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ADVANCES IN THE DIAGNOSIS AND SURGICAL MANAGEMENT OF CHOLESTEATOMA: A CONTEMPORARY REVIEW

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ABSTRACT

Cholesteatoma is a chronic, locally destructive disease of the middle ear characterized by the presence of keratinizing stratified squamous epithelium within the tympanic cavity and mastoid process. Despite its histologically benign nature, it may lead to the destruction of bony structures, damage to the auditory ossicles, and the development of serious intra- and extracranial complications. Its complex pathogenesis and tendency to recur make cholesteatoma a significant diagnostic and therapeutic challenge. In recent years, substantial progress has been made in both the diagnosis and surgical treatment of cholesteatoma. High-resolution computed tomography and magnetic resonance imaging with non-echo-planar diffusion-weighted imaging (non-EPI DWI) sequences enable accurate assessment of primary, residual, and recurrent lesions. Surgical treatment remains the cornerstone of therapy, while advances in endoscopic techniques have improved visualization of anatomical structures and enhanced surgical effectiveness while reducing invasiveness. Artificial intelligence systems are also gaining increasing importance in supporting imaging analysis, treatment planning, and clinical decision-making. The aim of this review is to present current advances in the diagnosis and surgical management of cholesteatoma, with particular emphasis on modern imaging techniques, endoscopic ear surgery, and applications of artificial intelligence. The development of these technologies may contribute in the future to improved treatment outcomes and reduced risk of disease recurrence.

KEYWORDS

Cholesteatoma; Mastoidectomy; Endoscopic Ear Surgery; DWI MRI; Artificial Intelligence; Bone Resorption; EESS

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1. Introduction

Despite a name suggesting neoplasia, cholesteatoma is not a malignant lesion. Its aggressiveness results from enzymatic and inflammatory activity that leads to the destruction of adjacent bony structures [1,2]. Morphologically, cholesteatoma consists of three components: (1) the matrix—a layer of keratinocytes capable of active proliferation and migration; (2) the perimatrix—a stromal layer rich in fibroblasts, blood vessels, and inflammatory cells; and (3) the core—composed of accumulated layers of desquamated keratin. This morphological triad determines the destructive and expansile nature of the lesion [2,3]. Cholesteatoma is primarily classified into acquired and congenital forms, with acquired cholesteatoma being the most common [4,5]. Congenital cholesteatoma represents a distinct entity and is defined as a pearly white mass located behind an intact tympanic membrane in a child with no history of middle ear infections or previous otologic surgery [6,7]. Isolated mastoid cholesteatoma is observed less frequently [8,9]. The incidence of acquired cholesteatoma is estimated at approximately 9–12 cases per 100,000 individuals annually, with the highest incidence occurring in children and middle-aged adults [4,10]. Congenital cholesteatoma accounts for approximately 2–5% of all cholesteatoma cases and is most commonly diagnosed in children younger than 5 years of age [6,11–13].

A particularly important clinical issue is the more aggressive disease course observed in children, which is associated with a higher risk of recurrence and intracranial complications [14,15]. The clinical presentation of cholesteatoma depends on its location and extent. The most common symptoms include chronic foul-smelling otorrhea, conductive hearing loss, aural fullness, and tinnitus [4,10]. In more advanced cases, vertigo, labyrinthine fistulae, and facial nerve palsy may occur [16,17]. Congenital cholesteatoma may remain asymptomatic for a prolonged period, making early diagnosis difficult [6,7,11].

Table 1. Comparison of Clinical Symptomas of Acquired and Congenital Cholesteatoma

Symptom / Feature	**Acquired Cholesteatoma**	**Congenital Cholesteatoma**	References
Ear discharge (otorrhea)	Very common; often foul-smelling and purulent	Rare in the early stages	[4,6,10,11]
Hearing loss	Conductive (70–85%)	Conductive or mixed	
Ear pain (otalgia)	Moderate, chronic	May be absent	
Sensation of ear fullness	Frequently reported	Possible	
Tinnitus	Present in ~30–40%	Less common	
Dizziness / Vertigo	Associated with labyrinthine fistula (~7%)	Occasional	
Facial nerve palsy	0.5–3.5% of cases	Rare	
Tympanic membrane changes	Retraction pocket / perforation of pars flaccida or posterosuperior quadrant	Tympanic membrane remains intact	
Peak age of presentation	Any age; peak at 5–10 years	Typically <5 years	

If left untreated, cholesteatoma may lead to labyrinthine destruction, facial nerve canal erosion, mastoiditis, meningitis, intracranial abscesses, and sigmoid sinus thrombosis [4,14,15,17].

