Safety and Health at Work 11 (2020) 249–261

Contents lists available at ScienceDirect

Safety and Health at Work

journal homepage: www.e-shaw.net

Review Article

The Association Between Occupational Exposure to Hand–Arm Vibration and Hearing Loss: A Systematic Literature Review

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ARTICLE INFO

Article history:
Received 15 August 2019
Received in revised form
6 April 2020
Accepted 12 April 2020
Available online 21 April 2020

Keywords:
Hand-arm vibration
Hearing loss
Raynaud
Vibration
White finger

ABSTRACT

Background: Hearing loss is one of the most prevalent worker health conditions worldwide. Although the effect of noise exposure on hearing is well researched, other workplace exposures may account for significant hearing loss. The aim of this review was to determine whether occupational hand–arm vibration exposure through use of power or pneumatic tools, independent of noise exposure, is associated with permanent hearing loss. Do workers suffer from hand–arm vibration–induced hearing loss?
Methods: Peer-reviewed articles published in English between 1981 and 2020 were identified through five online databases with five search keywords. Preferred Reporting Items for Systematic Reviews and Meta-analyses guidelines, including online database search methodology, study selection, article exclusion, and assessment of potential study design confounders and biases, were followed.
Results: Database searches retrieved 697 articles. Fifteen articles that reported 17 studies met the criteria for review. All but two studies revealed statistically significant associations between occupational exposure to hand–arm vibration and hearing loss. The majority of the study results revealed associations between hand–arm vibration and hearing loss, independent of potential age and noise confounders.
Conclusion: Few studies have examined the association between occupational exposure to hand–arm vibration and hearing loss. Dose response data were limited as only one study measured vibration intensity and duration. Although the majority of studies identified statistically significant associations, causal relationships could not be determined. Further research using standardized and uniform measurement protocols is needed to confirm whether the association between occupational exposure to hand–arm vibration and permanent hearing loss is causal and the mechanism(s).

1. Introduction

Hearing loss—impaired function of normal, optimal hearing—is a significant disabling condition worldwide. The World Health Organization estimates more than 466 million people across the globe suffer from impaired hearing [1]. Among the various causes or aggravating factors of hearing loss, workplace noise exposure is one of the primary injurious agents [2]. In the United States (US), after hypertension and arthritis, hearing loss is the third most common chronic condition, with more than 11% of US workers suffering from impaired hearing [3]. Each year, between 22 million and 30 million US workers experience permanent noise-induced hearing loss (NIHL) in their employments [4,5], representing approximately 12% of recorded US industrial injuries and occupational diseases (also referred to as workplace illnesses) [6].

The prevalence of occupational hearing loss is also high in other countries. In Great Britain, approximately 23,000 workers suffer from work-related NIHL, including 1,395 new claims filed under the United Kingdom's Industrial Injuries Disablement Benefit for work-related deafness from 2008 to 2017 [7]. In Singapore, a national health survey revealed 26.5% of survey participants had at least mild hearing loss in 3 of 4 measurable hertz (Hz) frequencies [8]. In Germany, each year, an estimated 4 to 5 million people are exposed to hazardous workplace noise levels that could cause permanent hearing loss [9,10].

Upper extremity conditions caused by workplace exposure to hand–arm vibration, although less prevalent than occupational NIHL, are also significant global industrial injuries and workplace illnesses. Chain saws, grinders, riveters, drills, jackhammers, impact wrenches, sanders and polishers, lawn mowers, and hedge trimmers are some of the vibrating power and pneumatic hand

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2093-7911/$ – see front matter
https://doi.org/10.1016/j.shaw.2020.04.003

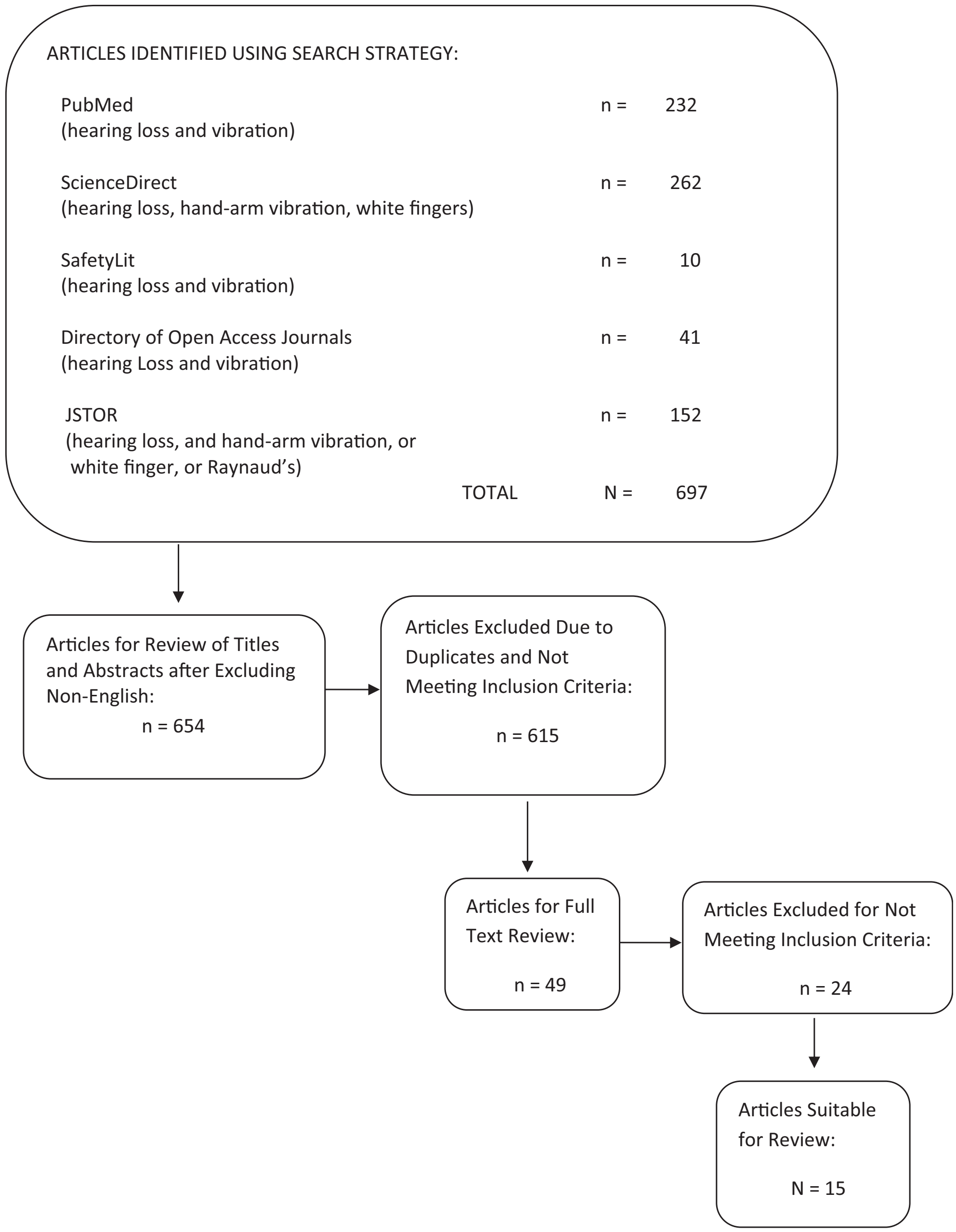

Fig. 1. Article review matrix flowchart.

tools used by millions of workers worldwide. Various upper extremity conditions are caused or exacerbated by workplace exposure to vibration through use of vibrating power tools. These conditions include hand–arm vibration syndrome (HAVS), vibratory-induced white finger (VWF), and Raynaud's phenomenon [11,12].

The US National Institute for Occupational Safety and Health estimated 1.45 million US workers are exposed to injurious hand–arm vibration each year [13]. In Canada, VWF is the most common condition among workers using handheld vibrating tools [11]. Between 2004 and 2016, workers in Great Britain filed more than 10,000 claims for occupational VWF under the Industrial Injuries Disablement Benefit program [14,15].

Use of handheld power and pneumatic tools exposes workers to noise that may cause NIHL and to hand–arm vibration that may cause VWF, HAVS, and Raynaud's phenomenon. Causal associations between noise exposure and cause and between hand–arm vibration exposure and hand and upper extremity conditions are well established. But does exposure to handheld tool vibration also cause permanent hearing loss? In other words, independent of NIHL, does worker use of power and pneumatic tools cause vibration-induced hearing loss (VIHL)?

