible implant prosthesis (Eshraghi and Telischi, 2018). The stapedectomy technique has been widely accepted and improved over the years. Rather than removing the footplate entirely or partially, Myers created a small hole and used piston prostheses in the 1970s (Myers and Ronis, 1956). Early in the 1980s, Perkins used LASER for stapedotomy (Pauli et al., 2020).

Traditionally, microscopic surgery was the most appreciated way to perform stapes surgery (SS). Microscopic stapes surgery (MSS) has become successful, but some limitations still exist (Vincent et al., 2016). Especially for patients with narrow segments of the external auditory canal, tunnel vision is a significant problem, often requiring an external incision to access the tympanic membrane and middle ear structures (Tarabichi, 1999).

Belluci technique suggests bypassing the otosclerotic segment by removing the head and crura of the stapes. As a result, the footplate is subluxated and slightly depressed into the vestibule. Therefore, a polyethylene tube holds the footplate in place without contacting vestibular bone. (Cinca, 1972)

House describes another kind of surgical procedure that involves the development of the stapedectomy surgery from footplate removal and implantation of a single loop wire prosthesis to small fenestra stapedectomy associated with platinum ribbon piston prosthesis. (Ataman, 1993)

4. Endoscopic stapes surgery

It's generally accepted that there is a growing interest in transcanal endoscopic stapedotomy (TES) worldwide (Eren et al., 2021). As a result, TES offers surgeons benefits such as exposure to hidden recesses, zooming into complex structures, and reducing bone curettage (Fisher and Fishman, 2020). By-passing a narrow isthmus in a transcanal approach, the endoscope could view the ossicular chain and oval window more clearly (Kuo and Wu, 2018a). Nevertheless, the endoscope does not meet all requirements (Hu et al., 2020). Due to the lack of depth perception, the necessity of operating one hand, and the relatively long learning curve, many otolaryngologists prefer not to use endoscopic technology for otological surgery (Surmelioglu et al., 2017). When performing the two-handed technique of endoscopic stapes surgery using the endoscope holder, the surgeon can enjoy the benefits of endoscopic exposure and overcome some of the disadvantages associated with the one-handed technique (Parab and Khan, 2019).

Stapes surgery will be more effective when more endoscopic instruments are developed that are compatible with endoscopic ear surgery (Eren et al., 2021).

TES performed by surgeons has demonstrated that endoscopic access to the middle ear eliminates the need to divide chorda tympani to reach the stapes and oval window niche (Yong et al., 2016).

A transcanal endoscopic procedure may not expose the chorda tympani, while conventional microscopic surgery places it at risk and sometimes requires it to be sacrificed (Berteretche et al., 2008). TES was mentioned first by Poe et al., (2000). An endoscope measuring 3 mm in diameter and 14 cm in length can be used in association with instruments and surgical techniques similar to those suitable for conventional microscopic ear surgery (Yong et al., 2016).

Tympanomeatal flaps can be raised at the 5 and 12 o'clock positions of the EAC wall using a 0° endoscope., It may be necessary to curet or drill the posterior bony portion of the EAC to better expose the incudostapedial joint (Kozin and Lee, 2017). In the case of curetting or drilling, special care must be taken to avoid possible lesions to the chorda tympani (Saito et al., 2001). Drilling is usually avoided when good endoscopic visualization of the incudostapedial joint and pyramidal eminence is possible. Some EACs may require curettage of the posterosuperior aspect to provide better visualization and more maneuvering space (Badr-El-Dine et al., 2013). Drilling should be done with extreme caution to avoid injury to the ossicles and the tympanic membrane. The surgeon should stop drilling when the desired space is achieved and proceed with the endoscopic visualization (Nogueira et al., 2021).

