Noise Exposure and Hearing Loss among Workers at a Hammer Forge Company

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ABSTRACT

The National Institute for Occupational Safety and Health (NIOSH) evaluated continuous and impact noise exposures and hearing loss among workers at a hammer forge company. Full-shift personal noise exposure measurements were collected on forge workers across 15 different job titles; impact noise characteristics and one-third octave band noise levels were assessed at the forge hammers; and 4,750 historic audiometric test records for 483 workers were evaluated for hearing loss trends. Nearly all workers' noise exposures exceeded regulatory and/or recommended exposure limits. Workers working in jobs at or near the hammers had full-shift time-weighted average noise exposures above 100 decibels, A-weighted. Impact noise at the hammers reached up to 148 decibels. Analysis of audiometric test records showed that 82% of workers had experienced a significant threshold shift, as defined by NIOSH, and 63% had experienced a standard threshold shift, as defined by the Occupational Safety and Health Administration (OSHA). All workers with an OSHA standard threshold shift had a preceding NIOSH significant threshold shift which occurred, on average, about 7 years prior. This evaluation highlights forge workers' exposures to high levels of noise, including impact noise, and how their hearing worsened with age and length of employment.

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More than 25% of all U.S. workers have been exposed to hazardous noise with an estimated 22 million U.S. workers exposed to workplace noise levels at or above 85 decibels, A-weighted sound pressure level (dBA SPL).[1,2] The National Institute for Occupational Safety and Health (NIOSH) estimates that workers exposed to an average daily noise level of 85 dBA over a 40-year working lifetime have an 8% excess risk of material hearing impairment, defined as an average of the hearing threshold levels (HTLs) for both ears that exceeds 25 decibels (dB) at frequencies of 1,000, 2,000, 3,000, and 4,000 Hertz (Hz) audiometric test frequencies. This excess risk increases to 25% for an average daily noise exposure of 90 dBA.[3] Although hearing ability can decline with age, exposure to excessive noise can contribute to and increase the rate of hearing loss. Noise-induced hearing loss (NIHL) usually develops slowly from repeated exposures to noise over time, but the progression of hearing loss is typically the greatest during the first several years of noise exposure.[4] NIHL can also result from short duration exposures to high noise levels or even from a single exposure to an impulsive noise or a continuous noise, depending on the intensity of the noise and the individual's susceptibility to NIHL.[5] Noise-exposed workers can develop substantial NIHL before it is clearly recognized. Even mild hearing losses can affect speech and sound perception. In addition, workers with NIHL may also develop tinnitus, which is estimated to affect 8% of all workers.[6]

In response to a union request, the NIOSH Health Hazard Evaluation (HHE) program assessed noise exposures and evaluated hearing loss among workers at a hammer forge company. Hammer forges produce impression die forgings through the repeated downward stamping motion of a ram and upper die onto a hot metal ingot positioned on a lower die and anvil. Hammer forges can generate intense pressure and impact noise during the stamping process. Impact noise refers to noise that is characterized by a sharp rise and rapid decay in sound levels and is less than 1 second in duration.[3] Noise exposures and hearing loss among hammer forge workers have not been studied extensively. An early study of noise exposures and hearing loss among hammer forge workers in seven different facilities in the United Kingdom reported that hammer forge operators' full-shift time-weighted average (TWA) noise exposures reached 108 dBA and that forge workers experienced much greater hearing loss compared to control subjects.[7] A comparison of hearing loss among auto company workers at two different forge workshops with similar average noise exposures (104 and 105 dBA) found greater than predicted hearing loss among the workers in the workshop who were exposed to higher peak SPLs combined with greater number of impact noise exposures.[8] Forge workers have also been found to have a higher prevalence of tinnitus.[9]

This research describes the findings of the HHE which included the following objectives: measurement of forge workers' full-shift noise exposures, impact noise levels and characteristics, and one-third octave band noise frequency levels; identification of potential noise controls; assessing attenuation of hearing protection used by forge workers; and evaluation of hearing loss trends among the forge workers.

Facility and Process Description

The company produced customized impression die hot metal forgings made from carbon or alloy steel. Most production operations ran 5 days per week with three 8-hour shifts. At the time of the evaluation, the company had about 145 workers on the first shift, 45 workers on the second shift, and 22 workers on the third shift. Most production was done on the first shift. The worksite included several different production buildings.

The forging process began with workers using metal saws, hydraulic shear presses, or mechanical shear presses to cut metal rods of varying thickness into shorter pieces, referred to as "ingots." Forklift drivers transported ingots to furnaces, located adjacent to forge hammers or upset presses, where furnace operators (referred to as "heaters") manually loaded ingots into the furnaces. Ingots were heated to a temperature of approximately 2,400 degrees Fahrenheit for 20 to 25 minutes. While a batch of ingots (which consisted of a varying number of ingots depending on the production order) were heating (referred to as a "heat wait") in the furnaces, workers (specifically hammer operators, trim press operators, and heaters) commonly left the immediate vicinity of the furnaces or forge hammers and waited on benches located about 15 ft away. During the heat wait, workers sometimes went to production offices or to picnic tables outside the forge building, depending on weather conditions. Some workers preferred to remain in the vicinity of the forges while waiting for the next production cycle to start.

Once ingots were heated to the appropriate temperature, workers used long metal tongs to manually move the molten ingots from the furnace onto short conveyors which then moved ingots to the hammer or upset press. For heavier ingots, the tongs were connected via heavy gauge wire to an overhead hoist to help support the ingot weight. Hammer and upset press operators also used metal tongs to pick up and properly position the ingot onto the die. Operators used foot-operated control bars to activate the forge hammers or upset presses. Molten ingots placed between the dies on the hammers were shaped into forgings through multiple vertical impact blows (Fig. 1). At the upset press, one end of a molten metal rod ingot was held in place by dies, while a series of horizontal impacts shaped the other end of the rod. Forge hammers and upset presses were the primary contributors to high levels of impact noise exposure in those work areas. During the initial series of hammer blows, a chemical releasing agent was sprayed onto the hammer and die to help prevent the ingot from sticking. Forge hammers generated up to 35,000 pounds of force to produce forgings weighing up to 200 pounds, upset presses produced forgings up to 10 inches in diameter, and hydraulic screw presses applied nearly 3,500 tons of force to produce forgings weighing up to 100 pounds. Trim operators used metal tongs to move forgings from the hammers, upset presses, or screw presses to the trim press where excess metal trim, a by-product of the forge process, was removed by the trim press. Completed forgings were put into metal bins to cool. Each production run took about 30 to 45 minutes to complete.

Figure 1 Hammer operator at a pneumatic forge hammer. (Photo by NIOSH.)

After cooling, small forgings were placed inside fully enclosed shot blast units which used steel shot to smooth rough edges. The rough edges on larger forgings were smoothed by workers using machine grinders. Forgings also underwent "heat treatment," a process in which the forgings were immersed in heated quenching oil or placed in annealing furnaces to increase the strength, hardness, or machining characteristics of the metal. Metal dies were custom machined on site and changed by die operators or machinists as needed.