Workers' use of hearing protection such as ear plugs or earmuffs during workplace exposure to loud noise is the standard prophylactic measure against occupational NIHL. If, however, vibration exposure is also a cause of hearing loss, then use of ear plugs and muffs may have limited preventative value. Ear protectors limit noise exposure and thereby reduce the incidence of NIHL, but they are unlikely to prevent or reduce hearing loss that may be caused by concomitant hand–arm vibration exposure.

Table 1
Study design, primary variables, findings and results, and study characteristics

First author (year), country	Research question	Design and time period	Setting and sample	Primary variables	Findings and results	Comments
Turcot et al. (2015) [16], Canada	Whether HL is worse in workers with NE and VWF than in workers with NE but no VWF. Whether HL differs between workers with NE and HAV and workers with HAV alone.	Cohort, 1983 −1996	Source population: 59,339 male workers, age 25 to 64 years, ≥1audiometric examination in QNI; 15,757 mining and forestry workers; 43,582 nonmining and nonforestry workers	Exposure: - Noise - Hand–arm vibration Outcome: - Hearing loss	15,757 workers: 1093 (7%) HL, 96 (0.6%) VWF, 21% with VWF compensation* and HL compensation, 47% with VWF compensation also met HL compensation criteria., 1.34 PR VWF risk of HL HL was greater among workers with VWF than among workers without VWF. HL among forestry and mining workers was greater than HL among nonforestry and nonmining workers.	Large study sample population. HL calculated via air conduction as per ISO.† Exposures were based on ambient noise and VWF diagnosis and VWF compensation. Antecedent HL, use of hearing protection, ototoxic drugs, and smoking habits were not considered. Workers with VWF may be more likely to apply for compensation than workers without VWF.
Pettersson et al. (2014A) [26], Sweden	What is the risk among workers with VWF who use handheld vibrating tools compared with workers without VWF?	Cohort, 21years: 1987, 1992, 1997, 2002, and 2008	Source population: not reported Sample population: 184 male welders	Exposure: - Noise - Hand–arm vibration Outcome: - Hearing loss	Approximately 90% of workers were right-hand dominant. Right-ear HL risk was greater in workers with VWF in the right hand than workers without VWF in the right hand (OR = 2.3; 95% CI). Increased risk of HL in the right ear for workers with VWF in the right hand.	Small sample; long observation period. Noise exposure: measured in 2008 and tool manufacturer noise emission. Workers reported use of hearing protectors and estimated daily exposure duration. Vibration exposure: random tool vibration measurements. VWF determined by participants' answer to the questionnaire. HL outcome determined by audiograms. Use of hearing protectors and ototoxic medications were not addressed.
Pettersson et al. (2014B) [27], Sweden	What is the occurrence of Raynaud's phenomenon among workers with NIHL in relation to vibration exposure?	Cross-sectional survey, 1995–2004	Source population: male and female workers with claims for NIHL accepted by AFA Insurance Company Age: 18–55 years Sample population: 261 male and 81 female workers	Exposure: - Noise - Hand–arm vibration Outcome: - Hearing loss - Raynaud phenomenon or white finger	Forty-four male and 39 female workers with compensable hearing loss claims participated in the survey. Most common occupations among the participants were teachers (n = 15), military personnel (n = 13), and welders (n = 4). Twenty-three male participants had white finger, including 15 exposed to HAV. Six female participants had white finger, including 3 exposed to HAV. Forty-one percent of the participants used handheld vibrating tools.	Small sample with a 41% response rate (38% of men; 50% of women). All study participants had medicolegal determinations of work-related NIHL. On average, less use of hearing protectors among participants who were not exposed to HAV than those exposed to HAV when the participants discovered they had hearing loss. Low participation rate of 41% (n = 133), with 38% (n = 94) for men and 50% (n = 38) for women with NIHL. Determination of white finger was based on participants' self-reports of symptoms.
Chao et al. (2012) [29], Taiwan	What are the combined effects of noise, vibration, and environmental temperature on physiology, including hearing?	Experimental date not reported	Source population: 23 volunteers (15 men; , 08 women) Age: 19 to 22 years	Exposure: - Noise - Hand–arm vibration - Environmental temperature Outcome: - Hearing loss	Noise had greatest influence on temporary hearing loss. HAV had no effect on hearing loss.	Small sample HAV simulated via electric hand drills Exposure at 30, 60, and 120 minutes HL determined by audiograms Use of hearing protectors not noted
House et al. (2010) [17], Canada	Are duration of construction work and severity of VWF predictors of hearing loss?	Cohort, 2006–2007	Source population: 191 male construction workers Sample population: 169 participants (81.7% pipefitters) Age: 28–75 years (median: 57 years)	Exposure: - Hand–arm vibration (VWF as an indicator of HAV) Outcome: - Hearing loss	HL increased as the number of years in construction increased. High prevalence of clinically significant HL, limited to 1 of 14 specific frequencies tested, among workers assessed for HAVS.	Given the high correlation between years worked in construction and age, it is likely that age contributed to hearing loss.

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Table 1 (*continued*)

First author (year), country	Research question	Design and time period	Setting and sample	Primary variables	Findings and results	Comments
Pyykkö et al. (2009) [28], Sweden	What are the risk factors in the development of SNHL?	Cohort, 1995–2004	199 forestry workers in Sweden who received insurance benefits for hearing loss. Age: 18 to 55 years	Exposure: - Hand–arm vibration - Noise Outcome: - Hearing loss	Among 199 forestry workers, 23 men and 6 women had cases of white finger. Among 29 participants with white finger, 8 men and 2 women were not exposed to HAV. Prevalence of white finger among men with NIHL not exposed to HAV was 20%.	Small sample 41% participation rate. On average, less use of hearing protectors among participants not exposed to HAV than participants exposed to HAV.
Palmer et al. (2002) [30], United Kingdom	What is the relation of HL to finger blanching according to exposure to noise and HAV?	Cross-sectional survey, date not reported	Source population: 21,201 random working-age male and female workers from 34 occupations. Mailed survey 7,335 men, 5,271 women Age: 35–64 years	Exposure: - Hand–arm vibration (finger blanching as an indicator of HAV) Outcome: - Hearing loss	2.3% severe HL 5.4% persistent tinnitus 14.1% history of cold-induced finger blanching HL increased with age and years of work in noisy jobs. HL was greater in men than women.	Large study sample population. Subject workers were chosen at random from British general employment practices, excluding member of the armed services. All data for hearing difficulties, exposure to HAV and noise, and lifetime history for finger blanching, age, gender, and smoking habits were obtained from the questionnaire. 65% response rate.
Iki et al. (1994) [25], Japan	What is the association between VWF and HL and between VWF and postural instability[†]?	Cross-sectional study, date not reported	Source population: 289 male forestry workers Study population: 37 pairs, matched for age and hours of noise exposure	Exposure: - Hand–arm vibration - Noise Outcome: - Hearing loss - Postural stability[‡]	Participants with VWF had greater HL then participants without VWF.	Small sample How 289 forestry workers were recruited is not reported. Participants had no history of ear diseases or exposure to ototoxic drugs. Exposure to noise from chain saws, bush cutters, and winches. Whether participants used hearing protectors is not reported. Pure-tone audiometry was conducted in a sound-proof chamber after the absence of noise exposure for 18 or more hours. Hearing levels of the left ear were analyzed. Participants with VWF, on average, were older and exposed to noise for longer periods than participants without VWF.
Pyykkö et al. (1994) [19], Finland	What are the effects of HAV on the inner ear (HL) and cardiac functions[†]?	Cohort, 1972–1990	Source population: 118 to 217 forestry workers who completed a compulsory health survey in NE Finland. Sample population: 98 participants were followed up from 1972 to 1990.	Exposures: - Hand–arm vibration Outcome: - Hearing loss - Cardiac function[‡] (as assessed via ECG)	Based on Robinson's model: - Age explained 25% of variance in SNHL. - VWF correlated significantly with initial SNHL. - VWF could not explain aggravation of NSHL during follow-up. - Noise exposure could not explain aggravation of SNHL during follow-up.	Use of earmuffs but not other forms of hearing protectors, such as ear plugs, was asked of worker participants on a questionnaire in conjunction with a compulsory health examination. The authors speculated a common mechanism caused by hand–arm vibration exposure may produce peripheral vascular constriction or vasospasm that restrict finger circulation and cochlear circulation and cause VWF and SHL, respectively.
Murata et al. (1990) [22], Japan	What are the effects of HAV tool operation on the central and peripheral nervous system, including hearing?	Cohort of forestry workers, 1987	Source population: unreported Sample population: 20 male forestry workers (12 chain saw operators, age = 44 to 63 years, worked for a mean of 16 years; 8 brush saw operators, age = 22 to 56 years, worked for a mean of 12 years) with matched controls.	Exposure: - Hand–arm vibration - Noise Outcome: - Hearing loss - Auditory nerve conduction - Median nerve conduction	Moderately worse hearing loss was observed in chain saw and bush saw operators compared with control participants. I–V interpeak latency and V peak latency of BAEP were significantly delayed in chain saw operators, and I–V interpeak latency of BAEP was significantly correlated with years worked for bush saw operators. Median NCV was significantly slowed in both vibration tool operators compared with control participants	Whether participants used earmuffs, ear plugs, or other forms of hearing protectors is not reported. Controls were randomly selected from 52 adults without otitis, tinnitus, and endocrinological or neurological disorders, residing in the same area as that of vibratory tool operators, and matched to chain saw and brush saw operators by age, gender, and alcohol use.