Middle ear anatomy is evaluated using a 0° or 30° endoscope (Kapadiya and Tarabichi, 2019). The ossicles and tympanic membranes are delicate structures that can easily be damaged or destroyed if the drilling is done too aggressively (Ridge et al., 2021). Taking the time to inspect the middle ear with an endoscope properly is an important step to ensure that the structures are not damaged or destroyed. Furthermore, hidden recesses like the sinus tympani, anterior epitympanum, and protympanum may be explored. This is because curetting or drilling can cause damage to important anatomical landmarks, which may lead to further complications. Therefore, if good endoscopic visualization can be achieved, it is usually preferred over curetting or drilling.

Bartel et al., 2021 suggested that stapes surgery can be performed using an endoscope with a 0° angle and a 4-mm diameter for sinus surgery. A variety of otolaryngology departments should be able to offer this type of surgery without difficulties. The audiological outcomes should be comparable to those obtained with microscopic approaches. (Bartel et al., 2021).

The endoscope technique is also less invasive and can reduce the risk of complications (Bickerton et al., 2019). It also has the potential to reduce the time of surgery and the surgical cost. Finally, it can provide a more clear view of the surgical field for the otolaryngologist. This can help to reduce the number of patients who need to have a second operation due to complications.

The current state of research has no report of temperature-related adverse effects following EES. The issue of heat has been debated in EES. However, insufficient evidence focuses on the potential adverse effects of heat exposure for the sensitive anatomical structures in the auditory area. This process depends on the endoscope's diameter and the light source utilized. To protect against any potential effects of heat, it is recommended that the temperature of the endoscope be monitored during the procedure. Another suggestion for preventing damage is to avoid approaching the structure too closely. In addition to the factors listed above, other variables, such as the length of the procedure and the use of suction, can also contribute to higher temperatures in the middle ear.

Monitoring the temperature of the endoscope during the procedure can help to ensure that it does not reach a level that could be harmful to the patient.

Additionally, cooling systems are recommended.

5. Surgical technique

1. *Patient position* - Patients were positioned the same way as usual MSS. Transcanal surgery was performed using rigid endoscopes (angles of 0° and 30°) with diameters of 3 mm and lengths of 14 cm.
2. *Tympanomeatal flap elevation* - Using the 0° endoscope, a posterior tympanomeatal flap was raised transcanal and then positionated anteriorly. During tympanomeatal flap elevation, cotton balls soaked in 1:2000 are used for hemostasis by placing them in the ear canal for a few minutes (Giri et al., 2022; Nomura et al., 2014).
3. *Incudostapedial disarticulation* - Using curved microscissors, the stapes tendon was sectioned, followed by the removal of the superstructure by gently fracturing the anterior and posterior crura (Albera et al., 2022).
4. *Prosthesis placement* - Prostheses are sized based on the distance between the footplate and the long process. LASER or micro-drilling is used to create an opening in the footplate (Fang et al., 2014). The platinum or fluoroplastic piston prosthesis is positioned in the footplate's opening and fitted along the long process of the incus (Moneir et al., 2023).

Recently, research has focused on how the prosthesis is better fixed to the incus. The wire loop is secured to the incus by crimping it down around the incus using forceps or laser (Wegner et al., 2016).

To ensure the correct tension of the wire loop, the forceps should be placed as close as possible to the incus and tightened until the wire loop is secure but not overly tight. The wire loop should be checked to ensure it is not too loose or tight before and after the crimping process (Tange and Grolman, 2008).

5.1. Contraindications

It is generally contraindicated to perform stapes surgery if the patient is in a poor state of health, the affected ear is the only hearing ear, has a deficient cochlear reserve as demonstrated by diminished speech discrimination scores, has untreatable vertigo, has active otospongiosis as revealed by a positive flamingo sign, or has Ehlers-Danlos syndrome-associated conductive deafness (Necula et al., 2023). These contraindications are important to be aware of because they can increase the risk of complications from the surgery, such as further hearing loss. Additionally, if the patient has Ehlers-Danlos syndrome, the conductive hearing loss caused by this condition may not be treatable with stapes surgery (Miyajima et al., 2007).