Table 2. Complications of Middle Ear Cholesteatoma

Complication	**Description**	**Frequency**	**References**
Labyrinthine fistula	Erosion of a semicircular canal (most commonly the lateral/horizontal canal)	~7%	[4,14-17]
Meningitis	Spread into the middle cranial fossa	1–3%	
Epidural / subdural abscess	Intracranial complication	<1%	
Sigmoid sinus thrombosis	Spread through the mastoid process	<1%	
Facial nerve palsy	Exposure/erosion of the Fallopian canal	0.5–3.5%	
Cervical abscess (Bezold's abscess)	Extension through the mastoid tip into the neck	<1%	
Mastoiditis	Chronic inflammation or acute exacerbation	Common	
Sensorineural hearing loss	Destruction of the ossicular chain and cochlea	Variable	

2. Materials and Methods

This study was conducted as a narrative literature review in accordance with the principles of Evidence-Based Medicine (EBM). The review focused on the etiology, pathogenesis, diagnosis, treatment, and recent advances in the management of cholesteatoma.

A structured literature search was performed using the PubMed/MEDLINE database. Publications available up to May 2026 were considered for inclusion. Search terms were combined using Boolean operators (AND, OR) and included the following keywords: “cholesteatoma,” “congenital cholesteatoma,” “acquired cholesteatoma,” “middle ear cholesteatoma,” “cholesteatoma surgery,” “endoscopic cholesteatoma surgery,” “mastoidectomy,” “diffusion-weighted magnetic resonance imaging,” “DW-MRI,” “artificial intelligence,” “hearing outcomes,” “recurrence,” and “complications.”

The inclusion criteria comprised original research articles, clinical studies, observational studies, case series, systematic reviews, meta-analyses, and peer-reviewed narrative reviews published in English. Studies addressing the pathogenesis, classification, imaging diagnostics, surgical management, treatment outcomes, complications, recurrence, and emerging technologies in cholesteatoma care were included.

The exclusion criteria consisted of publications not directly related to cholesteatoma, conference abstracts, editorials, letters to the editor, and non-peer-reviewed materials.

Following the initial database search, studies were screened based on title and abstract relevance. Full-text analyses were subsequently performed for articles meeting the inclusion criteria. To complement the electronic search strategy, the “Similar Articles” function in PubMed was utilized, and the reference lists of eligible studies were manually screened using a snowballing approach to identify additional relevant publications.

A total of 47 publications were included in the final analysis. Extracted data were organized thematically and synthesized using a narrative approach, covering the pathogenesis, classification, diagnostic methods, surgical treatment strategies, treatment outcomes, recurrence patterns, and future perspectives, including the application of endoscopic techniques and artificial intelligence in cholesteatoma management.

3. Pathogenesis

The pathogenesis of cholesteatoma is complex and multifactorial, and despite many years of research, it has not yet been fully elucidated. It is currently believed that the development of the disease results from the interaction of middle ear ventilation disorders, chronic inflammation, epithelial proliferation, and osteolytic processes [2,3,5,18]. The most widely accepted theory of acquired cholesteatoma formation is the retraction pocket theory, according to which chronic Eustachian tube dysfunction leads to negative pressure within the tympanic cavity, retraction of the tympanic membrane, and accumulation of desquamated keratin within the retraction pocket [2,3,5]. Other hypotheses include the epithelial migration theory, which assumes the displacement of keratinocytes from the external auditory canal into the middle ear cavity, and the metaplasia theory, according to which chronic inflammation induces the transformation of middle ear mucosal epithelium into keratinizing stratified squamous epithelium [2,3,18]. In congenital cholesteatoma, the lesion is thought to arise from embryonic epithelial cell remnants present in the middle ear since fetal life [6,7,8,9,19]. Chronic inflammation plays a key role in cholesteatoma progression. Increased expression of pro-inflammatory cytokines, including TNF-α, IL-1β, IL-6, and IL-17, has been demonstrated within the cholesteatoma matrix and the surrounding perimatrix, promoting osteoclastogenesis and bone resorption [2]. Particular importance is attributed to the RANK/RANKL/OPG signaling axis, considered one of the principal mechanisms of osteodestruction, as well as to matrix metalloproteinases (MMPs), which are responsible for degradation of extracellular matrix components [2,20]. Cholesteatoma keratinocytes also actively participate in these processes, exhibiting increased proliferative activity, the ability to produce inflammatory mediators and proteolytic enzymes, and the capacity to promote angiogenesis [2,18]. The consequence of these processes is progressive destruction of the osseous structures of the middle ear. The auditory ossicles, particularly the incus, are most commonly affected, leading to conductive hearing loss. In more advanced cases, damage to the facial nerve canal, formation of labyrinthine fistulas, and the development of severe intracranial complications such as brain abscess or meningitis may occur [1,16,17,21,22]. Contemporary concepts of cholesteatoma pathogenesis therefore emphasize the close interplay between inflammatory processes, middle ear ventilation disorders, epithelial proliferation, and osteolytic mechanisms responsible for the locally aggressive behavior of the disease [2,3,5].