Iki et al. (1989) [24], Japan	What is the association between VWF and HL?	Case–control matched pairs; 5-year follow-up; dates not reported	Source population: unknown Sample population: 108 male forestry workers with and without VWF Every worker participant used vibratory tools, most commonly a chain saw.	Exposures: - Hand–arm vibration (VWF as an indicator of HAV) Outcome: - Hearing loss	17.4% had VWF without improvement during the study period. 72.1% had no history of VWF. 10.5% had atypical blanching of fingers or VWF that developed or ceased during the follow-up period. HL increased predominantly in workers with VWF compared with workers without VWF, although no difference existed in exposure time to noise between the two groups. HL developed more severely in workers with VWF than in workers without VWF.	Small study sample population. Annual interviews for 5 years. Subject workers were divided into two groups by age: $<$50 years and $\geq$50 years. Subject workers were further divided into two groups by total hours of use with vibrating tools (i.e., more or less exposure). HL and age matched between the two exposure groups. HL was determined by audiometric air conduction examination in a portable soundproof chamber in a room with background noise $<$40 dBA. VWF was diagnosed by 2 authors through participant interviews and coldwater immersion tests. Workers with history of ear diseases, vertigo, head injury, conductive HL, or intake of ototoxic drugs were excluded.
Pyykkö et al. (1989), FinlandStarck et al. (1988) [20], Finland	What are the measured and predicted hearing levels of workers exposed to noise and vibration from handheld power tools?	Cohort of forestry workers, 1972–1986Cohort of shipyard platers, 1986	Source population: unknown Sample population: - 199 forestry workers ; 171 shipyard platers	Exposure: - Noise - Hand–arm vibration Outcome: - Hearing loss	Among forestry workers: - HL was not significantly different from predicted by Robinson's model. - Two-tailed ttest; t(184) = 1.083) Among shipyard workers: - Measured HL was significantly greater than predicted by Robinson's model. t (170) = 8.117; P $<$ 0.005. There was no observed excess risk of HL in groups exposed to vibration.	Pyykkö et al. (1989) reported on the study of 199 forestry workers; Starck el al. (1988) reported on both studies of 199 forestry workers and 171 shipyard platers. Small study sample populations: one long and one short observation period. HL was determined by audiometric measurements, and Robinson's model was used to predict HL for comparison. Noise and vibration measurements were obtained using a microcomputer-controlled digital multichannel sampling unit. Noise exposure was estimated using a microphone attached to the middle of the ear canal entrance. Outside-of-ear protection exposure was determined using a microphone attached to the outside of the earmuff. Vibration transmission (exposure) was estimated by measurements of unweighted vibration acceleration. Data were obtained regarding use of earmuffs but not ear plugs Workers with HL caused by disease or injury were excluded. Use of ototoxic drugs and smoking habits were not considered.
Pyykkö et al. (1987) [21], Finland	What is the relative risk on SNHL due to noise and hand–arm vibration exposure?	Cohort, date not reported	Source population: 217 forestry workers in Finland. Sample population: 122 forestry workers, restricted to age, 35–55 years.	Exposure: - Noise - Hand–arm vibration Outcome: - Hearing loss - VWF	Based on Robinson's model: No observed increased risk of SNHL due to smoking tobacco, increased SBP systolic blood pressure, or combination of exposures to noise and HAV. Age explained 15.4% of SNHL. VWF explained 5.2% for SNHL. Participants with elevated DBP,[‡] 4.1% for SNHL.	Hearing threshold for the left ear at 4000 Hz was measured. The effects of age, systolic and diastolic blood pressure, tobacco smoking, noise exposure, HAV exposure, and use of earmuffs (but use of no other hearing protectors, such as ear plugs) were evaluated.
Iki et al. (1985) [23], Japan	Is there an association between Raynaud phenomenon and HL without confounding by age or duration of noise exposure?	Cohort, date not reported.	Source population: unreported number of forestry workers in Japan. Sample population: 37 forestry workers with Raynaud phenomenon and 37 forestry workers of similar age and working hours but without Raynaud phenomenon.	Exposure: - Noise - Hand–arm vibration - Raynaud phenomenon Outcome: - Hearing loss	Cases of forestry workers with Raynaud phenomenon had more advanced types of SNHL than controls. Cases had a higher mean threshold than controls at every frequency from 2,000 Hz through 8,000 Hz.	Use of and types of hearing protectors (e.g., earmuffs and ear plugs) are unknown.

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Table 1 (*continued*)

First author (year), country	Research question	Design and time period	Setting and sample	Primary variables	Findings and results	Comments
Pyykkö et al. (1981) [18], Finland	Whether a common mechanism operates in both NIHL and VWF.	Cohort, 1972–1978	Source population: forestry workers employed by the Finland National Board of Forestry during the years 1972 and 1974–1978 Sample population: 72 in 1972, increased to 203 in 1978	Exposure: - Noise - Hand–arm vibration Outcome: - Hearing loss - VWF	HL was greater among workers with VWF than among workers without VWF. HL increased with advancing age.	Small study sample population. HL assessed at 4000 Hz. Antecedent HL, ototoxic drugs, and smoking habits were not considered. Use of hearing protectors (earmuffs) was required after 1972, although not consistently used by forestry workers.

BAEP, brainstem auditory evoked potential; DBP, diastolic blood pressure; ECG, electrocardiogram; HAV, hand–arm vibration (also referred to as hand-transmitted vibration); HAVS, hand–arm vibration syndrome; HL, hearing loss; NCV, nerve conduction velocity; NE, noise exposure; NIHL, noise-induced hearing loss; PR, prevalence ratio; SBP, systolic blood pressure; SNHL, sensorineural (or sensory neural) hearing loss; VWF, vibration-induced white finger; QNI, Quebec National Institute of Public Health.

* Quebec Workers' Compensation Disability Compensation Award.

† International Organization for Standardization 6189 (1983).

‡ Postural instability and cardiac functions were not assessed in this review.

To assess occupational causes of hearing loss other than noise exposure, it is necessary to consider the associations between the various workplace activities and hearing loss. Exposure to vibration through use of handheld power and pneumatic tools is one type of occupational activity that warrants investigative consideration.

The objective of this systematic review article is to summarize and examine the published literature of descriptive or experimental studies that address the association between occupational exposure to hand–arm vibration through use of power and pneumatic hand tools and hearing loss. If a positive association is shown, a subobjective is to investigate whether the relationship is causal for VIHL.

2. Methods

2.1. Systematic search strategy

A literature review protocol was developed and followed in accordance with Cochrane and Preferred Reporting Items for Systematic Reviews and Meta-analyses guidelines. Searches for peer-reviewed articles with search terms "hearing loss," "hand-arm vibration," "vibration," "Raynaud's," and "white finger" were performed without limitation on study design or publication date using five large online electronic databases: MEDLINE (PubMed), ScienceDirect, SafetyLit, the Directory of Open Access Journals, and JSTOR.

2.2. Screening process

The literature was searched without regard to the publication date to March 2020 to identify articles of observational or experimental studies that examined the association between hearing loss and occupational or workplace exposure to vibration of the upper extremities (fingers, hands, or arms) alone or in combination with occupational exposure to noise. Eligible articles for review were limited to those published in English language to avoid interpretation bias and included studies that addressed the relationship between permanent (nontemporary) hearing loss among workers with HAVS, VWF, finger blanching (a sign of VWF), or Raynaud's phenomenon. Any article in which the setting was not a workplace (or did not simulate a workplace through experimental design), the study participants were not workers (or did not simulate workers via experiment), or the primary study outcome was not permanent hearing loss was excluded.