METHODS

Full-shift personal noise exposure measurements were collected on 36 forge workers in 15 different jobs over 2 days. Noise dosimetry was conducted using Quest Technologies NoisePro DLX Type-2 dosimeters (TSI Quest, Oconomowoc, WI) equipped with 0.335-in random incidence microphones. The dosimeters had a dynamic range of 70 to 140 dB SPL. The dosimeter sampling rate was 50 Hz and the instruments had been set up to integrate sound every second during sampling. For personal samples, the dosimeter was attached to the worker's belt and the microphone fastened to the worker's shirt at a point midway between the ear and the outside of the shoulder (called hearing zone). Windscreens were placed over the microphones to reduce or eliminate artifact noise potentially generated by air from blowing fans or incidental bumping of the microphone. The dosimeters averaged noise levels each second and simultaneously integrated noise using the OSHA's Permissible Exposure Limit (PEL), OSHA Action Level (AL), and NIOSH Recommended Exposure Limit (REL) measurement parameters. Dosimetry data were downloaded to a computer for review and interpretation with QuestSuite Professional II software (TSI Quest, Oconomowoc, WI). Instrument calibrations were checked before and after each use according to the manufacturer's instructions. During data collection, NIOSH researchers observed and documented work processes, equipment, engineering controls, and hearing protection use. In addition, NIOSH researchers privately interviewed a convenience sample of 10 forge workers from seven different job titles across production departments to ask whether they had workplace health concerns.

Because previous research had shown that noise dosimeters do not adequately measure impulsive noise greater than 140 dB, impact noise was measured using a system designed by NIOSH researchers based on the design used for previous NIOSH research.[10–13] The system used a National Instruments model 9162/9215 USB data acquisition board (National Instruments [NI], Austin, TX) and Brüel and Kjær (B&K) ¼-in microphones (model 4136) and B&K preamplifier (model 2699C) powered by a Nexus signal conditioner to acquire impact noise and one-third octave band data at a 100-kHz sampling rate (Hottinger Brüel & Kjær A/S, Virum, Denmark). During measurements, the microphones were supported on boom stands and oriented in grazing incidence (90-degree angle from the noise source) at a height of 5 to 6 ft above the floor, representing the nominal hearing zone. Two noise measurements were simultaneously taken at each location. One measurement near the worker and a second measurement were taken approximately 6 ft from the worker. Time records were acquired and streamed to a binary format and later reprocessed. Multiple short duration measurements (15–60 seconds each) were taken at four forge hammers, an upset press, a shear press, and in the grinder area. The microphones were calibrated before each day of use with a B&K pistonphone calibrator (model 4228). MATLAB data analysis software was used to analyze and describe impact and continuous sound (Mathworks, Natick, MA).

Performance and attenuation of the two foam earplugs (3MTM E-A-RTM Classic™ and 3MTM E-A-Rsoft™) worn by workers were measured using an acoustic mannequin head custom manufactured by the Institut Franco-Allemand de Recherches de Saint-Louis. The mannequin head was equipped with the Head Acoustics HMS II pinna and ear canal on the right side of the mannequin head and was coupled to a B&K 60711 ear simulator (model 4157) fitted with a B&K ½-in microphone (model 4165) which was positioned inside the ear canal and connected to the impulsive noise measurement system. The mannequin ear canal was approximately 13 mm in length. For measurements, the mannequin was placed near the hammer operator at a height of 5 to 6 ft. For the measurement of hearing protection attenuation, the NIOSH researcher properly inserted the hearing protection into the ear canal of the mannequin. Noise levels outside the hearing protection were measured using a B&K ¼-in microphone (model 4136) that was placed on a boom stand and positioned at grazing incidence near the ear of the mannequin. Differences between sound levels measured outside the mannequin head and those simultaneously measured inside the ear canal under the hearing protection provided an estimate of the hearing protector attenuation.

The company provided an electronic database of 7,908 historical audiograms for 618 current or former workers for the years 1981–2006. Personal identifiers were removed to maintain privacy. Before analysis, NIOSH audiometric quality assurance screening guidelines were used to identify and remove incomplete audiograms or those with audiometric patterns indicating hearing loss was likely a result of inaccurate audiometric thresholds or non-occupational factors such as indications of excessive background in the audiometric test room, large inter-aural differences in hearing thresholds, and large adjacent-frequency differences.[14] Audiometric screening based on these guidelines has been used in previous NIOSH research.[15,16] After screening, the dataset had 4,750 audiograms from 483 workers. Most audiograms were eliminated due to large intra-aural differences in the same frequency thresholds between ears, which are rarely caused by occupational noise exposures.[17] The mean number of audiograms per worker was 7.7 (range: 1–27). Following screening, analysis of audiometric test history was done using SAS Institute SAS version 9.3 software (SAS Institute, Cary, NC).

RESULTS AND DISCUSSION

Personal Noise Exposures

Table 1 summarizes full-shift personal noise exposures by job title. Workers in all of the jobs monitored, except machinist, had 8-hour TWA noise exposures above the NIOSH REL and OSHA AL of 85 dBA. Noise exposures also exceeded the OSHA PEL of 90 dBA, except for workers in the die repair and machinist jobs.

The primary source of noise exposure for jobs at or near the hammers (hammer operators, trim press operators, heaters) was high levels of impact noise from hammer strikes during the forging process. Additional contributors included combustion noise from the gas burners on furnaces, mechanical noise from the drive chain links and sprockets during chain conveyor movement, and compressed air. Hammer operators and trim press operators had TWA noise exposures greater than 100 dBA based on NIOSH and OSHA measurement criteria.

Table 1 Range of full-shift time-weighted average (TWA) personal noise exposure measurement results

Job title	No. of measurements	TWA noise measurements (dBA)		
		NIOSH REL measurement criteria[a]	OSHA AL measurement criteria[b]	OSHA PEL measurement criteria[c]
Hammer operator	7	98.8–110.4	97.4–107.0	97.0–106.8
Trim press operator	6	98.9–104.1	97.3–101.7	97.1–101.6
Heater	6	98.8–101.2	96.6–99.5	96.4–99.2
Shear operator	2	97.4–98.4	94.5–96.1	93.9–95.6
Forklift operator	1	98.3	96.5	96.1
Shot blast operator	2	95.3–97.9	91.9–93.4	90.2–91.6
Upset heater	2	95.7–97.7	94.4–96.6	94.0–96.6
Tow motor driver	1	97.1	95.1	94.2
Line-up	2	95.4–96.8	93.2–93.5	91.9–92.3
Maintenance	1	96.4	93.3	92.9
Upset operator	2	94.0–96.1	93.1–95.4	92.3–95.3
Grinder operator	1	94.8	94.2	93.9
Heat treat helper	1	94.2	92.0	90.9
Die repair	1	91.4	86.9	85.3
Machinist	1	83.4	81.4	65.2
Noise exposure limits		85	85	90

[a]NIOSH Recommended Exposure Limit (REL) criteria: 3-dB exchange rate and 80-dB threshold.
[b]OSHA Action Level (AL) criteria: 5-dB exchange rate and 80-dB threshold.
[c]OSHA Permissible Exposure Limit (PEL) criteria: 5-dB exchange rate and 90-dB threshold.