4. Contemporary Diagnostic Methods

4.1. Clinical Examination and Otoscopy

A detailed clinical examination using otomicroscopy or magnifying otoscopy remains the cornerstone of cholesteatoma diagnosis. During the examination, the appearance of the tympanic membrane, the presence of retraction pockets, marginal or attic perforations, keratin debris visible as a characteristic "pearl-white mass," otorrhea within the external auditory canal, and signs of chronic otitis media are assessed [4,10]. In acquired cholesteatoma, the most common findings include chronic ear discharge, conductive hearing loss, and retraction changes of the tympanic membrane [4,10].

Endoscopic otoscopy using high-resolution cameras enables photographic documentation, more precise assessment of middle ear anatomy, and facilitates surgical planning and communication with the patient [23]. Furthermore, the use of endoscopes with different viewing angles allows evaluation of difficult-to-access recesses of the tympanic cavity, such as the sinus tympani, facial recess, and epitympanic space, thereby increasing the detection rate of lesions not visible during conventional microscopic otoscopy [23,24].

In the diagnosis of congenital cholesteatoma, the key finding is the presence of a pearly white mass behind an intact tympanic membrane in a patient without a history of chronic ear infections or previous otologic surgery [6,7,11]. The Potsic classification is widely used to assess disease extent in congenital cholesteatoma, with Stage I representing a lesion confined to a single quadrant of the tympanic cavity, whereas Stage IV indicates extension of the disease process into the mastoid [6,7].

4.2. Audiometry and Functional Assessment

Audiological evaluation constitutes an integral component of cholesteatoma diagnostics. Pure-tone audiometry and speech audiometry enable assessment of the degree and type of hearing loss and are essential for planning reconstruction of the sound-conducting apparatus [25,26]. Conductive hearing loss resulting from damage to or immobilization of the auditory ossicles by cholesteatoma is the most common finding; however, in advanced cases, a sensorineural component may also occur due to labyrinthine involvement [17,20].

Tympanometry serves as a complementary diagnostic tool, allowing assessment of middle ear function and indirect evaluation of Eustachian tube patency. Measurement of the stapedius reflex may provide additional information regarding the integrity of the ossicular chain and the extent of disease progression [25]. Comprehensive audiological assessment before surgery and during the postoperative period is currently considered the standard of care [25,26].

4.3. High-Resolution Computed Tomography (HRCT)

High-resolution computed tomography (HRCT) of the temporal bones remains the primary imaging modality performed before surgical treatment of cholesteatoma. It enables detailed assessment of the extent of disease, the anatomy of the middle ear and mastoid process, and the presence of complications [10,22].

A typical HRCT appearance of cholesteatoma includes the presence of a homogeneous soft-tissue mass within the tympanic cavity or mastoid process, accompanied by destruction of adjacent bony structures. The most commonly observed findings include ossicular erosion, erosion of the lateral attic wall (scutum), dehiscence of the facial nerve canal, and labyrinthine fistulas involving the lateral semicircular canal [16,17,22]. Assessment of these abnormalities is crucial for surgical planning and for anticipating potential intraoperative challenges.

The sensitivity of HRCT for detecting cholesteatoma is estimated at approximately 85–95%; however, its principal limitation is the inability to reliably differentiate cholesteatoma from granulation tissue, postoperative scar tissue, or inflammatory effusion [10,22].

