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Systematic Review

Slag Injuries to the Tympanic Membrane and Middle Ear—A Systematic Review

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Abstract: Objectives: Slag injuries in industrial settings pose risks of hearing loss and complications. The aim of this study is to provide specialists with a better understanding of the sequelae, treatment, and long-term outcomes that a patient may have following a slag injury to the tympanic membrane. **Data Sources:** PubMed, Embase, and Web of Science. **Methods:** Following the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA), multiple databases were queried for articles published from inception to 2023 describing Tympanic membrane injuries from welding. The publications were screened by two independent viewers. The Joanna Briggs Institute 2017 Critical Appraisal Checklist was used to assess the quality of studies. **Results:** A total of 227 articles were identified, and 9 full-text articles were included in this review, comprising a total of 18 patients. The patients' ages ranged from 18 to 75 years. Most commonly, patients were welding overhead in a tight working space, and none of the patients were wearing protective ear equipment in addition to their welding masks. Patients experienced otalgia (n = 10; 55%), hearing loss (n = 11; 65%), vertigo (n = 6; 35%), chronic otorrhea (n = 5; 29%), and facial paralysis (n = 4; 23%). A total of 12 patients (70.6%) required surgery, most requiring debridement of metallic foreign body multiple times, some undergoing surgery up to four years post-injury. **Conclusions:** Tympanic membrane injuries from welding are often overlooked. They cause hearing loss and facial nerve damage. Following a period of observation, sturdy reconstruction with cartilage grafting is recommended, given the poor vasculature and inflammation after this injury.

Keywords: slag injury; middle ear; tympanic membrane; welding

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1. Introduction

Metal workers and welders face a variety of occupational hazards, including burns, ocular injury, and lung cancer [1,2]. Less commonly reported and investigated, injury to the tympanic membrane and middle ear can occur and can cause significant and chronic dysfunction. A slag is a spark composed of molten metal that flies off or drops from the welding site; it can reach temperatures of 1000 degrees Celsius [3]. For reference, a fourth-degree burn can be caused by exposure to heat at 60 degrees Celsius [4]. The most common mechanism of middle ear slag injury occurs when slag enters the ear canal, directly inducing thermal injury and retaining foreign bodies [5]. Damage from slag injuries is difficult to repair because the devascularized and scarred tympanic membrane remnant furnishes a poor framework for grafting [3,6,7]. Slag has the opportunity to induce both mechanical and thermal injury, the latter being the most widely accepted reason for impactful sequala.

Due to the relatively low water content circulating in the middle ear, there is a lack of biological buffers to prevent thermal injury [6]. The extremely high temperature has the opportunity to damage the nerves without direct penetration of the bone [3]. Sensorineural hearing loss and vestibular abnormalities are suggested to develop from the "boiling" of endolymph [3].

Welders are encouraged to wear face and eye protection, but there tends to be a lack of standard ear protection recommendations for welders and metal workers [8]. Slag injuries to the tympanic membrane and middle ear are generally a rare occurrence, as welding positioning tends to avoid slag entry into the relatively narrow external auditory canal. However, this remains an occupational hazard that is avoidable through the use of ear protection. When slag injury does occur, physicians must be aware of the potential complications and understand the potential for significant damage to middle ear structures. The literature on the topic is sparse, and there are no recommendations or guidelines for treating such injuries. Our goal was to systematically review the literature for slag and welding injury to the middle ear and tympanic membrane to understand the typical progression, sequelae, and treatment for these injuries and to provide recommendations for management.

2. Methods

2.1. Data Sources and Search Strategies

A comprehensive search of several databases from each database's inception to 31 October 2023 was conducted in compliance with the Preferred Reporting Items for Systematic Reviews and Meta-analyses guidelines [9]. The databases included PubMed, Embase, and Web of Science. The search strategy was designed and conducted by an experienced research librarian with input from the study's principal investigator. A combination of Medical Subject Headings (MeSH), another controlled vocabulary, and keywords was used to search for "slag", "weld", "injury", "middle ear". An example of the comprehensive search strategy used to query the databases is described in Supplementary Table S1. All languages were included in the search algorithm, but only English-language studies or full-length international journals with English translations were included for further analysis. References of all publications were also subjected to review for potential inclusion criteria. Articles with available full texts were screened, and duplicated articles were removed. A qualitative synthesis of the presentation, risk factors, treatment, and long-term outcomes for all of the studies was employed to integrate study results. This review was not registered. The level of evidence is considered level V.