Table 2 Range of percent time that noise exposures exceeded 100 and 90 dBA during the work shift

No. of measurements	Job title	Noise exposures > 100 dBA (%)	Noise exposures > 90 dBA (%)
7	Hammer operator	18–56	56–89
6	Trim press operator	15–59	54–91
6	Heater	29–37	59–98
2	Shear operator	14–22	50–56
2	Upset operator	0.5–19	69–92
2	Upset heater	2–18	80–84
1	Forklift operator	19	66
1	Tow motor driver	15	54
1	Maintenance	9	46
2	Line-up	8–9	42–47
2	Shot blast operator	4	41–47
1	Die repair	4	19
1	Grinder operator	2	83
1	Machinist	0.03	2

Heaters had TWA noise exposures greater than 100 dBA based on NIOSH measurement criteria, but slightly below 100 dBA based on OSHA criteria. These noise exposure measurement results for hammer operators were similar to those reported by Taylor et al[7] and Suvorov et al.[8]

Because workers' TWA noise exposures are heavily influenced by the total time exposed to high noise levels during the work shift, the percent time that noise exposures exceeded 100 and 90 dBA for each job were determined from the dosimetry data. These results are presented in Table 2. Jobs near the hammer (hammer operator, trim press operator, and heater) had the highest percentage of time exposed to noise exceeding 100 and 90 dBA. Workers in other jobs worked farther away from the hammers or in a different building on the worksite and as a result had a lower overall percentage of time exposed to noise of 100 dBA or greater. Jobs at or near hammers or upset presses had the highest percentage of time exposed to noise above 90 dBA.

Variability in personal noise exposures within jobs near the forge hammers was influenced by the number and length of production runs during the shift. The number of production runs per shift at the hammers and upset presses ranged from 7 to 21 depending on number of forgings needed for each job order, type or complexity of the forging, size of forging, number of strikes per forging, and downtime due to changing dies or maintenance needs.

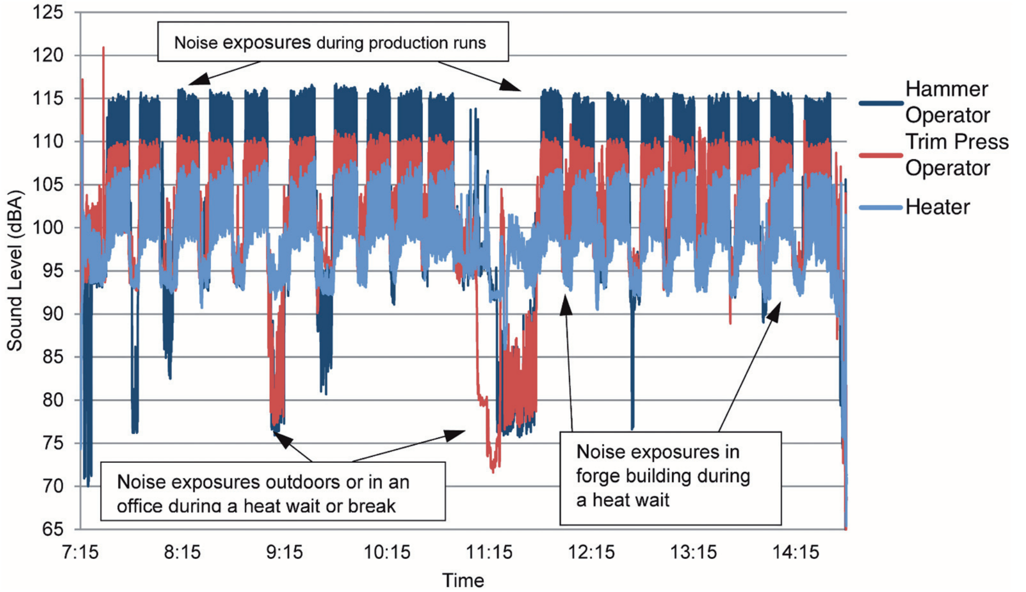


Figure 2 Noise exposure time-history profile for a hammer operator, trim press operator, and heater.

To further illustrate within-shift variation in noise exposures at the forge hammers, a time-history profile for a hammer operator, trim press operator, and heater working at a single hammer is presented in Fig. 2. This profile shows 19 production runs at this hammer during the shift. The time-history profile for these three jobs were similar, but clearly show that noise exposures for each job during production runs differed slightly based on the distance of the worker from the hammer. The hammer operator, working closest to the hammer, had noise exposures reaching 115 dBA or more during production runs. However, the trim press operator and heater worked farther from the hammer and had lower noise exposures during production runs of approximately 110 and 107 dBA, respectively.

Noise exposures for workers in all three job titles decreased similarly to 92 to 97 dBA when they stayed in the forge area during the heat wait due to background noise from other hammers and furnaces in the area. However, it is noteworthy that noise exposures decreased an additional 10 to 15 dBA, to less than 80 dBA, when workers went outdoors or into a production office during the heat wait or other breaks. Similar noise exposure time-history patterns were observed during production runs at the upset presses, reaching noise exposures of 102 to 107 dBA during the production runs and decreasing to 90 to 95 dBA during heat waits in the production building and less than 80 dBA when workers left the building.

The time-history noise exposure profile for a shear operator also shows variability in noise exposure during the work shift (Fig. 3). Noise levels reached 105 to 110 dBA during the process of cutting long metal rods into shorter ingots and when the ingots dropped into metal transport bins. Noise levels decreased to less than 80 dBA when the shear was not operating during maintenance downtime or the time the operator was waiting for additional metal rods to be brought to the shear for cutting. The shear was housed in a different building than the hammers and furnaces and did not have substantial background noise.

Impact Noise Exposures

Noise generated during hammer forging can be caused by several factors such as sudden deceleration of impacting dies, rapid sideways expansion of the forging during the strike, discharge of air from between dies, transmission of vibration to the surrounding floor, and structural ringing of the hammer following the hammer strike which can be much greater if the hammer strike is off center. The peak SPL during hammer strikes is influenced by the magnitude and duration of the hammer blow pulse from decelerating dies, intensity of the strike, velocity of the strike, die design, cross-

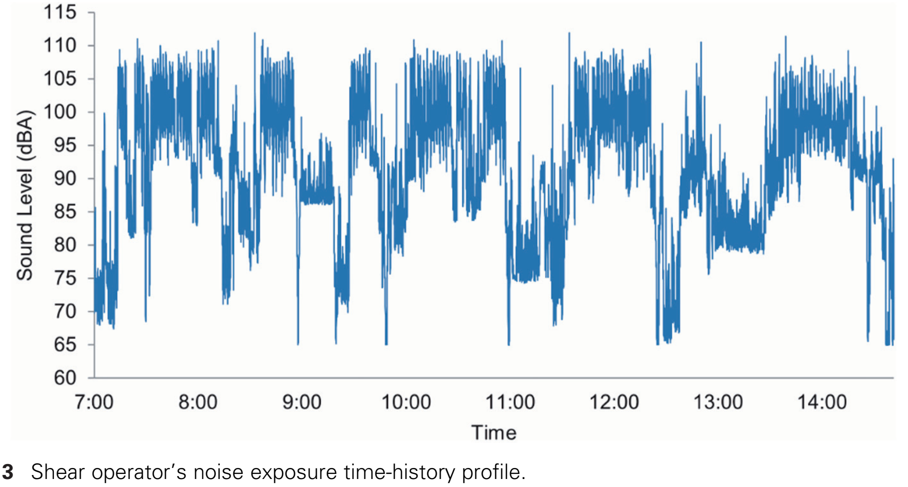


Figure 3 Shear operator's noise exposure time-history profile.