This limitation is particularly relevant during postoperative follow-up. Contemporary multiplanar reconstruction (MPR) and three-dimensional reconstruction protocols have improved the preoperative assessment of anatomy and surgical planning. In addition, image fusion techniques combining CT and MRI are increasingly being utilized, enabling simultaneous evaluation of bony changes and soft-tissue structures [27,28].

4.4. Magnetic Resonance Imaging with DWI Sequences

Magnetic resonance imaging (MRI) with diffusion-weighted imaging (DWI) sequences currently represents the most important complement to computed tomography in the diagnosis of cholesteatoma. This technique exploits the characteristic restriction of water molecule diffusion within accumulated keratin, resulting in high signal intensity on DWI images and low signal intensity on apparent diffusion coefficient (ADC) maps [22,29,30]. Unlike computed tomography, DWI MRI allows differentiation of cholesteatoma from inflammatory granulation tissue, postoperative scarring, and other soft-tissue lesions, making it particularly valuable for postoperative surveillance [22,30].

4.4.1. Non-EPI DWI MRI – the Standard for Postoperative Surveillance

Non–echo-planar imaging (non-EPI DWI) sequences, such as HASTE, PROPELLER, and BLADE TGSE, are currently considered the most valuable diffusion-weighted MRI techniques. Compared with conventional EPI sequences, they are substantially less susceptible to geometric and magnetic susceptibility artifacts, allowing more accurate evaluation of middle ear structures [29].

In the diagnosis of primary middle ear cholesteatoma, non-EPI DWI sequences achieve high diagnostic performance. For the 2D BLADE TGSE technique, sensitivity of up to 88% and specificity of 92% have been reported [29]. Non-EPI DWI MRI is currently regarded as the imaging modality of choice for postoperative surveillance, particularly following canal wall up (CWU) procedures, where the risk of residual disease is increased [10,30]. Residual lesions can also be detected during the early postoperative period, allowing earlier planning of further treatment and, when necessary, revision surgery [30]. In the pediatric population, this method demonstrates high sensitivity and specificity for the detection of residual cholesteatoma, outperforming conventional computed tomography in postoperative monitoring [31]. The introduction of non-EPI DWI MRI has reduced the need for routinely performed second-look procedures, which for many years represented the standard method of postoperative surveillance following cholesteatoma surgery [30,31,32].

4.4.2. The Value of DWI MRI in Congenital Cholesteatoma

Diffusion-weighted MRI also plays an important role in the diagnosis of congenital cholesteatoma. It enables precise localization of lesions and assessment of their extent before planned surgical treatment [33].

It has been demonstrated that diffusion-weighted MRI (DWI MRI) can detect lesions as small as 3–5 mm, achieving diagnostic performance comparable to computed tomography (CT) while simultaneously providing additional information regarding soft-tissue characteristics [33].

4.5. CT–MRI Image Fusion

The fusion of computed tomography and magnetic resonance imaging data represents one of the most advanced diagnostic tools currently used in otology. This approach combines the high anatomical resolution of HRCT with the superior soft-tissue characterization provided by MRI [27,28].

It has been demonstrated that fusion of CT and MRI images enables cholesteatoma localization with an accuracy of approximately 95%, surpassing the diagnostic performance of either modality when used alone [27]. Similarly, the combination of TSE DWI and HRCT imaging has demonstrated high effectiveness in the localization of primary middle ear cholesteatoma and facilitates surgical treatment planning [28].

5. Treatment Methods

Surgical treatment remains the only effective therapy for cholesteatoma. Owing to the locally aggressive nature of the disease, conservative management cannot provide durable control of disease progression. The primary goals of surgery are complete removal of the cholesteatoma matrix, eradication of chronic inflammation, prevention of recurrence, and preservation or restoration of normal ear anatomy and function, with particular emphasis on hearing preservation and protection of the facial nerve [34,35,36,37]. The choice of surgical technique depends on multiple factors, including disease extent, the degree of ossicular and temporal bone destruction, mastoid status, the presence of complications, patient age, hearing status, and surgeon experience [21,36,37].

5.1. Classical Mastoidectomy Techniques

5.1.1. Canal Wall Up (CWU)

The canal wall up (CWU) technique, also referred to as combined approach tympanomastoidectomy, involves removal of the cholesteatoma while preserving the posterior wall of the external auditory canal [34,35]. The principal advantage of this technique is the preservation of more physiological ear anatomy, which facilitates better hearing outcomes and reduces the need for long-term postoperative cavity care [34,37].