The screening process commenced with initial selection based on article titles. Article titles that purportedly considered the association between occupational exposure to hand–arm vibration and hearing loss were retained for further consideration. Exposures of interest consisted of workers' use of hand power and pneumatic vibration tools or diagnoses of upper extremity hand–arm vibration conditions in workers, including HAVS, VWF, finger blanching, or Raynaud's phenomenon. Outcomes of interest consisted of diagnoses of hearing loss in workers, including sensorineural hearing loss and NIHL, or audiograms of workers that revealed less than normal hearing. Articles in which the titles did not address the association in question were excluded.

Articles retained subsequent to initial screening of titles were then evaluated based on their abstracts. Abstracts that reflected consideration of the association between occupational hand–arm vibration exposure and hearing loss were retained. Abstracts that did not address the association were excluded. Finally, the entire text of each retained article was reviewed to confirm the studies addressed the association between workplace exposure to hand–arm vibration (including use of power or pneumatic tools) and hearing loss. Studies that did not address the association of interest were excluded. Studies that examined and assessed the relationship between occupational hand–arm vibration exposure and hearing loss were included.

3. Results

3.1. Literature search

Initial online searches yielded 697 articles; of which, 648 were excluded as duplicates, non-English language, or titles and abstracts that did not otherwise satisfy the inclusion criteria. Full-text review of 49 articles resulted in exclusion of 24 articles, in which exposure to vibration from handheld power or pneumatic tools was not the primary exposure or hearing loss was not the primary outcome, thereby not meeting the inclusion criteria. Fifteen articles that reported 17 studies (13 articles reported one study each; 2 articles reported 2 studies each) met the inclusion criteria for systematic review (Fig. 1).

3.2. Literature study designs

Fifteen original research articles reporting the results of 17 separate study populations obtained through online database literature searches met the criteria for inclusion in this systematic review. Table 1 summarizes the studies from Canada [16,17], Finland [18–21], Japan [22–25], Sweden [26–28], Taiwan [29], and the United Kingdom [30]. Search results revealed no study in which the research question of interest (i.e., what is the relationship between hand–arm vibration exposure from occupational use of power and pneumatic hand tools and permanent hearing loss?) was directly considered in the US.

The studies included 12 cohort studies (the study by Turcot et al [16] reporting 2 study populations and the study by Starck et al [20] reporting 2 populations) [16–23,26,28], two cross-sectional surveys [27,30], one case–control matched pair study [24], one cross-sectional study [25], and one experimental study [29].

One cohort study had a large study sample of more than 59,000 participants with a long observation period of 13 years [16], whereas ten cohort studies [17–23,26,28], the case–control matched pair study [24], and the cross-sectional study [25] had small samples of 370 participants or less with long observation periods ranging from 5 to 21 years. One cohort had a small sample of 72 to 203 participants over a period of less than 4 years [18], and the experimental study had a small sample of 23 volunteer participants with a very short vibration exposure period of 30, 60, and 120 minutes [29]. One cross-sectional survey had an overall response rate of 41% among a sample population of 342 [27], whereas the other cross-sectional survey had a 65% response rate among a source population of more than 21,000 [30].

All participants in each of the descriptive, observational studies were workers from occupational source populations. The sole experimental study by Chao et al [29] simulated a workplace by exposing volunteer participants to noise and hand–arm vibration from handheld power drills.

Participants in most studies were from a population of forestry workers (also referred to as forest workers and lumberjacks) [16,18,20,24,25]. One study selected participants from a population of welders [26], one study included mine workers [16], and one study comprised participants from a population of shipyard platers (also known as steelworkers) [20]. One cross-sectional survey randomly selected participants from a broad range of general, nonmilitary occupations [29], while the most common occupations in the other cross-sectional survey were teachers, military personnel, and welders [27]. Five studies specifically limited participants to male workers [16,17,22,25,26], whereas three studies expressly included male and female workers [27,29,30]. Two studies did not declare the gender(s) of the source or study populations [18,20]. The source populations, however, were forestry workers in Finland—a predominantly male-dominated occupation [31].

3.3. Hearing loss as the primary outcome

Hearing loss was the primary outcome of interest in each study. Hearing was measured in a variety of manners, although principally through some form of audiometric testing. Five studies used data from pure-tone air conduction tests [16,18,20,24,26]; of which, three obtained audiometric test data at multiple frequencies, ranging from 500 Hz to 6000 Hz [16,24,26], and two limited air conduction audiometric testing to a single frequency of 4000 Hz [18,20]. One study reported results from bone conduction tests [24]. Five studies obtained multiple audiometric tests over time for each worker participant [16,18,20,24,25], and one study relied on data from a single audiometric test [26].

Audiometric testing in three studies was reportedly conducted in a manner consistent with the International Organization for Standardization (ISO) [16,18,24], whereas one study used an alternate means of audiometric test standardization, the Klockhoff method [26].

Four studies compared multiple audiometric studies over time [16,18,24,26], whereas one study used Robinson's model to obtain an estimate of NIHL [20]. Robinson's model predicts NIHL based on a standardized *A*-weighting of sound pressure, duration of exposure, and age of the noise-exposed person. The study subtracted model NIHL estimates from individual worker participant audiometric results, which provided hearing loss unrelated to noise exposure. The hearing loss remainder was presumptively associated with vibration exposure.

The cross-sectional surveys did not rely on any audiometric testing to determine hearing loss.

One cross-sectional survey used worker participants' question responses and self-reports to obtain histories of hearing difficulties [30]. The survey included questions that classified hearing loss as "severe" and tinnitus (ringing in ears without an external sound source) as "persistent." The other cross-sectional survey relied on medicolegal determinations of hearing loss from accepted claims of an insurance company [27].

3.4. Hand–arm vibration as the primary exposure

Upper extremity vibration through workers' use of handheld power tools was the primary exposure of interest in all studies. Two studies measured hand–arm transmitted vibration exposure directly from the tools used by the worker participants: chain saws for forestry workers and pneumatic hammers, grinders, and circular saws for shipyard platers [18,20]. Worker participants also responded to questions regarding their respective history of handheld vibratory tool use, frequency (regularity), and duration.

Seven studies used HAVS, VWF, finger blanching (white or pale fingers), or Raynaud's phenomenon as a proxy for hand–arm transmitted vibration exposure [16,18,24–27,30]. The researchers presumed workers with diagnoses or symptoms of the upper extremity conditions were exposed to injurious hand–arm vibration during employment. To diagnose VWF, worker participants with a history of finger blanching submitted to confirming cold provocation tests [18,26]. One study obtained VWF diagnoses from government workers' compensation data, purportedly also based on cold provocation tests [16]. VWF was also diagnosed when two of the study article physician authors concluded through interviews that the worker participant had a history of findings consistent with VWF [24]. The cross-sectional matched pair study relied on workers' medical histories to classify participants with and without diagnoses of VWF [25], whereas a cross-sectional survey relied on participants' self-reporting of hand conditions [27].

3.5. Noise as a concomitant exposure, secondary exposure, or confounder

Power and pneumatic hand tools typically emit and expose workers to noise in addition to the primary exposure of interest, hand–arm vibration. Noise was combined with hand–arm transmitted vibration as the exposures of interest in four studies [16,18,25,27]. Two studies hypothesized a common mechanism accounted for hearing loss and VWF or HAVS [18,25], one of which expressly surmised vasoconstrictions may occur in the cochlear blood vessels with exposure to loud noise and in the peripheral vessels of the upper extremities when exposed to hand–arm transmitted vibration [18]. Occupational noise exposure was otherwise considered as a potential confounder for hearing loss in all other studies.

Occupational ambient noise levels were measured directly in four studies [16,18,20,26]. For comparative purpose, one study categorized worker participants into two groups of noise exposure over time-weighted daily averages of eight hours: less than 90 decibels (dBA) and equal to or more than 90 dBA [16].

Noise emitted from power and pneumatic tools used by the workers was determined by review of the tool manufacturers' noise data sheets or measured directly in three studies [16,18,26]. The cross-sectional survey study determined the intensity and duration of noise exposure through survey responses to questions regarding "the number of years of employment in noisy jobs where it was necessary to shout to be heard" [30].

One study used miniature microphones attached to each worker participant's ear canal entrance and to the earmuff headband to measure middle ear and ambient noise exposures, respectively [16]. Another study measured noise dose from two worker participants using personal noise dosimeters [18]. One study did not measure noise exposure as all workers were reportedly exposed to the same noise level [24]. The researchers were reportedly interested in the "difference" in hearing loss, if any, between workers with VWF and without VWF, rather than in aggregate hearing loss findings.