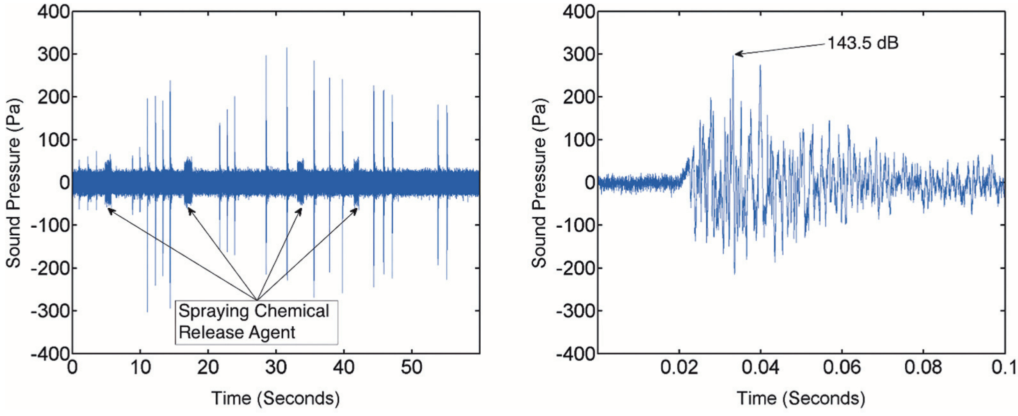


Figure 4 Sequence of hammer strikes during forging of an ingot at a 5,000-pound hammer (left) and the sound pressure waveform for a single hammer strike during the sequence (right). The peak impact sound pressure of 300 Pa is equivalent to a SPL 143.5 dB.

sectional area of the forging and die, and transverse stiffness of the forging.[18]

Fig. 4 (left) shows the waveform characteristics during a sequence of 22 hammer strikes on an ingot at a 5,000-pound hammer. The hammer strikes occurred in groups of two, three, or four with about 1 to 2 seconds of time elapsing between successive strikes within a group. Approximately 5 to 10 seconds elapsed between these groups of hammer strikes. The hammer strike sequence also shows the noise generated as the hammer operator sprays the chemical-releasing agent on the forging and die. Not all hammer strikes were applied with the same force. The intensity varied with several preliminary strikes of relatively lower intensity followed by strikes of higher intensity. The highest peak tended to occur during the final series of strikes due to die-to-die impact as the forging reached its final shape.[18] The number, impact noise intensity, and sequence pattern of hammer strikes per forge part varied by size and type of part. Smaller or less complex parts usually required fewer hammer strikes than larger or more complex parts.

Fig. 4 (right) shows the sound pressure waveform for a single strike of the 5,000-pound forge hammer over a period of 0.1 seconds. The initial 0.02 seconds of the waveform reflects background noise. The hammer strike itself is characterized by the rapid increase in sound energy to a maximum of 300 pascals (Pa) during impact, followed by "ringing" of decreasing intensity caused by vibration of the hammer forge structure. Research has shown the ringing to last several tenths of a second and to account for most of the total sound energy from a hammer strike.[19] The relationship between Pa and dB is shown by the following formula:

Table 3 Peak sound level characteristics measured at forge operation equipment

Forge equipment	Peak range (dB SPL)	25–75% percentile range (dB)	Average peak (dB)	Time between impacts robust mean (seconds)
Hammer 5-1	123–148	131–141	138	0.8
Hammer 5-2	135–148	140–145	143	3.1
Hammer 5-4	128–147	132–144	140	1.3
Hammer 10-1	135–148	138–143	141	0.9
8-in upset press	118–127	119–122	120	1.3
700-pound shear	128–140	131–133	132	1.8
Grinder	119–135	120–128	125	1.3

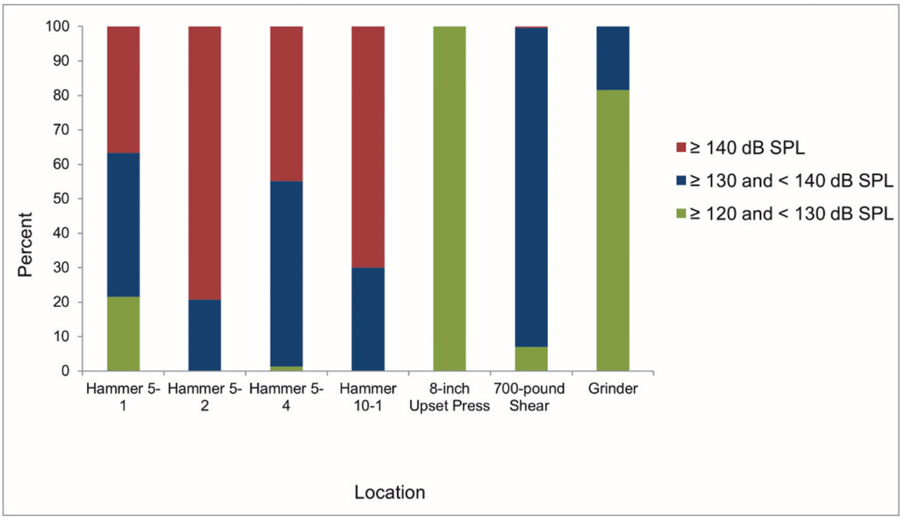


Figure 5 Stacked bar charts showing the relative proportion of impact peaks within three different SPL ranges during hammer strikes.

$$\text{dB} = 20\ \log_{10}\frac{p(t)}{2\times10^{-5}}$$

where $p(t)$ is the instantaneous sound pressure (Pa) and 2×10^{-5} Pa is the reference pressure.