A limitation of the CWU technique is the increased risk of residual or recurrent disease due to restricted visualization of certain anatomical spaces, particularly the sinus tympani and facial recess [32,34]. Consequently, patients require careful postoperative surveillance, most commonly using non-EPI DWI MRI [30,31].

5.1.2. Canal Wall Down (CWD)

The canal wall down (CWD) technique involves removal of the posterior wall of the external auditory canal and creation of a common cavity encompassing both the external auditory canal and the mastoid process [34,35]. This approach provides wide access to all compartments of the middle ear and mastoid, allowing more complete removal of disease.

The main advantage of this technique is the reduced risk of residual disease and recurrence, particularly in cases of extensive cholesteatoma and significant bony destruction [34]. Its disadvantages include the need for periodic postoperative cavity cleaning and follow-up, increased susceptibility to infections, and potentially less favorable hearing outcomes [34,35]. The choice between CWU and CWD techniques should be individualized and based on disease severity, anatomical considerations, and the feasibility of long-term postoperative surveillance [36,37].

5.1.3. Retrograde Mastoidectomy

Retrograde mastoidectomy represents an alternative to the classical surgical techniques. This method involves dissection of the disease from the middle ear toward the mastoid process without performing a conventional antromastoidectomy. It is primarily used in cases of limited disease with relatively preserved mastoid anatomy. The technique allows a reduction in the extent of tissue dissection while maintaining treatment efficacy comparable to that of the CWU approach [38].

5.2. Endoscopic Middle Ear Surgery

Endoscopic Ear Surgery (EES) represents one of the most significant achievements of modern otologic surgery. This technique utilizes rigid endoscopes introduced through the external auditory canal, enabling a wide field of view without the need for extensive surgical approaches [10,23]. Compared with the operating microscope, the endoscope provides superior visualization of anatomically challenging areas, such as the sinus tympani, facial recess, hypotympanum, and epitympanic space [10,23]. This facilitates the identification of residual disease and may improve the effectiveness of surgical treatment.

5.3. Reconstruction of Middle Ear Structures

Reconstruction of damaged middle ear structures is an integral component of contemporary cholesteatoma management. Particular emphasis is placed on the reconstruction of the lateral attic wall (scutum), as its destruction promotes the formation of new retraction pockets and recurrent disease [39]. Another important stage of surgery is the reconstruction of the ossicular chain (ossiculoplasty). Depending on the extent of damage, partial ossicular replacement prostheses (PORP), total ossicular replacement prostheses (TORP), or autologous materials such as cartilage and preserved ossicular remnants may be used [25,37]. Properly performed reconstruction can result in significant hearing improvement following surgical treatment. Particularly favorable outcomes are observed in patients with a preserved stapes and limited destruction of the sound-conducting structures [21,25].

5.4. The ChOLE Classification

The ChOLE classification has gained increasing importance in the evaluation of cholesteatoma treatment outcomes. This system incorporates four main components: cholesteatoma extension (Ch), ossicular chain status (O), presence of labyrinthine fistulae (L), and extracranial or intracranial complications and disease extension beyond the middle ear (E) [21]. The ChOLE classification enables standardization of medical documentation, comparison of treatment outcomes between centers, and assessment of recurrence risk and expected hearing outcomes [21].

5.5. Cholesteatoma in Special Clinical Situations

5.5.1. Pediatric Cholesteatoma

Cholesteatoma in children is often characterized by a more aggressive course, faster growth, and a greater tendency toward recurrence than in adults [14,15]. Advanced stages of disease and complications related to bony destruction are also observed more frequently in this patient population [14,]. Surgical management requires meticulous planning and long-term postoperative follow-up. In many centers, preservation of the posterior canal wall (CWU) is preferred, combined with postoperative monitoring using DWI MRI or a planned second-look procedure. The CWD technique remains reserved primarily for more advanced cases [14,15].

5.5.2. Congenital Cholesteatoma

Congenital cholesteatoma requires surgical treatment regardless of the presence of clinical symptoms. The extent of surgery depends on disease stage. In early stages, minimally invasive techniques, often using an endoscopic approach, may be employed, whereas more advanced disease requires extended surgery involving the mastoid process [6,7,11,13]. Early diagnosis and treatment are associated with better hearing outcomes and a lower risk of complications [13].