3.6. Association between occupational exposure to vibration and hearing loss

In thirteen studies, a statistically significant association was observed between hearing loss and exposure to hand–arm transmitted vibration through occupational use of power and pneumatic tools [16–19,21–28,30]. Two studies found no statistically significant association between workers exposed to hand–arm vibration and hearing loss [20,29]. Meta-analysis under Preferred Reporting Items for Systematic Reviews and Meta-analyses guidelines or otherwise, however, was not performed by researchers for the studies under the current review owing to limited study population data.

The prevalence ratio of 1.34 (95% confidence interval: 1.21–1.49) of one study reflected the presence of VWF and indicated hand–arm transmitted vibration exposure was associated with increased risk of increased hearing loss [16]. When exposure time was included in another study, the risk of hearing loss for workers with VWF compared with workers without VWF increased by an odds ratio of 2.3 (95% confidence interval: 1.4–3.0) [26]. Adjusting for age and noise exposure during the study periods in three other studies, hearing loss developed more severely—reportedly up to twice as much—in workers with VWF than in workers without VWF [18,24,30]. Two studies reflected no observed increased risk of hearing loss in groups exposed to hand–arm transmitted vibration [20,29]; whereas all other studies reported statistically significant associations between workers' exposure to occupational hand–arm vibration and hearing loss.

4. Discussion

4.1. Objective: to assess the association between hand–arm vibration and hearing loss

The objective of the current review was to identify, summarize, and evaluate the published literature to determine whether exposure to workplace hand–arm vibration through use of power or pneumatic tools is associated with sensorineural hearing loss, independent of any damage to hearing as a result of concomitant noise exposure. Moreover, should a positive relationship be identified, then the subobjective was to determine whether the association was causative of VIHL.

Comparison between studies of differing designs and predominantly with small samples is admittedly challenging and imperfect. Moreover, study methods used to determine any hearing loss lacked uniformity and thereby prohibited pooling of data and meta-analysis. Nonetheless, the results of 15 of the 17 studies reported in the articles under current review (two articles reported two studies each [16,20]) revealed statistically significant positive associations between occupational hand–arm transmitted vibration exposure from use of power and pneumatic tools and hearing loss.

4.2. Definitions of hearing loss terms

Hearing impairment, hearing handicap, and hearing disability are frequently used synonymously. The terms, however interrelated, are neither identic nor interchangeable but have discrete and precise definitions.

The American Speech–Language–Hearing Association and the American Medical Association define hearing "impairment" as a significant deviation, or loss of use, of any body structure or function; "handicap" as the disadvantage on a person's performance in activities of daily living; and "disability" as the determination of a financial award for the actual or presumed loss of ability to perform activities of daily living due to the impairment [32,33].

In this review article, the terms hearing handicap and hearing disability are not used, and consistent with American Speech–Language–Hearing Association and American Medical Association definitions, the terms hearing loss and hearing impairment are used synonymously as a significant deviation (reduction or loss) from full function of the human auditory system.

4.3. Initial seminal study to assess the association between hand–arm vibration exposure and hearing loss

In 1981, Pyykkö et al [18] published the first known study that addressed the relationship between occupational exposure to hand–arm transmitted vibration and hearing loss. The researchers conducted a longitudinal observational study among a group of Finnish forestry workers in the years 1972 and 1974 through 1978. Only forestry workers who had used chain saws a minimum of 500 hours per year for at least 3 consecutive years were included in the study. Worker participants were classified by history of VWF, age, duration of vibration exposure from chain saws, and earmuff use (to limit noise exposure). Permanent hearing loss was determined by audiogram results at 4000 Hz.

Pyykkö [18] observed statistically significant associations between noise and hearing loss and between VWF (a proxy for hand–arm transmitted vibration) and hearing loss. The researchers hypothesized a common vibration-related mechanism might exist in both hearing loss and VWF. Pyykkö theorized vibration exposure through use of vibratory hand tools (i.e., chain saws) caused vasoconstriction of the peripheral blood vessels of the fingers that produced VWF and also of the cochlear blood vessels that impeded cochlear function and led to hearing loss.

4.4. Tests to determine hearing ability and loss

Hearing—functional ability and loss—is customarily assessed through audiometric tests of pure-tone air conduction or bone conduction from low frequencies to high frequencies of 500, 1000, 2000, 3000, 4000, 6000 Hz, and occasionally up to 8000 Hz. The results are typically quantified in comparison with “normal” hearing volume in dBA [34,35].

Hearing loss may be sensorineural, conductive, or both. Pure-tone air conduction testing aids in the assessment of whether hearing loss is sensorineural, which is commonly caused by damage to the cochlea, the hair cells within the cochlea, or the auditory nerve.

The typical audiometric pattern of sensorineural hearing loss caused by noise exposure is a “V-shape notch,” reflecting progressive worsening of hearing loss from 3000 Hz to 6000 Hz and then recovering at 8000 Hz. Although an important diagnostic sign, the V-shape notch is variable and not dispositive for a diagnosis of NIHL [36]. Sensorineural hearing loss is generally the result of exposure to loud noise and is diagnosed and otherwise referred to as NIHL. Other known causes of sensorineural hearing loss include presbycusis (hearing loss due the natural aging process), exposure to ototoxic chemicals and medications, diseases, and head trauma [37].

Bone conduction testing is used to evaluate whether hearing loss is due to ineffective transfer of sound waves through the ear canal to the eardrum and the ossicles, the three tiny bones of the middle ear. Common causes of conductive hearing loss include infection in the ear canal, fluids or other blockages in the middle ear, perforation of the tympanic membrane, and benign tumor [38,39].

As summarized in Hearing loss as the primary outcome and discussed in Noise exposure as a confounder, the researchers in the studies under the current review used various methods to assess hearing ability and determine hearing loss.

Although the majority of studies used some form of audiometric evaluation, they collectively did not follow the same processes and procedures.

Lack of adequate standardized method and uniform procedures for assessing hearing function in clinical trials not only impedes the ability to perform proper comparisons between and among studies, which results in variability in presentation and reporting of data among studies, but also obstructs pooling of data and hinders the meta-analysis necessary for statistical analysis [40]. Accordingly, the Hearing Committee of the American Academy of Otolaryngology-Head and Neck Surgery (AAO-HNS) has endorsed a minimal standard for reporting hearing results in clinical trials that consist of a scattergram of average pure-tone threshold to word recognition score.

None of the studies under the current review provided a scattergram of average pure-tone thresholds to word recognition scores. Moreover, no study under the current review documented the average pure-tone or conductive thresholds to word recognition scores via scattergram, graph, alternate visual analytics, or otherwise. Indeed, the reporting of data between and among the various studies lacked the uniformity necessary for adequate data accumulation and collation required for comprehensives tatistical synthesis and integrated analysis.

Admittedly, the specific AAO-HNS Hearing Committee recommendations for standardization of hearing ability and loss assessments were directed to clinical settings and not to assessments of workers' hearing function subsequent to exposure to hand–arm vibration. Nonetheless, test uniformity in accordance with standardized methodology among the various cohorts in the studies under the current review would have allowed for pooling of data and meta-analysis to aid in a determination whether any observed association between exposure to hand–arm vibration and hearing loss was causal.

4.5. Procedures to determine hand–arm vibration exposure

The collective studies under review also used various methods of determining subject workers' exposures to hand–arm vibration. Several researchers used methods directly measured vibration to which workers were actually exposed while engaged in work activity. Alternatively, some researchers measured vibration in simulated work situations, whereas others used diagnoses or symptoms of vibration-caused medical conditions such as HAVS, VWF, or Raynaud's phenomenon as proxies for vibration exposure.

The seminal and subsequent studies of Pyykkö et al [18,21,28] measured vibration from an accelerometer fixed to the front handles of chain saws in the direction of the metacarpal bones while cutting slices of uniform shape from a spruce log. Similarly, Stark et al [20] measured vibration from a chain saw commonly used by Finnish forestry workers as pine or spruce logs supported horizontally were cut and from pneumatic power tools (e.g., hammers, grinding machines, and circular saws) typically used by shipyard platers. Although vibration was measured directly from the power and pneumatic hand tools used by subject workers, the workplace field conditions were simulated. Accordingly, the accuracy of worker exposures to vibration through use of chain saws and pneumatic power tools could only be as good as the authenticity of the simulated work conditions.

The experimental study by Chao et al [29] did not directly measure vibration exposure from power or pneumatic hand tools. Rather, the researchers simulated workplace vibration exposure by participants' use of a hand drill for 30, 60, and 120 minutes. The brief periods of exposure and lack of vibration measurements are the weakest points of the experimental design.