Peak SPL characteristics during measurements at representative forge operation equipment are summarized in Table 3. Peak impact sound levels at the forge hammers during hammer strikes ranged from 123 to 148 dB SPL and averaged 138 to 143 dB SPL. These peak levels were similar to those reported in other studies.[7–9,20] The average repetition rate (i.e., the time between impacts) for hammer impacts (0.8–3.1 seconds) was similar to that reported by Taylor et al.[7]

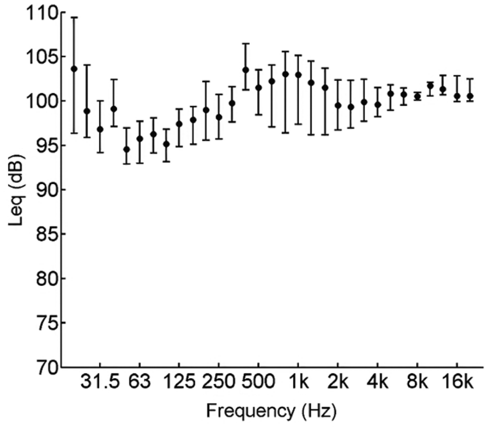
Fig. 5 shows the proportion of impact peak sound levels in three SPL ranges at the forge hammers, upset press, shear press, and grinder. Nearly all hammer strikes generated peak SPLs greater than 130 dB SPL and 37 to 80% of peaks exceeded 140 dB SPL. In contrast, less than 1% of the peak SPLs at the upset press, shear, and grinder was above 140 dB SPL. The total number of impacts and the peak levels that hammer operators are exposed to on a given day depend on the type of forging, number of production runs, number of parts per production run, and number of hammer strikes per part. This number could range from a few hundred to a few thousand per day.

One-Third Octave Band Noise Frequency Analysis

Generally, most industrial noise is considered to be broadband (distributed over a wide range of frequencies). Analysis of the frequency distribution characteristics of workplace noise is useful for identifying predominant frequencies of noise sources and determining potential engineering or other noise control measures. One-third octave band measurement results taken at the operator position at two different hammers are shown in Fig. 6.

The highest one-third octave band noise levels at the hammers were below 63 Hz, between 250 and 2,000 Hz, and above 8,000 Hz. Low-frequency noise below 63 Hz was likely related to vibration from hammer strikes transmitted through the metal structure of the hammer to surrounding floor surfaces. Noise in the 250- to 2,000-Hz frequencies at the hammers reflects sudden deceleration of the ram and upper die at impact and ringing of the hammer structure immediately following impact. Research evaluating and predicting ringing noise from forge hammers reported that the major energy content from deceleration of the ram occurred in noise frequencies of 500 to 1,000 Hz, as well as around 2,000 Hz.[19]

Noise levels at frequencies above 8,000 Hz at the hammers were likely due to noise from discharging compressed air and spraying the



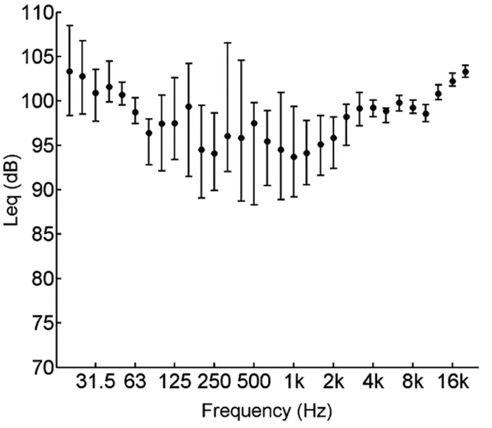


Figure 6 One-third octave band measurement results at a 5,000-pound hammer (left) and 10,000-pound hammer (right).

chemical releasing agent onto the dies through open-ended hollow tubes. Workers also used compressed air to clean debris off forgings or work surfaces. Blowing air out of an open tube generates air turbulence and high noise levels, particularly high-frequency noise, as the air exits the tip of the tube. Some manufacturers of engineered compressed air nozzles have shown that open tube nozzles generated noise levels that were up to 10 dB higher than properly engineered nozzles. In addition, efficient air nozzles not only produce less noise but also reduce compressed air consumption by 30 to 60%, resulting in cost savings.[21] Open tube nozzles also pose a safety risk because the nozzle is not equipped with a mechanism to adequately reduce air pressure if the end of the nozzle was blocked.

Forge hammer impacts generated the highest noise levels in the facility. However, other metal-to-metal noise was prevalent from ingots and forgings falling onto or being dumped onto metal chutes, conveyor pans, and metal bins (Fig. 7) and the subsequent noise and reverberation of metal surfaces that were struck, particularly when a metal bin was empty or mostly empty. Some areas had vibrating conveyor pans to move forgings which generated mechanical noise from the conveyor vibration in addition to the noise from forgings bouncing on the conveyor pan as they moved to a metal bin. Noise reduction strategies recommended to facility management to decrease metal-to-metal noise included reducing the distance that ingots and forgings fell into bins or onto conveyor pans, increasing the thickness or adding constrained layer damping to metal surfaces, covering metal surfaces with durable polymers, and replacing metal bins with durable polymer bins.

Figure 7 Forgings being dumped from a shot blast onto a vibrating conveyor pan and moving down the conveyor to fall into a metal bin. (Photo by NIOSH.)

One-third octave band measurements revealed that upset presses, shears, and grinders had predominant noise at frequencies below 63 Hz due to metal-to-metal impacts and operational vibration of the equipment and transmission of vibration to surrounding surfaces. Noise reduction strategies suggested to company management included placement of appropriately designed vibration isolation pads or springs under heavy equipment.

Additional suggested noise controls included preventive maintenance of equipment such as replacing or repairing poorly operating hammer clutch mechanisms, worn motor bearings, and loose and rattling metal parts on equipment. Construction and use of observation booths near the heat wait benches was also suggested as a strategy to provide workers the ability to observe operations during heat waits or at other times, but with lower noise levels. While noise engineering controls are an important part of noise reduction efforts, an overall long-term strategy may also include implementing a "Buy Quiet" program.[22] "Buy Quiet" is a concept for reducing hazardous noise levels through the procurement process. As part of this process, purchasers consult with equipment and tool manufacturers, compare noise emission levels for differing models of equipment, and, whenever possible, choose equipment and tools that produce less noise and vibration.

Estimation of Potential Hearing Protector Attenuation

Workers were provided with a choice of two different foam earplug hearing protectors, 3MTM E-A-RTM Classic™ and 3MTM E-A-Rsoft™ (3M Company, Minneapolis, MN). The company also offered earmuffs (unidentified model) and workers had the option to wear dual hearing protection, that is, both insert earplugs and earmuffs, but this was not required. In general, workers reported preferring to wear insert earplugs, but a few were observed using dual protection. During annual audiograms, the audiometric test provider conducted training on how to wear hearing protection.

The hearing protector manufacturer's reported noise reduction ratings (NRR) for the two different earplugs provided, based on laboratory test procedures specified by the U.S. Environmental Protection Agency (EPA), were 31 dB for the 3MTM E-A-RTM Classic™ and 33 dB for the 3MTM E-A-Rsoft™.[23] Although NIOSH recommends de-rating the NRR of earplugs to account for imperfect fit,[3] attenuation measurements of these hearing protectors, which had been carefully inserted by a NIOSH researcher into an acoustic mannequin positioned near two different operating forge hammers, estimated that peak noise levels during hammer strikes were attenuated by 20 to 30 dB and an overall attenuation of 42 to 44 dB was possible for well-fitting hearing protectors. However, it should be noted that previous human subject fit-test studies measured an average attenuation several decibels lower (28–29 dB) for these hearing protectors.[24]

Proper fit of the hearing protection is critically important and the noise attenuation of insert-type hearing protection by individual users depends on the type of hearing protector, shape of the user's ear canal, proper insertion of the hearing protector, and how well the hearing protector fits after insertion. During the site visits, some workers were observed wearing earplugs that had not been fully inserted into their ears. Additionally, hearing protectors can appear to be properly inserted but still provide poor noise attenuation because of factors such as improperly sized hearing protectors or channeling of foam hearing protectors in which a narrow gap formed during the process of rolling them permits additional noise to enter the ear canal through the channel.