5.5.3. Facial Nerve Canal Dehiscence

Facial nerve canal dehiscence represents an important intraoperative challenge. Exposure of the facial nerve occurs relatively frequently in patients with advanced cholesteatoma and increases the risk of nerve injury during surgery [16]. In many tertiary referral centers, intraoperative facial nerve monitoring has become standard practice, enabling rapid identification of hazardous situations and improving surgical safety [16].

5.6. Disease Recurrence and Postoperative Follow-Up

Despite advances in surgical techniques, cholesteatoma remains associated with a risk of recurrence. A distinction is made between residual cholesteatoma, resulting from incomplete removal during the initial procedure, and recurrent cholesteatoma, which develops secondarily within newly formed retraction pockets [32]. Contemporary postoperative surveillance is based on regular otolaryngological examinations and imaging studies, particularly magnetic resonance imaging with non-EPI DWI sequences [30,31,32].

6. Future Directions in Diagnosis and Treatment

6.1. Novel Biomarkers and Molecular Diagnostics

The identification of specific tissue biomarkers associated with cholesteatoma aggressiveness, such as MMPs, RANKL, and IL-17, may enable non-invasive monitoring of disease activity and prediction of recurrence risk. Proteomic and genomic studies of the cholesteatoma matrix may contribute to the identification of novel therapeutic targets that could be exploited in pharmacological treatment strategies [2,20].

6.2. Biological Therapies Targeting Bone Destruction

One of the most promising therapeutic perspectives is the pharmacological inhibition of osteodestruction. Denosumab, an anti-RANKL monoclonal antibody approved for the treatment of osteoporosis and bone metastases, may theoretically limit bone destruction induced by RANKL produced by cells within the cholesteatoma perimatrix [2]. Other potential candidates include bisphosphonates and cathepsin K inhibitors. Studies conducted in animal models have demonstrated promising results; however, none of these therapies has yet entered clinical trials involving human subjects [2,20].

6.3. Ossicular Regeneration and Three-Dimensional Printing

Bone and cartilage tissue engineering offers promising prospects for the regeneration of damaged ossicles. Three-dimensional printing technologies and hydroxyapatite-based biomaterials already enable the production of patient-specific prostheses. Future developments may include the in vitro cultivation of bioengineered ossicles using the patient's own stem cells [20].

6.4. Telemedicine and Remote Detection

Tele-otolaryngology applications enable remote otoscopic assessment and preliminary triage of patients with suspected cholesteatoma. Integration of artificial intelligence with mobile tele-otoscopy systems may facilitate the early detection of retraction pockets and disease recurrence, particularly in settings with limited access to specialized care [40,41].

6.5. The Role of Artificial Intelligence

One of the most rapidly developing areas in cholesteatoma diagnostics is the application of artificial intelligence (AI), particularly models based on deep learning and convolutional neural networks (CNNs) [41,42]. AI systems are increasingly being used for the analysis of otoscopic images, as well as computed tomography (CT) and magnetic resonance imaging (MRI) scans. In otoscopic diagnostics, CNN-based models enable the automated classification of middle ear pathologies using otoscopic images. Available data indicate that AI systems achieve a sensitivity of 87–93% and a specificity of 88–94% in the detection of ear diseases, demonstrating diagnostic performance comparable to, or even exceeding, that of primary care physicians [42].

7. Discussion

In recent years, significant progress has been made in both the diagnosis and surgical treatment of cholesteatoma, resulting in earlier disease detection, more precise treatment planning, and improved clinical outcomes [4,10,11,36]. Knowledge regarding the pathogenesis of cholesteatoma has also expanded considerably; however, classical theories such as the retraction pocket theory, epithelial migration theory, and metaplasia theory remain fundamental in explaining the mechanisms underlying its development [3,5].

Contemporary therapeutic approaches have gradually shifted away from uniform treatment strategies toward individualized patient management. The choice of surgical technique should take into account the location and extent of the lesion, the condition of middle ear structures, the patient's age, and the feasibility of long-term postoperative follow-up [36,37]. The Canal Wall Up (CWU) technique allows better preservation of ear anatomy and is often associated with more favorable hearing outcomes; however, it carries a higher risk of residual disease and recurrence [32,34,36,]. In contrast, the Canal Wall Down (CWD) technique provides greater surgical radicality at the cost of requiring periodic postoperative cavity care and potentially less favorable functional outcomes [34,35].