A surgeon must observe the EAC prior to performing a transcanal stapedotomy or stapedectomy with an endoscope. Tortuous and relatively small-diameter EACs do not represent barriers to an endoscopic approach, but they may present some challenges, especially in the early stages for a physician who is less experienced in this field. Therefore, it is essential to carefully consider the EAC anatomy before performing the procedure (Wenig, 2009).

Another controversial topic is prosthesis selection. There are two types of stapes prostheses currently available: those that require crimping and those that do not (Lavy and Powell, 2013). Faramarzi et al., 2020 reported similar improvements in hearing in the short term by utilizing prostheses of both types (Faramarzi et al., 2020). A malleus palpation ensured the appropriate motion of the ossicles with the positioned prosthesis. According to this perspective, the prosthesis should be stabilized by adding fat (Faramarzi et al., 2019). Gelfoam® filled with eardrops containing antibiotics were inserted into the external auditory canal after the tympanomeatal flap had been repositioned. To avoid vestibular complications, it is strongly recommended to avoid frequent suctioning after fenestration at any stage of surgery (Lucidi et al., 2021).

5.2. Complications

A stapedectomy can cause complications, such as allergic reaction to the packing material, vertigo, facial palsy, infection at the surgical site, tinnitus, and worsening hearing (Roberson, 2010). Any surgery for footplate fixation can cause sensorineural hearing loss, one of the most feared complications (Moyano and Zernotti, 2020). SS is associated with approximately 1% new sensorineural loss in most modern studies (Henning et al., 2006).

Perilymphatic gusher upon SS, has been observed both in otosclerosis and in cases of congenital footplate fusion (Thomas et al., 2018; Luryi et al., 2021). Patients with inner ear anomalies have been seen with much higher rates of cerebrospinal fluid otorrhea during SS (Brackmann et al.). The presence of a prolapsed facial nerve or an anomalous facial nerve course can significantly affect a surgeon's surgical decision (Wycherly et al., 2010). It is listed by Purohit et al. that CT exams for SS should report the volume and site of the otosclerotic lesion, the status of the ossicular chain, the passage of the facial nerve canal, the abnormal features of the oval and round niches, the sinus plate and jugular bulb, inner ear disorders, and also the comparative aspect of the contralateral ear (Causse and Causse, 1983).

6. Discussions

Despite the widespread impact of endoscopy on most surgical disciplines, microscopic surgery continues to dominate otological surgery (Iannella and Magliulo, 2016). However, the introduction of endoscopes to the ear surgery field has the potential to revolutionize the diagnosis and treatment of ear disorders (Lucidi et al., 2021). Microscopic surgery is still an expensive technology and not widely available (Bianconi et al., 2020).

There is no doubt that, in theory, the endoscopic operative provides a clear field, and otologic surgeons could easily determine the anatomy of the middle ear, which would result in fewer bony structures being sacrificed or none at all, which would, to a certain extent, reduce the operative time (Kuo and Wu, 2018b). According to some studies (Kuo and Wu, 2018b; Tolisano et al., 2019), TES takes longer than MSS regardless of the experience of the surgeon, suggesting that this is not simply the result of a "learning curve" (Iannella and Magliulo, 2016; Tseng et al., 2017). Generally, established surgeons possess higher cognitive biases (concerning the benefit of traditional microscopic methods) and are more adept at controlling their emotions (Pothier, 2013; Cordero et al., 2015).

There is an interesting point of view to consider. Considering that the external auditory canal is similar to a keyhole, a microscope provides an enhanced image far away from the field of action, as long as the endoscope is passing through the keyhole. In addition to providing a 360-degree view, EES also allows the surgeon to examine hidden areas such as the sinus tympani. When the periosteum of the manubrium of the malleus is observed closely, it is possible to obtain a more accurate elevation of the tympanomeatal flap. In contrast, managing bleeding without suction in a non-dominant hand is challenging (Hunter and Rivas, 2016).