While the noise attenuation measurements in an acoustic mannequin showed that substantial attenuation was possible for well-fitting hearing protectors carefully and fully inserted into the ear canal, NIOSH has previously identified that poor insertion of formable earplugs into the ear canal reduces the hearing protector noise attenuation.[3] Furthermore, human subject fit-test data have shown that poorly fitting hearing protectors provide attenuation much worse than reported NRR values.[24–28]

Analysis of Audiometric History

The company brought a contractor to the worksite each year to complete annual audiometric testing of workers. The audiometric provider conducted pure-tone air-conduction threshold testing at frequencies of 500, 1,000, 2,000, 3,000, 4,000, and 6,000 Hz. NIOSH recommends that employers also test at 8,000 Hz to improve decisions about probable etiology of hearing loss.[3]

Analysis of the audiometric history for the 483 forge workers who had more than one valid audiometric test completed revealed that 395 (82%) workers had experienced a significant threshold shift based on NIOSH criteria, defined as a change in hearing threshold, relative to the baseline, of 15 dB or more in any of the audiometric test frequencies. Using OSHA STS criteria, defined as an average change in hearing threshold, relative to the baseline, of 10 dB or more across the audiometric test frequencies of 2,000, 3,000, and 4,000 Hz, 303 (63%) workers had experienced an OSHA STS. Other researchers have also found that NIOSH criteria for identifying significant threshold shifts was more sensitive and identified more workers than OSHA STS criteria. Notably, an analysis of a large audiometric database of aluminum company workers to identify early indicators of recordable hearing loss found 68% with a NIOSH significant threshold shift and 29% with an OSHA STS.[29] Additionally, a cross-sectional retrospective cohort study comparing the prevalence of worker's hearing threshold shifts using NIOSH and OSHA criteria found that, for most industries, OSHA STS criteria identified 28 to 36% less workers than NIOSH significant threshold shift criteria.[30]

Our analysis also showed that all of the forge workers who were found to have an OSHA STS previously had a NIOSH significant threshold shift. However, 23% (92/395) of workers with a NIOSH significant threshold shift had not advanced to an OSHA STS. For the 303 workers who had an OSHA STS, the average length of time between when workers were first identified with a NIOSH significant threshold shift and when they were first identified with an OSHA STS is shown in Fig. 8. Overall, 7.25 years (range: 0–24 years) elapsed between the occurrence of a NIOSH significant threshold shift to an OSHA STS. When stratified by age group, the elapsed time was longest for the 25- to 34-year and 35- to 44-year age groups and shortest for the 55- to 64-year age group.

For workers with a normal baseline audiogram (HTL < 20 dB) preceding hearing threshold shifts ($n = 308$), the length of time

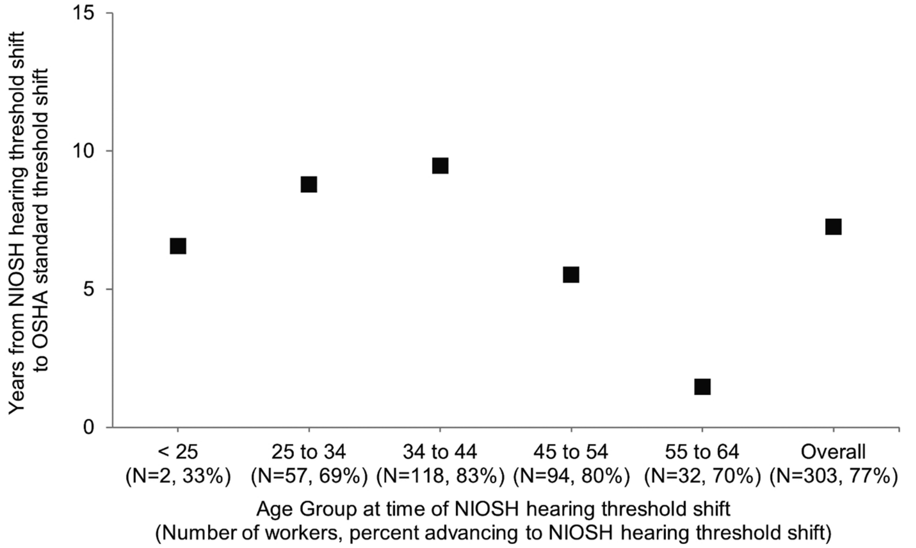


Figure 8 Elapsed time from NIOSH-defined significant threshold shift to OSHA-defined standard threshold shift.

Table 4 Mean number of years from normal baseline audiogram to NIOSH significant threshold shift and OSHA standard threshold shift (STS), stratified by age at the time of baseline audiogram

Age group	No. of subjects	Years to NIOSH significant threshold shift	Number of subjects with OSHA STS (%)	Years to OSHA STS
<25	21	5.0	8 (38%)	9.4
25–34	135	4.8	107 (79%)	9.3
35–44	104	4.5	85 (82%)	9.0
45–54	43	4.5	35 (81%)	5.5
55–64	5	3.5	3 (60%)	5.1
Overall	308	4.6	238 (77%)	8.6

from their baseline audiogram to a NIOSH significant threshold shift or OSHA STS, stratified by age group at the time of the baseline audiogram, is provided in Table 4. On the basis of NIOSH significant threshold shift criteria, little difference was evident between age groups. Overall, 4.6 years elapsed from a normal baseline to a NIOSH significant threshold shift. Using OSHA STS criteria, workers younger than 45 years at the time of their baseline audiogram had an OSHA STS after approximately 9 years of employment in the forge, whereas older workers progressed to an OSHA STS after approximately 5 years.

It is unclear why older workers progressed to OSHA STS more quickly. However, workers in the older age groups who began working at the facility before the OSHA hearing conservation standard went into effect may not have worn hearing protection, may have used protection less consistently, or used less effective hearing protection. Another possible explanation may include assignment of older, more experienced workers to jobs with higher noise exposures. Hearing protection use or job title information to further examine these possibilities was not available. Adjustments were not done for potential age-related effects so, this higher rate of progression could potentially be influenced by aging along with noise exposure.

Analysis of the audiometric data revealed that NIOSH significant threshold shifts always preceded OSHA STS in this worker population. In addition, every worker with an OSHA STS previously had a NIOSH significant threshold shift. While these results are perhaps not surprising due to the greater sensitivity of NIOSH hearing loss criteria, this analysis indicates that using NIOSH criteria for identifying significant threshold shifts can lead to earlier identification of hearing loss and the opportunity for earlier intervention to prevent and limit progression to further hearing loss.