The studies by Iki et al [23,24] and Iki [25] did not report measurements of hand–arm vibration exposure but used VWF diagnoses as proxies for vibration exposure. Diagnoses of VWF were rendered when one or two researcher physicians obtained medical histories and findings typical of the condition, such as finger blanching of the digits, through detailed interviews of the subject workers. The VWF diagnoses were then confirmed through provocative cold water immersion tests.

Similarly, rather than obtaining handheld power and pneumatic tool vibration measurements, Turcot et al [16] categorized forestry worker participants and miners with and without diagnoses of VWF; Murata et al [22] used medical histories of VWF or white finger attacks of subject workers who used chain saws and brush saws (i.e., grass trimming and tree limbing); and House et al [17] used subject workers' medical histories of assessments (diagnoses and treatments) for HAVS. Diagnoses of conditions or symptoms known to be caused by hand–arm vibration (i.e., VWF, white finger, HAVS, Raynaud's phenomenon) as proxies for vibration exposure may be a clever and efficient means of estimating worker exposures to vibration. The accuracy of the vibration estimate, however, is only as good as the validity and reliability of the proxies.

Palmer et al [30] also did not obtain direct hand tool vibration measurements. Rather, vibration exposure was determined through a questionnaire that requested subject workers to declare and otherwise estimate their respective lifetime exposures to hand–arm vibration [30].

The cohort study by Pettersson et al [27] probably obtained the most reliable data of hand–arm vibration exposure among subject workers. The researchers measured a random selection of handheld vibrating tools used under normal working conditions by subject workers in accordance with ISO 5349 (ISO, 2001). The strength of Pettersson's accuracy is based on the following: (1) random sampling of tools; (2) tools used in the field under normal working conditions; and (3) tools used by subject workers. There were no occupational simulations as substitutes for workplace field conditions, no medical diagnoses or symptom histories as proxies for hand–arm vibration exposures, and no vibration exposure guesstimates. Rather, vibration exposure was measured directly from the hand tools used by the subject workers in workplace field conditions. (Note that Pettersson et al. [41] reported the results of the 21-year cohort study in a prior article, subsequently updated in the article under current review [27].).

The lack of uniformity in methods and procedures for measuring vibration exposure among the studies under the current review suffers from the same limitations as variation in hearing measurements (as discussed in Tests to determine hearing ability and loss): Comparison between and among the studies is compromised, and pooling of vibration exposure data cannot be made for proper assessment and meta-analysis.

4.6. Confounding, bias, test uniformity, and study sample size

In the current literature review, significant limitations of the studies were discovered. The studies under review considered possible confounders of the association between hearing loss and occupational exposure to hand–arm vibration to varying degrees. The researchers collectively considered confounding by noise exposure, age, gender, smoking status, antecedent hearing loss, exposure to ototoxic chemicals and medications, head trauma, disease, and infection. Notably, no study addressed all of the identified potential confounders. Moreover, as discussed previously (Hearing loss as the primary outcome, Tests to determine hearing ability and loss, Procedures to determine hand–arm vibration exposure), the studies did not use uniform means of testing for hand–arm vibration (the primary exposure of interest) and hearing loss (the primary outcome of interest), which limits a more systematic and accurate analysis.

4.6.1. Noise exposure as a confounder

The most obvious confounder was occupational noise exposure that could cause or worsen sensorineural hearing loss or NIHL. Some studies addressed noise exposure as a confounder better than others. For example, Starck et al [20] used sophisticated microphones that provided separate readings for ambient noise and for noise that reached the middle ear. Noise emissions were also measured directly from the tools used by the workers, and subject workers were questioned with regard to history and use of vibratory handheld tools. In contrast, Palmer et al [30] made no quantitative workplace noise level measurements; rather, noise exposure determinations were based on extensive but imprecise subjective qualitative assessments of occupational noise through worker participants' responses to survey questions.

The majority of studies identified hearing loss through audiometric testing— by pure-tone air conduction, bone conduction, or both.

In the seminal and subsequent studies by Pyykkö et al [18,19,21,28], audiometric testing was limited to median results at 4000 Hz to assess hearing ability and loss. Consideration of the singular frequency, however, prevented any immediate or subsequent determination regarding the existence of the standard V-shape notch result to aid in the diagnosis of sensorineural hearing loss generally or NIHL specifically.

Stark et al [20] similarly considered audiogram results solely at 4000 Hz. However, hearing loss was determined not through direct audiogram analysis, but by comparison of the average of left and right ear audiometric results against Robinson's model for predicting hearing loss. Robinson's model uses A-weighted noise level equivalents, age of the subject worker, and duration of exposure to predict hearing ability or loss. The standard V-shape notch neither was considered nor could be studied subsequently as only one frequency was used in testing subject workers' hearing.

Turcot et al [16] obtained air conduction audiometric test results at 500, 1000, 2000, and 4000 Hz. As frequencies at the highest levels of 6000 and 8000 Hz were not tested, a determination could not be made for the existence of a typical V-shape notch to aid in diagnoses of sensorineural hearing loss.

The studies reported by House et al [17], Muratal et al [22], and Pettersson et al [26] determined levels of hearing loss from audiometric test results through a range of frequencies from 500 to 8000 Hz. The researchers, however, neither reported nor otherwise summarized the data sufficiently to determine the existence of any V-shaped notches as an aid to the diagnoses of sensorineural hearing loss. Moreover, the cohort study by Pettersson et al [26] uniquely defined hearing loss in accordance with the Klockhoff method as a hearing threshold above 30 dBA at 500 Hz or above 25 dBA at 1000–2000 Hz plus one of the higher frequencies of 3000, 4000, or 6000 Hz.

Chao et al [29] tested hearing at the broadest range of frequencies from 125 to 8000 Hz using an audiometer and a hearing test box (Bilson Taipei). Although specific or median test results were not summarized, it was reported that hearing loss was especially severe at 4000 Hz, suggesting some form of recovery at higher frequencies consistent with the V-shape notch.

In contrast to the researchers who obtained audiometric test result data to assess hearing, Palmer et al [30] determined hearing loss as "severe" using a postal questionnaire in which the forestry worker participants reported use of a hearing aid or whether it was difficult or impossible to hear conversations in a quiet room. Moreover, the researchers in the cross-sectional survey by Pettersson et al [27] relied on an insurance company's medicolegal determination and acceptance of claims for occupational NIHL.

In addition to quantitative measurement variations, noise exposure may have "qualitative" characteristic differences that may result in varying degrees of sensorineural hearing loss. One astute reader of the study by Turcot et al [16] noted the researchers acknowledged a limitation in their study with regard to the differences in exposure among forestry workers and mine workers versus other types of workers, but did not report possible differences in noise exposure "between" forestry workers and miners [42]. Turcot et al [16] essentially considered the noise and vibration exposures of forestry workers and miners as indistinguishable. Although quantitative noise levels may have been similar, there could have been significant qualitative differences. For example, exposure to ambient noise in an enclosed mine cavity may have a significantly different effect on auditory function compared with exposure to an identical noise level measurement in an open forest.

4.6.2. Other potential confounders

Other potential confounders, including age, gender, smoking status, antecedent hearing loss, exposure to ototoxic chemicals and medications, head trauma, disease, and infection, were also variously addressed.

Studies by Pyykkö et al [18,19,21,28] and Starck et al [20] excluded workers with hearing loss caused by disease or trauma but did not account for exposures to ototoxic medications and chemicals or for smoking habits. Studies by Iki et al [23,24] and Iki [25] excluded workers with histories of ear diseases, vertigo, head injury, conductive hearing loss, or exposures to ototoxic drugs but did not obtain specific noise level exposure measurements. Turcot et al [16] accounted for worker participants' age but did not consider the effects on hearing loss from ototoxic medications, smoking habits, or consistent use of hearing protectors. Although worker participants reported use of hearing protectors, Pettersson et al [26] did not describe the impact of the variable, if any, on the nature and extent of hearing loss. Palmer et al [30] considered the effects on hearing loss by age, gender, and smoking habits but not from a history of ototoxic chemicals, medications, trauma, or disease.

The varying degrees to which the researchers addressed potential confounders also limit the ability to conduct comparisons between and among studies or pool the data to assess the association between hand–arm vibration exposure and hearing loss in the aggregate.