2.2. Eligibility Criteria and Quality Assessment

Eligible studies were studies that must meet all of the following inclusion criteria: (1) adult participants older than or equal to 18 years who experienced slag injury to their middle ear and tympanic membrane; (2) reporting complication as the result of the injury. Exclusion criteria included abstracts, commentaries, and publications that were deemed outside the scope of the study's aims. We used the Joanna Briggs Institute's critical appraisal tools to assess the quality of included papers. Selected studies were examined for inclusion criteria, sample size, description of study participants, and setting. Two reviewers (SF, NA) independently assessed the methodological quality of each paper.

3. Results

3.1. Inclusion Criteria and Study Design

Of 227 articles initially reviewed by title and/or abstract, we identified 12 for full-text screening. Nine articles met the criteria for inclusion. The most common reasons for

exclusion were wrong outcomes and inappropriate study design. Among the included studies, seven were case reports [3,5,6,10–13], and two were case series [14,15] (Table 1). Figure 1 demonstrates the PRISMA algorithm for article collection and review. In the case of missing data for included studies, it was the authors' intention to avoid bias by reporting only what was explicitly stated in the literature. Statistical analysis was not performed, and therefore, our study lacks statistical biases. Bias analysis is not applicable to our study due to the qualitative review of included case reports and case series. Due to variability in study design and outcome measured, formal synthesis in the form of a meta-analysis was not possible. The following discussion represents a consolidation of findings describing slag injuries to the tympanic membrane in welders and subsequent management. The methods for data collection are not public template collection forms; the data used for qualitative analysis in this study is available through the cited materials with appropriate access to the cited journals.