Table 5 shows the relationship between length of tenure and the probability of a NIOSH-defined material hearing impairment and hearing threshold shifts for workers in eight different tenure categories. The probability of a NIOSH significant threshold shift was greater than the probability of an OSHA STS and material hearing impairment. These differences were greatest during the first 15 years of tenure. The probability of OSHA STS and material hearing impairment were similar for the first 20 years of tenure, after which the probability of material hearing impairment was nearly double the probability of an OSHA STS. In general, the probability of a NIOSH significant threshold shift, OSHA STS, and NIOSH-defined material hearing impairment increased with length of tenure, particularly after the first 10 years of working in the facility.

Table 6 shows the mean HTL for the forge workers stratified by age at the time of their most recent audiogram. The two youngest age groups had similar HTLs at the audiometric test frequencies greater than 1,000 Hz and neither age group showed substantial hearing loss. The under 25-year-old age group showed a relatively worse HTL at 500 Hz; however, that

Table 5 Percent probability of hearing threshold shifts and material hearing impairment, stratified by length of tenure

Tenure range (years)	Mean tenure (years)	No. of workers	Mean age (years)	Probability of NIOSH-defined material hearing impairment (%)	Probability of hearing threshold shift (%)	
					NIOSH	OSHA
< 2	0.9	68	32	6	10	2
2–4	2.9	45	34	4	24	4
4–6	4.9	38	33	0	24	5
6–10	8.0	82	34	3	13	6
10–15	12.5	112	36	8	22	6
15–20	17.3	107	40	12	26	9
20–30	24.5	88	46	21	31	11
> 30	33.3	66	54	32	39	18

Table 6 Hearing levels stratified by age group, based on age at the time of most recent audiogram

Age group	No. of workers	Mean hearing threshold levels in dB by test frequency (Hz)					
		500	1,000	2,000	3,000	4,000	6,000
< 25	8	21.6	9.4	5.6	7.2	8.1	11.9
25–34	19	10.4	4.7	4.1	9.1	10.1	12.6
35–44	92	10.4	7.7	8.3	18.2	22.0	23.4
45–54	115	12.1	9.9	15.3	30.5	37.0	36.4
55–64	212	15.6	15.9	25.1	41.4	47.1	49.6
> 65	6	13.3	12.5	25.4	41.7	53.3	55.4

group had a small number of workers, and this result could be related to background noise during testing or undiagnosed ear pathology in one or more of the workers. Analysis showed the HTLs were progressively higher (worse hearing) with increasing age. The highest HTLs were in the 4,000- and 6,000-Hz frequencies which is typical for NIHL.[3]

The trend of worse hearing with age was also observed in hammer forge workers in the United Kingdom.[7] The HTLs of press operators and hammer operators in that research were higher than the HTLs among forge workers at this facility. Job title and work history information were not available for these forge workers; therefore, analysis could not be further stratified by these factors to determine to what extent hearing loss was greater in jobs with the highest TWA and impact noise exposures, specifically those jobs closest to the hammer.

Hearing protection use among forge workers at this facility was not quantified historically. However, differences in HTLs compared to the population studied by Taylor et al[7] may be related to better use of hearing protection among these forge workers, particularly after the OSHA hearing conservation standard went into effect in 1983. During the site visit, all workers were observed to be wearing hearing protection. Workers also reported during interviews and informal conversations that they consistently used hearing protection. In contrast, some long-term workers noted that before 1980, hearing protection use was not consistent. Some workers also reported stuffing cotton into their ears at that time for hearing protection. Limited hearing protection use was also

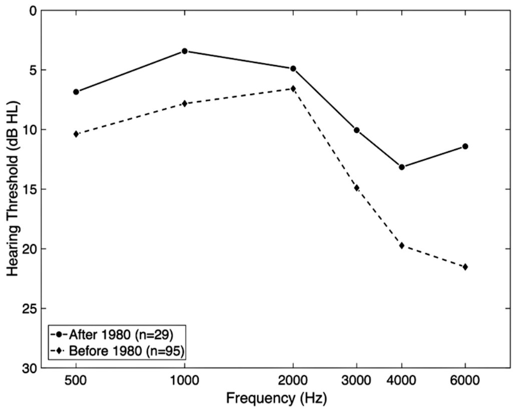


Figure 9 Comparison of hearing threshold levels after 10 years of noise exposure in forge workers by hire date (before or after 1980).

reported by Taylor et al[7] among the United Kingdom forge workers prior to 1984.

Fig. 9 shows the differences in HTLs after 10 years of noise exposure in the forge workers who started working before 1980 compared to workers who started after 1980. HTLs for forge workers starting after 1980 were better than for workers who started before 1980. This may be further evidence of positive effects of improved hearing protection use beginning in the 1980s after the OSHA hearing conservation standard went into effect.

Fig. 10 shows the HTLs in the forge population in this facility, stratified by age group, compared to an ISO reference population, consisting of unscreened workers from the ISO 1999:2013 standard, Annex B3, from the U.S. population.[31] The 50th percentile HTLs for the forge population was similar to the 50th percentile HTLs for the ISO reference population for most age groups. However, HTLs for the 45- to 54-year and 55- to 64-year age group appeared slightly worse at the higher frequencies, particularly at 4 kHz, which is a characteristic NIHL pattern. The 90th percentile HTLs among these forge workers were slightly worse than the 90th percentile for the ISO reference population for some