4.6.3. *Study design effects on bias, validity, and strength of reported associations*

The current literature review also identified likely bias in the study designs. Misclassification of the worker participant's VWF status may have occurred as the diagnosis was made when one or two of the authors determined the worker participant's history was consistent with VWF in the studies by Ike et al [23,24] and Ike [25] or when the sole examining physician may have been aware of the research question in the study by Pyykkö et al [18]. In the studies by Turcot et al [16] and Pettersson et al [27], data regarding VWF and hearing loss were obtained from the Quebec Workers' Compensation Board and AFA Insurance Company, respectively. Workers with VWF who file claims for compensation benefits may be more likely to also apply for benefits for hearing loss than workers with similar hearing loss but without VWF. Consequently, the resultant data may have erroneously inflated an association between VWF and hearing loss. Information bias was likely in the cross-sectional surveys as response rates were 65% in the study by Palmer et al [30] and 41% in the study by Pettersson et al [27]. The medical and work histories of 35–59% of the surveyed populations who did not respond may be significantly different than the participants who answered the survey questions. Such a difference may skew the data and thereby alter the results.

Apart from potential confounding and bias, the size of the study populations may have had an effect on the validity and strength of associations. In general, small sample sizes limit statistical power. The studies of Pyykkö et al [18,19,21,28], Pettersson et al [26,27], Starck et al [20], Iki et al [23, 24], and Iki [25] each had small samples. Accordingly, their respective statistical strength to determine the existence of association between exposure to hand–arm transmitted vibration and hearing loss is less than the larger study populations in the studies by Turcot et al [16] and Palmer et al [30].

4.7. *Possible causes*

The majority of studies that considered the research question observed a positive association between hand–arm transmitted vibration and hearing loss. No study under the current review, however, identified a specific, causative mechanism.

Notwithstanding the previously referenced potential confounding, biases, statistical power, and meta-analysis issues, all but two studies under the current review identified statistically significant positive associations between exposure to hand–arm vibration and hearing loss. A causal relationship could not be properly assessed as the biological gradient or dose response could not be evaluated, that is, the intensity and duration of exposure of workers to vibration was not adequately documented and the data among studies could not be properly pooled to evaluate whether increased exposure to vibration correlated with greater hearing loss.

Consequently, none of the study authors declared a definitive biologic cause for the apparent association. Collectively, however, they offered collectively possible theories for the positive association and potential causation: (1) vibration exposure may have precipitated vasoconstriction that effected blood flow in the cochlea, damaged hair cells of the inner ear, or harmed the sympathetic nervous system and thereby caused sensorineural hearing loss; and (2) vibration from use of handheld vibrating tools may have been transmitted by bone conduction to the inner ear and caused conductive hearing loss [16,18,24,26].

One possible theory of association, and potential agent of causation between exposure to hand–arm vibration and permanent hearing loss, is not mentioned in the literature. The theory, based on the physical properties of vibration, is a bit counterintuitive as it implicates the use of hearing protectors.

The physics of vibration is beyond the parameters of this literature review. Suffice it to say, however, vibration is oscillation or fluctuation of movement about a middle point equilibrium that produces a wave that transfers energy from one point to another. Moreover, in accordance with Newton's third law of motion (For every action, there is an equal and opposite reaction), an energy wave that collides with an object will reflect off the object. Accordingly, it is not difficult to imagine the vibration energy wave from a handheld power or pneumatic tool traveling through the fingers and hand, continuing up the arm, through the neck, and into the head, then colliding with the worker's ear plug firmly inserted in the ear canal, and reflecting back into the middle and inner ear. Abnormal physical vibration redirected into the middle ear that agitates the ossicles might precipitate structural fatigue or otosclerosis. Moreover, the reflective wave energy may damage the cochlea, hair cells, or auditory nerves of the inner ear and cause or worsen hearing loss. In theory, use of ear protectors intended to "reduce" noise exposure and limit sensorineural hearing loss may result in the transfer of vibration wave energy into the ear and thereby "cause" sensorineural or conductive hearing loss.

4.8. *Need for further research*

Additional research is needed to further address the association between hearing loss and hand–arm vibration from use of handheld vibratory tools. Potential confounders, such as noise, age, smoking history, exposure to ototoxic drugs and chemicals, should be adequately taken into account during any study design and analysis. Assuming a positive association is confirmed, research should also address causation through prospective studies. To that end, future studies should assess the association, if any, between hearing loss in workers with vibratory hand–arm exposure who use ear plugs versus workers with the same vibration exposure who use earmuffs or some other type of hearing protectors. Proper use of ear protectors undoubtedly reduces noise exposure. A soft, absorbent lining inside the bowl of an earmuff, however, may be less likely to reflect vibration waves back into the middle and inner ear than an ear plug placed securely inside the ear canal. Moreover, further research should also address the biologic gradient or dose response. A proper and thorough examination and assessment of the differences in hearing loss, if any, when exposed to increased intensity or duration of hand–arm vibration should reveal data that may be useful in the determination whether the association is causal. Regardless whether a specific theory of causation is explored and assessed, further research into the association between occupational hand–arm vibration through use of power and pneumatic tools and hearing loss is warranted.

5. Conclusion

Relatively few studies have been conducted in the nearly four decades since Pyykkö first examined the association between hand–arm vibration exposure from workers' use of power tools and hearing loss. The current review of the published literature that addressed the relationship revealed a majority of studies found a positive association. Significant study limitations, including design biases and potential confounders, were found that hindered a comparison between and among the studies, impeded an assessment of possible causation, and precluded pooling of data for proper meta-analysis.

Lack of standardized and uniform testing for hearing loss and for measuring vibration exposure limited comparisons between and among studies or an adequate assessment of the available data in the aggregate. Future studies should follow the recommendations of the Hearing Committee of the AAO-HNS and, in whatever manner hearing is assessed, ensure a minimal standard for reporting data that will allow for cross-study comparisons and pooling of data for proper meta-analysis. Moreover, prospective researchers should examine whether use of particular types of hearing protectors (e.g., ear plugs versus earmuffs) intended to prevent or otherwise limit injurious noise exposure and thereby reduce the incidence of NIHL may result in an unintended consequential reflective vibration wave that may cause VIHL or worsen hearing loss.

Notwithstanding the discovered limitations among the published studies in the current review, an association between hand–arm vibration exposure among workers who use hand power and pneumatic tools and hearing loss appears to exist. Whether or not the association is confirmed and, if so, deemed causal, it would behoove workers to take precautionary means to limit hand–arm vibration exposure and reduce the possible incidence of hearing loss. Prophylactic measures may include frequent break periods from use of vibratory hand tools, use of ear protectors that do not reflect vibration into the ear canal, and use of antivibration gloves while operating power and pneumatic tools.

Conflicts of interest

The author hereby certifies he has no affiliations with or involvement in any organization or entity with any financial or non-financial interest in the subject matter or materials discussed in this manuscript. Moreover, in the spirit of full disclosure, the author further certifies he is an attorney and a member of the bar associations of the states of Oregon and Washington, USA, in good standing. The author maintains an inactive status (i.e., semiretired) in the bar associations and, as such, does not actively engage in the practice of law. Accordingly, the author has no clients with any financial or nonfinancial interest in the subject matter or materials discussed in this manuscript. Moreover, to his knowledge, no former client is aware of his involvement in the research, review, or preparation of the article under submission.

Acknowledgments

The author would like to thank Brett Alyson Maiese, PhD, Assistant Director, Medical Communications, Xcenda, and former assistant professor at Drexel University, Department of Epidemiology and Biostatistics, for her mentoring and guidance.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.shaw.2020.04.003.

Funding

This work was not funded by any third party. Research and writing began while a graduate student in the Department of Epidemiology and Biostatistics at Drexel University and concluded subsequent to successful completion of the academic program.

References

[1] [Internet]Deafness and hearing loss. World Health Organization. 20 Mar 2019. Available from: http://www.who.int/news-room/fact-sheets/detail/deafness-and-hearing-loss.

[2] Nelson DI, Nelson RY, Marisol Concha-Barrientos M, Fingerhut M. The global burden of occupational noise-induced hearing loss. Am J Ind Med 2005;(6):446–58. See comment in PubMed Commons below48.

[3] [Internet]Worker Hearing Loss. US: Centers for disease controls and prevention. Department of health and human services. 2019 [cited 2019 Jul 12]. Available from: https://www.cdc.gov/features/worker-hearing-loss/index.html.

[4] [Internet]Noise and hearing loss prevention. US: National Institute for Occupational Safety and Health. Centers for Disease Control and Prevention. Department of Health and Human Services. 2019 [cited 2019 Jul 12]. Available from: https://www.cdc.gov/niosh/topics/noise/default.html.

[5] [Internet]Quick Statistics About Hearing. US: National Institute on deafness and other communication disorders. Department of health and human services. 2016 Dec 15 [cited 2019 Mar 20]. Available from: https://www.nidcd.nih.gov/health/statistics/quick-statistics-hearing.