In light of the fact that endoscopy surgery is extensively used in sinus surgery, it may be relevant to reconsider the learning curve for endoscopic ear surgery for surgeons who have experience performing rhinology procedures (Emrah Emre et al.).

Although, the major complications associated with stapes surgery are sensory hearing loss and vestibular dysfunction. It is possible to cause mechanical and thermal trauma to the stapes footplate by using a micro drill or a LASER during the procedure to make a hole in the footplate (MacKeith et al., 2008). This trauma can lead to damage of the inner ear structures, particularly the sensory cells, leading to hearing loss and balance problems (Bartel et al., 2021b). The surgeon must take extreme care to avoid damaging these structures during the procedure (Shaheryar Ahmed et al., 2020).

Consequently, corticosteroids are being administered perioperatively. The effectiveness of intravenous corticosteroid treatment during surgery has been demonstrated by Szekely et al. The authors concluded that further investigation could be conducted in a prospective manner (Szé et al., 2020).

There are several points of view in terms of hemostasis during the elevation of the tympanometry flap. It was believed that monopolar radiofrequency cautery would be better suited to this EAC's incision (Demir et al., 2020). Another perspective is to apply only a few spots of monopolar to avoid retraction of the skin within the ear canal and to facilitate faster healing.

As well, footplate fenestration may be performed by Fisch needle perforator, drill or laser. Many different types of lasers have been used in stapes surgery, including the carbon-dioxide (CO2) laser, potassium-titanyl-phosphate (KTP) laser, diode laser (Plodpai, 2023), and argon laser (Liu et al., 2020).

Following that, prosthesis selection may contribute to audiological outcome (Huber et al., 2003). It is possible to choose from a wide range of stapes prostheses. These designs include a long piston, short piston, bucket, clip, ribbon piston. Most frequently, Teflon, titanium, and nonmagnetic stainless steel are used as most common materials (Skinner et al., 2003).

Additionally, a new perspective on surgical skills of prosthesis crimping has been explored. Another method of prosthesis fixation is laser-assisted.

NiTiBOND® prosthetics are able to be fitted using minimal energy provided by a diode laser, without manual crimping (Schrö et al., 2018).

Gerlinger et al. concluded that avoiding manual crimping and using a "non-touch" hand-held laser technique improved midterm audiometric results for KTP laser stapedotomy. The study utilized a self-crimping, thermal shape memory Nitinol piston (Gerlinger et al., 2014).

Another challenge is considered stapes revision surgeries because of erosion or displacement of the prosthesis. According to the experience of Gargula et al., malleostapedotomy is considered a valuable option to bypass the incus with valuable results. In conclusion, it is reported to be the treatment of choice for patients with severe necrosis, incus misalignment, or epitympanic fixation (Gargula et al., 2020).

According to recent research, for mild and moderate necrosis of incus, hydroxyapatite cement is considered an effective treatment (Hudson et al., 2014).

7. Conclusions

Considering the patient's follow-up and long-term evolution, stapedectomy is a cost-effective strategy for treating otosclerosis, maximizes the quality of life, and minimizes cost for the patient (Danesh et al., 2018). Over time, otosclerosis becomes more severe, causing complete hearing loss and disability (Odat et al., 2021). Communication and care coordination between the audiologist, surgeon, occupational therapist, and psychotherapist may improve patient outcomes (Zafar et al., 2022).

In comparing surgery with hearing aids, surgery showed better patient self-evaluation of tinnitus according to the Tinnitus Handicap Inventory and visual analog scale (Molinier et al., 2022).

In terms of a comparison between TES and MSS, we can draw a few conclusions. Many surgeons are generally reluctant to use TES because of the extended initial operative times and the long learning curve (Isaacson et al., 2018). It is important that EES delivers live surgery images to operating room personnel, providing enhanced teaching opportunities. Moreover, an operating room configuration is essential for the conversion from the endoscope to the microscope to succeed.

In conclusion, a comprehensive understanding of ear pathology requires professional training in both microscopic and endoscopic surgery.

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