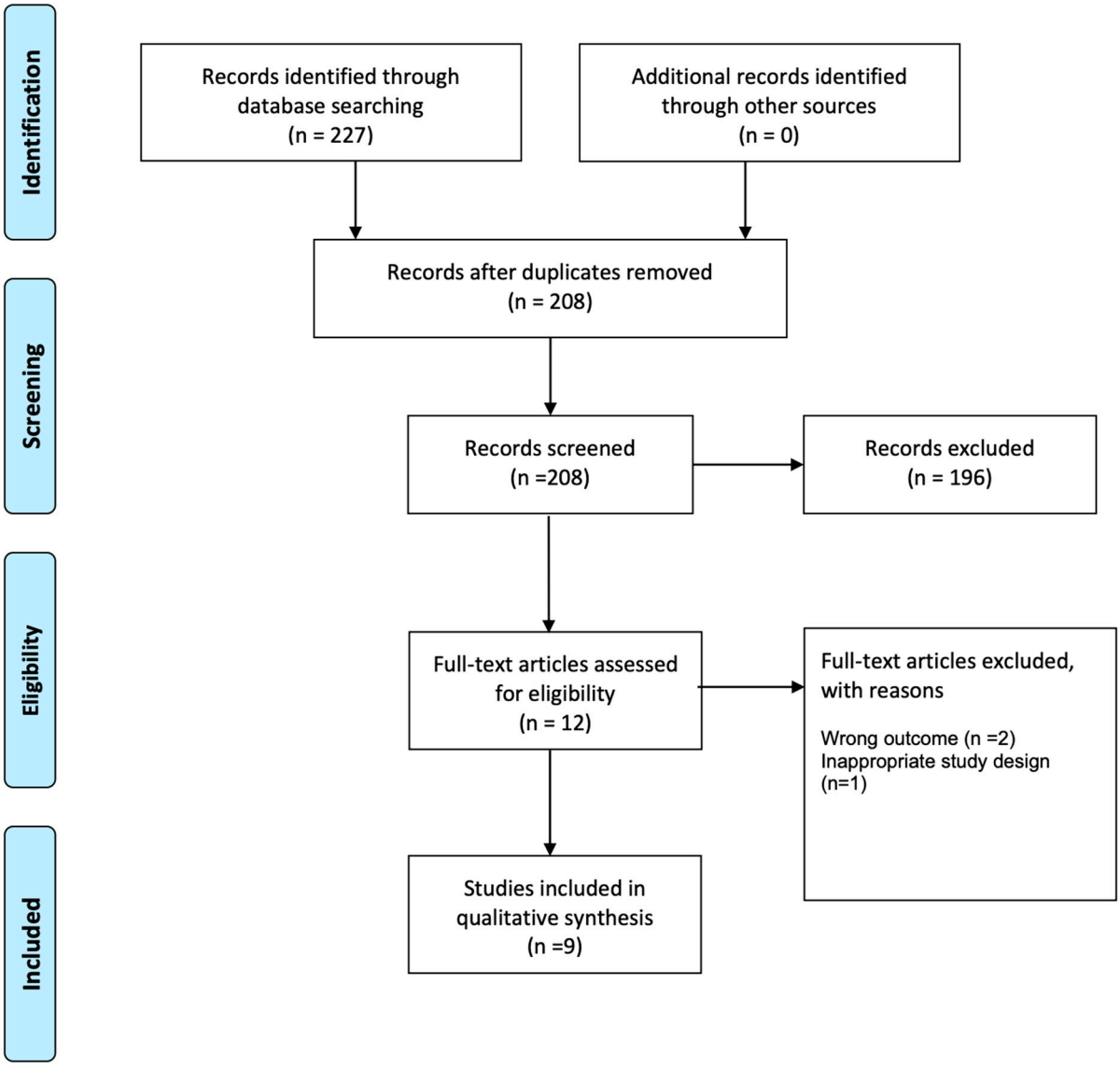


Figure 1. Preferred reporting items for systematic reviews.

Table 1. Baseline characteristics of included studies.

Study	Publication Year	Country	Study Type	Total No. of Patients N	Gender (male), N (%)	Age, Mean ± Range (SD)	Hearing Loss N	Intervention(s)	Clinical Features	Patient Outcome
Eleftheriadou et al. [5]	2007	Greece	Case Report	1	1 (100%)	36	Conductive	Ossiculoplasty, tympanoplasty	Otalgia	Resolution of symptoms in 6 months
Fisher et al. [15]	1991	UK	Case Series	5	4 (80%)	33.8 ± 7.62	NR	Removal of metal fragments, regular toilet	Otalgia, otorrhea, tinnitus,	Resolution of symptoms in 2–6 months
Keogh et al. [6]	2009	Ireland	Case Report	1	1 (100%)	55	Conductive	NR	Otorrhea, hearing loss	Resolution of symptoms was observed four years after the surgery.
Kupisz et al. [14]	2000	Poland	Case Series	5	NR	NR	Conductive (3) Mixed (2)	Myrigoplasty, Tympanotomy	Tinnitus, vertigo, bradyacusia	Three individuals experienced improved hearing, with no improvement in the other two
Leedman et al. [10]	2021	Germany	Case Report	1	1 (100%)	60	Conductive	Extraction of the foreign object	hearing loss and fullness	Improvement of symptoms in 2 weeks
Marchiano et al. [11]	2016	USA	Case Report	1	1 (100%)	53	Conductive	Extraction of the foreign object and a postauricular tympanoplasty	Tinnitus, hearing loss	Regain of hearing in 2 months post-op
Panosian et al. [3]	1993	USA	Case Report	2	2 (100%)	26.5± 8.5	Conductive	3.8 ± 0.9	Otalgia, otorrhea, facial paralysis	Mild conductive hearing loss at 1-year visit in one case and resolution of symptoms in the second case
Stage et al. [13]	2005	Denmark	Case Report	1	1 (100%)	36	Sensorineural	Extraction of the foreign object	Otalgia, hearing loss, dizziness, nystagmus, peripheral nerve palsy	Resolution of symptoms except peripheral palsy at the 15-month follow-up visit
Simons et al. [12]	2005	USA	Case Report	1	1 (100%)	75	Sensorineural	Removal of metal fragment	Otalgia, Otorrhea	Complete resolution of symptoms

3.2. Risk of Bias Within Studies

The detailed results of the quality assessment are provided in Supplementary Table S2. Included case reports (n = 7) had a mean score of six with scores ranging from five to seven [3,5,6,10–13]. Meanwhile, the case series conducted by Fisher et al. and Kupisz et al. yielded an average score of eight on a 1–10 scale [4,15].