[6] Monthly Labor Review: can you hear me now? Occupational hearing loss; 2004-2010 [Internet]. Bureau of Labor Statistics. Department of Labor. (US) 2012 July [cited 2019 Mar 20]. Available from: http://www.bls.gov/opub/mlr/2012/07/art4full.pdf.

[7] [Internet]Noise-induced hearing loss in Great Britain. Health and Safety Executive. (GB). 2018 Oct 17 [cited 2019 Mar 18]. Available from: http://www.hse.gov.uk/Statistics/causdis/deafness/index.htm.

[8] National Health Survey. Ministry of health. Epidemiology and disease control division [Internet], ISBN 978-981-08-8540-3; 2010. p. 56–9 (Singapore) Nov 2011 [cited 2019 Mar 15], https://www.moh.gov.sg/resources-statistics/reports/national-health-survey-2010. Available from:.

[9] Concha-Barrientos M, Campbell-Lendrum D, Steenland K. Occupational noise: assessing the burden of disease from work-related hearing impairment at national and local levels. [Internet]. World Health Organization. 2004 [cited 2019 Jun 15]. Available from: http://www.who.int/quantifying_ehimpacts/publications/en/ebd9.pdf.

[10] Occupational and community noise. Geneva (Switzerland): World Health Organization; 2001 February. WHO Fact Sheet No. 258. 5 p.

[11] [Internet]Vibration – Health Effects. Canada: Canadian centre for occupational safety and health. 2016 [updated 2017 Feb 01; cited 2019 Aug 17]. Available from: http://www.ccohs.ca/oshanswers/phys_agents/vibration/vibration_effects.html.

[12] Vibration syndrome. Centers for disease control and prevention. US: National Institute for Occupational Safety and Health. 1983 [updated 2014; cited 2019 Mar 18]. Available from: http://www.cdc.gov/niosh/docs/83-110/default.html.

[13] [Internet]Criteria for a recommended standard: occupational exposure to hand-arm vibration. US: Centers for disease control and prevention. National Institute for occupational safety and health. September 1989 [updated 2014 Jun 06; cited 2019 Jun 01]. Available from: https://www.cdc.gov/niosh/nioshtic-2/20000288.html.

[14] [Internet]Hand arm vibration – statistics. UK: Health and Safety Executive. 2018 [cited 2019 Jun 01]. Available at: http://www.hse.gov.uk/vibration/hav/statistics.htm.

[15] [Internet]Hand arm vibration (HAV) in Great Britain. UK: Health and Safety Executive. 09 Oct 2018 [cited 2019 Jun 01]. Available from: http://www.hse.gov.uk/statistics/causdis/vibration/index.htm.

[16] Turcot A, Girard SA, Courteau M, Baril J, Larocque R. Noise-induced hearing loss and combined noise and vibration exposure. Occup Med 2015;65(5):238–44.

[17] House RA, Sauvé JT, Jiang D. Noise-induced hearing loss in construction workers being assessed for hand-arm vibration syndrome. Can J Publ Health 2010;101(3):226–9.

[18] Pyykkö I, Starck J, Farkkila M, Hoikkala M, Korhonen O, Nurminen M. Hand-arm vibration in the aetiology of hearing loss in lumberjacks. Br J Ind Med 1981;38(3):281—9.
[19] Pyykkö I, Farkkila M, Inaba R, Stark J, Pekkarinen J. Effect of hand-arm vibration on inner ear and cardiac functions in man. Nagoya J Med Sci 1994;57:113—9.
[20] Starck J, Pekkarinen J, Pyykkö I. Impulse noise and hand-arm vibration in relation to sensory neural hearing loss. Scand J Work Environ Health 1988;14:265—71.
[21] Pyykko I, Pekkarinen J, Starck J. Sensory-neural hearing loss during combined noise and vibration exposure: an analysis of risk factors. Int Arch Occup Environ Health 1987;59:439—54.
[22] Murata K, Arakil S, Aono H. Central and peripheral nervous system effects of hand-arm vibrating tool operation: a study of brainstem auditory-evoked potential and peripheral nerve conduction. Int Arch Occup Environ Health 1990;62:183—8.
[23] Iki M, Kurumatani N, Hirata K, Moriyama T. An association between Raynaud's phenomenon and hearing loss in forestry workers. Am Ind Hyg Assoc J 1985;46(9):509—13.
[24] Iki M, Kurumatani N, Satoh M, Matsuura F, Arai T, Ogata A, Moriyama T. Hearing of forest workers with vibration-induced white finger: a five-year follow-up. International Archives of Occupational and Environmental Health 1989;61(7):437—42.
[25] Iki M. Vibration-induced white finger as a risk factor for hearing loss and postural instability. Nagoya J Med Sci 1994;57:137—45.
[26] Pettersson H, Burström L, Hagberg M, Lundström R, Nilsson T. Risk of hearing loss among workers with vibration-induced white fingers. Am J Ind Med 2014;57(12):1311—8.
[27] Pettersson H, Burström L, Nilsson T. Raynaud's phenomenon among men and women with noise-induced hearing loss in relation to vibration exposure. Noise Health 2014;16:89—94.
[28] Pyykkö I, Koskimies K, Starck J, Pekkarinen J, Inaba R. Evaluation of factors affecting sensory neural hearing loss. Acta Oto-Laryngologica 1988;105:155—8 (published online 2009).
[29] Chao PC, Juang YJ, Chen CJ, Dai YT, Yeh CY, Hu CY. Combined effects of noise, vibration, and low temperature on the physiological parameters of labor employees. Kaohsiung Journal of Medical Sciences 2013;29:560—7.
[30] Palmer KT, Griffin MJ, Syddall HE, Pannett B, Cooper C, Coggon D. Raynaud's phenomenon, vibration induced white finger, and difficulties in hearing. Occup Environ Med 2002;59(9):640—2.
[31] Time for action: changing the gender situation in forestry: report of the ENECE/FOA team of specialists on gender and forestry. United Nations Economic Commission for Europe [UNECE] and Food and Agriculture Organization of the United States [FOA]. 2006 [Internet][cited 2019 Aug 12] Available from: http://www.fao.org/forestry/10952-0dc39dc097e544f4dbe8167fb9b62ea99.pdf.
[32] [Internet]On the definition of hearing handicap. Rockville (MD): American Speech-Language Hearing Association. 1981 [cited 2019 Jul 20]. Available from: http://www.asha.org/policy/RP1981-00022/.
[33] Rondinelli RD, Genovese E, Brigham CR, editors. Guides to the evaluation of permanent impairment. 6th ed. Chicago (IL): American Medical Association; 2008. 634 p.
[34] Walker JJ, Cleveland LM, Davis JL, Seales JS. Audiometry screening and interpretation. Am Fam Physician 2013 Jan 1;87(1):41—7.
[35] [Internet]Pure-tone testing. Rockville (MD): American Speech-Language Hearing Association. 2019 [cited 2019 Aug 16]. Available from: http://www.asha.org/public/hearing/Pure-Tone-Testing/.
[36] Nondahl DM, Shi X, Cruickshanks KJ, Tweed TS, Wiley TL, Carmichael LL, de DI. Notched audiograms and noise exposure history in older adults. Ear Hear 2009 Dec;30(6):696—703.
[37] [Internet]Sensorineural hearing loss. Rockville (MD): American Speech-Language Hearing Association. 2019 [cited 2019 Aug 16]. Available from: http://www.asha.org/public/hearing/Sensorineural-Hearing-Loss/.
[38] [Internet]Conductive hearing loss. Rockville (MD): American Speech-Language Hearing Association. 2019 [cited 2019 Aug 16]. Available from: http://www.asha.org/public/hearing/Conductive-Hearing-Loss/.
[39] [Internet]Hearing loss basics: types, causes, and treatment. Bethesda (MD): Hearing Loss Association of America. 2019 [cited 2019 Aug 01]. Available from: http://www.hearingloss.org/hearing-help/hearing-loss-basics/types-causes-and-treatment/.
[40] Gurgel RK, Jackler RK, Dobie RA, Popelka GR. A new standardized format for reporting hearing outcome in clinical trials. Otolaryngol Head Neck Surg 2012;147(5):803—7.
[41] Pettersson H, Burström L, Hagberg M, Lundström R, Nilsson T. Noise and hand-arm vibration exposure in relation to the risk of hearing loss. Noise Health 2012;14:159—65.
[42] Mets JT. Letters to the editor: noise-induced hearing loss and combined noise and vibration exposure. Occup Med 2015;65(6):505.