An important area of development in modern otologic surgery is endoscopic middle ear surgery. By enabling visualization of anatomically difficult-to-access areas, endoscopy allows for a more accurate assessment of disease extent and potentially more complete cholesteatoma removal [24,27,43]. Available meta-analyses indicate that endoscopic techniques achieve outcomes comparable to those of microscopic surgery while reducing surgical trauma and shortening hospital stays [43]. Nevertheless, this approach requires appropriate surgical expertise, and conventional mastoidectomy techniques may still be necessary in cases of extensive mastoid involvement [24].

Significant advances have also been achieved in imaging diagnostics. The introduction of non-echo-planar diffusion-weighted magnetic resonance imaging (non-EPI DW-MRI) has revolutionized postoperative surveillance by enabling non-invasive detection of residual and recurrent cholesteatoma [22,31]. In many cases, this has reduced the need for routine second-look surgery. Despite the high sensitivity of this technique, very small cholesteatoma foci may remain undetectable on imaging studies; therefore, long-term follow-up remains an essential component of patient management [30,31].

Currently, treatment outcomes are evaluated not only in terms of surgical radicality but also with regard to functional results and patient quality of life. Increasing emphasis is placed on hearing preservation or improvement, reducing the need for additional surgical procedures, and minimizing the impact of the disease on daily functioning [21,26]. Despite successful disease eradication, some patients continue to report symptoms related to ear function or the burden of long-term postoperative surveillance [26].

The treatment of pediatric cholesteatoma remains a particular challenge. In children, cholesteatoma often exhibits a more aggressive course, a higher tendency toward recurrence, and a greater risk of complications than in adults [14,15]. Early diagnosis and appropriately planned treatment are crucial for limiting the destruction of middle ear structures and achieving favorable long-term hearing outcomes [11,13-15].

The application of artificial intelligence (AI) in cholesteatoma diagnostics has also attracted increasing attention. Particularly promising results have been obtained in the analysis of high-resolution computed tomography (HRCT) images of the temporal bone. AI models utilizing CT data achieve diagnostic accuracies of approximately 88–91% in differentiating chronic otitis media with and without cholesteatoma [44,45]. These findings have been confirmed in independent patient cohorts, suggesting that such solutions may serve as valuable diagnostic support tools, particularly in centers with limited access to magnetic resonance imaging [46]. In some studies, CT-based AI models demonstrated diagnostic performance comparable to or even slightly superior to conventional diffusion-weighted MRI [44].

Another important area of development is explainable artificial intelligence (XAI), which aims to improve the transparency and interpretability of AI algorithms. Three-dimensional convolutional neural

network models analyzing temporal bone CT images have achieved area under the curve (AUC) values of up to approximately 0.92 in multicenter validation studies [47]. Furthermore, the use of class activation maps enables the identification of anatomical structures that exert the greatest influence on the model's diagnostic decisions, potentially increasing clinicians' confidence in AI-based tools [47].

Models utilizing computed tomography, magnetic resonance imaging, and otoscopic image analysis currently demonstrate diagnostic performance comparable to that of experienced specialists [41,42,44,46,47]. In the future, these technologies may support diagnostic decision-making, surgical treatment planning, and recurrence risk assessment. However, most currently available solutions remain at the clinical research stage and require further validation before implementation into routine clinical practice [41,47].

Another important direction of development is the standardization of disease staging and treatment outcome assessment. The increasingly adopted ChOLE classification system enables objective evaluation of cholesteatoma extent, the degree of middle ear structural damage, and the presence of complications, while also facilitating comparisons of treatment outcomes among different institutions [21]. This may provide a foundation for the further development of personalized treatment strategies tailored to an individual patient's risk profile [21,36].

8. Conclusions

Middle ear cholesteatoma remains a significant clinical challenge because of its aggressive behavior, capacity for bone destruction, and high recurrence rate. Advances in endoscopic surgery and modern imaging techniques, particularly non-EPI DWI MRI, have substantially improved diagnostic capabilities and postoperative disease monitoring. Artificial intelligence technologies are also gaining increasing importance in imaging diagnostics and surgical planning. Furthermore, improved understanding of the molecular mechanisms responsible for osteodestruction may facilitate the future development of biological therapies as an adjunct to surgical treatment. Despite significant progress in diagnostics and therapy, recurrence of cholesteatoma—especially in the pediatric population—remains an unresolved problem that requires further research and the development of personalized treatment strategies.

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