3.3. Presenting Symptoms

A total of 18 participants were included in the selected studies. Eight out of nine studies reported on gender, skewing towards male patients with a total of 17 males vs. 1 female. The patients' ages ranged from 18 to 75 years old. Table 1 displays the study designs and patient demographics from the studies included in this systematic review. The most common sequelae of injury to the tympanic membrane was hearing loss. Most welders experienced conductive hearing loss due to damage from the implantation of slag in the tympanic membrane [3,5,6,11]. Two patients experienced sensorineural hearing loss, with one patient reporting profound loss on the ipsilateral side and mild to moderate high-frequency loss on the contralateral side [12,13]. Two patients experienced mixed hearing loss [14]. Three patients experienced tinnitus at the immediate time of injury, and

three patients experienced subsequent ear infections following the initial insult [11,14,15]. Otalgia was evident in 55.5% (n = 10) of patients [3,5,12,13,15]. Most patients with pain described a sharp "hissing" noise at the onset of otalgia [3,10]. Six patients described dizziness or vertigo; two of them described intense room spinning, while the remainder reported nonspecific dizziness and imbalance [13,14]. Tympanic membrane perforation was visualized at presentation in seven of the welders [3,5,11,14]. It is unclear how commonly perforation was present on the initial clinic visit as reporting was obfuscated by some reports noting foreign bodies or drainage precluding a complete view of the drum at the initial clinic visit. Five patients presented with concerns of chronic otorrhea [12,15]. Four patients (23%) experienced impairment of the facial nerve in different varieties: two experienced facial weakness, and one experienced the inability to produce tears, incomplete eyelid closure, and a disturbance in taste [3,13]. Two of these patients completely recovered facial nerve function, and two had incomplete recovery.

3.4. Risk Factors

The greatest risk factors among the welders were the position of welding and the lack of specific ear protection. Each case of tympanic membrane injury was the result of welding slag flying from the welding site and inserted into or around the tympanic membrane. Welders were most commonly injured by slag when working underneath the welding site, often working alone in a tight space with sparks flying overhead. Of the articles that mentioned the welders' position, 9 out of 10 welders were underneath their welding site or lying down, while the remaining welder was in a confined space and impacted by another welder's slag. The remaining articles do not make specific mention of the welders' position. Only one of the welders had any form of ear protection, which was "ear flaps" and not full ear canal inserts or covering [12]. Because of the small size of the slag, the flaps were inadequate protection in this case. In cases where workers were asked about their ear protection, they mentioned that it was never brought up to them in their formal training [16].

3.5. Treatment

The approach to the management of welders with tympanic membrane injuries varied greatly among the patients discussed in the literature. Twelve (70.6%) patients underwent surgical management. Observation has not been found to be effective for tympanic membrane perforations resulting from slag injury, as spontaneous closure after this degree of thermal injury is rare [12]. Nine patients had tympanoplasty alone, two patients received tympanomastoidectomy due to chronic inflammatory changes in the mastoid, and two received canaloplasty due to damage to the external auditory canal. In one case, the malleus handle had been completely eroded, and a foreign body was present in this location. Of the four patients with facial nerve involvement, only one was explored surgically, and facial tone returned at 14 weeks postoperatively with grade III/VI facial nerve function with good tone and symmetry one-year post-op [3]. One patient had foreign body removal under local anesthesia, which was the only case of an in-office foreign body removal. This patient experienced total destruction of the labyrinth and did not experience resolution of his facial nerve paralysis, nor did he regain complete lid closure.

Most of the welders (11) underwent surgical intervention after the six-month observation period, and others waited over a year for surgical management.

4. Discussion

The tympanic membrane is a generally well-protected structure, as its natural physical positioning shields it from most environmental hazards. In the case of welders, it is possible

for the arcing path of slag to navigate through the ear canal and cause significant damage to the tympanic membrane and middle ear. Welders are also much more likely to injure their tympanic membrane when welding overhead in tight spaces [12]. The slag itself contains very small bits of metal that can become lodged into the ear canal and middle ear, and the extreme heat can cause significant thermal damage to surrounding structures. Injuries to the ear canal alone were associated with pain and drainage in some cases. Deeper injuries involving the tympanic membrane and middle ear were also associated with risks of conductive and sensorineural hearing loss, dizziness, and facial nerve paralysis. These sequelae are hypothesized to be due to the extreme heat transferred from the slag through the middle and inner ear. The seventh and eighth cranial nerves are at high risk for injury due to their proximity to the tympanic membrane and connection with the cochlea [13,16]. Panosian et al. noted that one of the mechanisms of injury is the "frying" of endolymph in the semicircular canals.

Safety and prevention have driven the evolution of the work environment for many years, and the proper use of safety measures by welders is an important way of preventing or reducing a variety of health hazards they are exposed to while working [17]. Unfortunately, patients in the current review reported that ear protection for the prevention of slag-related injuries is rarely discussed in training and education about welding hazards [15]. In our patient population, only one welder had some ear protection in the form of additional flaps covering his ears associated with his other equipment, while the rest had no ear protection. There is much more attention devoted to preventing eye and lung injuries, but given the potential for serious complications, including permanent facial nerve injury, additional efforts for the prevention of otologic welding injuries should be implemented.

The management of the welders in this review ranged from observation to radically modified reconstruction. Clinical decision-making depends largely on the extent and location of injury, but it is clear that there is a potential for significant damage and scarring to the tympanic membrane and middle ear mucosa. Some of the otolaryngologists opted for immediate foreign body removal followed by a "wait and see" period, while others delayed foreign body removal for definitive delayed surgical management. Multiple authors noted that inflammation and chronic otorrhea reduce the likelihood of healing and graft success in these injuries [6,7]. Although reconstruction of the tympanic membrane provides the best route to healing, the nature of the injury makes it prone to surgical failure, and the injury is often larger in the operating room than expected based on evaluation in the clinic [7]. Furthermore, the timing of repair has not been evaluated thoroughly in the literature, and there is no consensus on the most appropriate time course for healing. Keogh et al. and Marchiano et al. both commented that delaying surgery until the limits of the damaged tissue are fully demarcated might result in fewer surgical complications and failures. This also provides the tissue with the opportunity to heal primarily [6,11].

Although otologic slag injury is rarely reported, this may be an underreported phenomenon in the literature. Slag injuries may be noted to cause tympanic membrane perforations and treated as all other perforations without much consideration for a mechanism of injury in general practice. Despite being often overlooked, special attention should be paid to this mechanism of injury due to its potential to cause severe damage to the middle ear mucosa, tympanic membrane, and facial nerve. We recommend sturdy reconstruction with total tympanic membrane cartilage grafting as there is poor vasculature and significantly scarred and inflamed middle ear mucosa prone to drainage in this setting, which would prevent acceptance of other graft materials. Foreign bodies may be present and would require removal at the time of surgery. A CT scan may provide information about the proximity of middle-ear foreign bodies to important structures like the facial nerve. Currently, there does not appear to be sufficient evidence for facial nerve decompression. Facial

paralysis is likely the result of a thermal injury in these cases, a mechanism not known to respond to decompression. We recommend a conservative approach with consideration for oral steroids and neurodiagnostic studies to follow complete loss of function.

Slag injuries to the tympanic membrane are relatively rare, but they threaten serious long-term complications. There is a paucity of information in the literature that examines the progression of the injury and the steps that should be taken to manage the injury in terms of timeline, prognosis, and need for surgical intervention. This systematic review found a relatively small number of studies and cases addressing these specific complications and outcomes, which raises the importance of bringing further attention to the topic. This review summarizes the evidence from 17 cases in the literature with the risk factors, outcomes, and management of tympanic membrane injury caused by welding slag.

There are several limitations to consider with this systematic review. The studies gathered during the review process lack uniformity in their data reporting. There was significant variability in details provided in each study regarding the patient cases, exact timeline before surgical intervention, immediate and long-term follow-up, and the method of evaluation for each symptomatic manifestation. This posed a challenge for direct comparison of findings among all studies. While there are many common factors that expose welders to injury and some recurring manifestations of tympanic membrane injury, the small sample size and heterogeneity of the cases make it difficult to draw significant conclusions on the best way to inform our patients on the long-term prognosis and treatment plan.

5. Conclusions

Metalworking and slag can cause significant damage to the middle ear and tympanic membrane that can have long-term consequences. In our review of the literature, complications sustained during slag injuries ranged from pain and eardrum damage to facial paralysis. Education and prevention are integral, as the injury is avoidable with sufficient use of ear protection and awareness of risk when working overhead in tight spaces. Following a period of observation to allow for demarcation of tissue damage, sturdy reconstruction with cartilage grafting is recommended, given the poor vasculature, fibrosis, and inflammation after this injury. Although this injury is a rare occurrence in the welding field, opportunities for further research can provide physicians with a better understanding of the timeline for foreign body removal, facial nerve management, and reconstructive surgery.

Supplementary Materials: The following supporting information can be downloaded at https://www.mdpi.com/article/10.3390/ohbm6010004/s1. Table S1: Database search strategy used for systematic review of slag injuries to the tympanic membrane and middle ear; Table S2: Quality assessment of the systemic review and Risk of bias of the included studies.

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