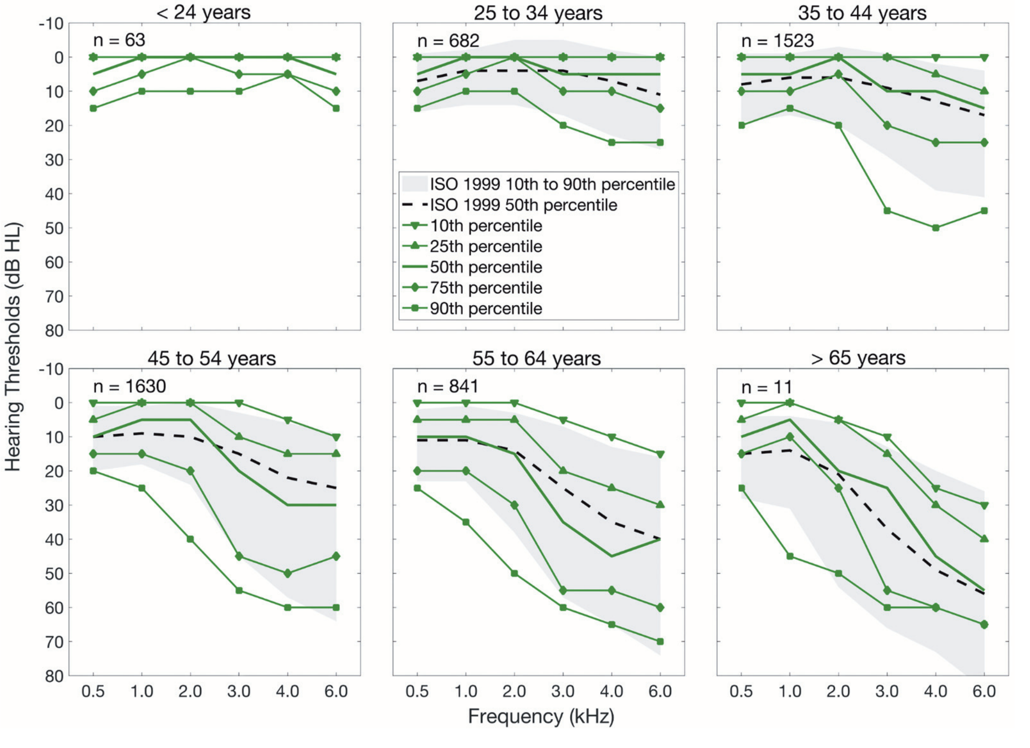


Figure 10 Comparison of forge worker hearing threshold levels (HTLs) to the ISO 1999:2013 standard, Annex B3 reference (unscreened) population HTLs.

frequencies in all but the youngest age group. Differences were more prominent in the 35- to 44-year and 45- to 54-year age groups. Evidence of potentially greater hearing loss in the forge worker population compared to the ISO reference population, particularly in higher frequencies and in the mid to older age groups, was not surprising given many forge workers' high noise exposures, including exposures to impulsive noise or high level complex noise (i.e., combination of continuous and impulsive noise), which research has shown as more likely to cause hearing loss than exposure to continuous noise alone.[32–37] However, the extent of hearing loss among these forge workers was less than expected. This could possibly be attributed to mitigation of hearing loss by the heat wait periods built into the work cycle, particularly in jobs at or near the forge hammers. Workers often rested in quiet areas during the heat wait period. Research has shown that recovery from the effects of high noise exposure can occur during time spent under low noise exposure conditions.[38,39] Improved use of hearing protection after the OSHA Hearing Conservation Standard went into effect could be another factor potentially limiting the extent of hearing loss among some of the forge workers. Other researchers have found that use of hearing protection was associated with decreased risk of hearing threshold shifts and NIHL.[15,40]

CONCLUSION

This evaluation describes hammer forge workers' exposures to high noise levels, including impact noise, as well as worsening hearing with age and length of employment. Personal noise exposure measurement results showed that workers in 14 of the 15 jobs monitored had full-shift noise exposures that exceeded the NIOSH REL and OSHA AL. Similarly, workers in 13 of the 15 jobs monitored were also exposed to noise levels exceeding the OSHA PEL. Noise exposures of hammer operators, trim press operators, and heater were found to exceed 100 dBA. Peak noise levels, measured at four different hammers during hammer impacts, ranged from 123 to 148 dB SPL, and averaged 138 to 143 dB SPL. Analysis of the audiometric history for 483 forge workers showed 82% had experienced a NIOSH-defined significant threshold shift, and 63% had experienced an OSHA STS since their baseline audiogram. The mean number of years from a normal baseline audiogram to a threshold shift was about 5 years for a NIOSH threshold shift and was about 9 years for an OSHA STS. All workers who had an OSHA STS had a NIOSH significant threshold shift that occurred on average about 7 years before, indicating that using NIOSH criteria to identify threshold shifts can lead to early identification of hearing loss and an opportunity for earlier interventions to prevent and limit further progression. HTLs after 10 years of employment at the facility were worse for those who started working in the facility prior to 1980 than for those who started working after 1980. This may be evidence of the positive effects of the OSHA hearing conservation standard which went into effect in the early 1980s. It is possible that the extent of hearing loss related to noise exposure in some jobs may have been mitigated somewhat by periods of lower noise exposure during natural work cycles, permitting some recovery from high noise effects. Implementation of a comprehensive hearing conservation program including engineering controls for noise, use of dual hearing protection, and administrative controls such as requiring quiet time and using NIOSH significant threshold shift criteria for early identification of hearing loss are important strategies to help reduce noise exposures and risk of hearing loss in hammer forge operations.

DISCLAIMER

The findings and conclusions in this report are those of the authors and do not necessarily represent the official position of the National Institute for Occupational Safety and Health, Centers for Disease Control and Prevention.

CONFLICT OF INTEREST

None declared.

REFERENCES

1. Kerns E, Masterson EA, Themann CL, Calvert GM. Cardiovascular conditions, hearing difficulty, and occupational noise exposure within US

industries and occupations. Am J Ind Med 2018;61 (06):477–491
2. Tak S, Davis RR, Calvert GM. Exposure to hazardous workplace noise and use of hearing protection devices among US workers–NHANES, 1999-2004. Am J Ind Med 2009;52(05):358–371
3. NIOSH. Criteria for a recommended standard: occupational noise exposure (revised criteria 1998). Cincinnati, OH: U.S. Department of Health and Human Services, Centers for Disease Control and Prevention, National Institute for Occupational Safety and Health, DHHS (NIOSH) Publication No. 98-126; 1998
4. Rösler G. Progression of hearing loss caused by occupational noise. Scand Audiol 1994;23(01): 13–37
5. Rabinowitz PM, Davies HW, Meinke DK. Auditory and non-auditory health effects of noise. In: Meinke DK, Berger EH, Driscoll DP, eds. The Noise Manual, 6th ed. Falls Church, VA: AIHA Press; 2022:79–97
6. Masterson EA, Themann CL, Luckhaupt SE, Li J, Calvert GM. Hearing difficulty and tinnitus among U.S. workers and non-workers in 2007. Am J Ind Med 2016;59(04):290–300
7. Taylor W, Lempert B, Pelmear P, Hemstock I, Kershaw J. Noise levels and hearing thresholds in the drop forging industry. J Acoust Soc Am 1984; 76(03):807–819
8. Suvorov G, Denisov E, Antipin V, et al. Effects of peak levels and number of impulses to hearing among forge hammering workers. Appl Occup Environ Hyg 2001;16(08):816–822
9. Sułkowski W, Kowalska S, Lipowczan A, Prasher D, Raglan E. Tinnitus and impulse noise-induced hearing loss in drop-forge operators. Int J Occup Med Environ Health 1999;12(02): 177–182
10. Kardous CA, Willson RD, Hayden CS, Szlapa P, Murphy WJ, Reeves ER. Noise exposure assessment and abatement strategies at an indoor firing range. Appl Occup Environ Hyg 2003;18(08): 629–636
11. Kardous CA, Willson RD. Limitations of using dosimeters in impulse noise environments. J Occup Environ Hyg 2004;1(07):456–462
12. Yan H, Kardous CA, Murphy WJ. NIOSH Impulsive-Noise Measurement System (NIMS). Proceedings of NoiseCon 2004;2004:1–8
13. Kardous CA, Willson RD, Murphy WJ. New dosimeter design for monitoring exposure to impulsive noise. Applied Acoustics Journal 2005;66 (08):974–998
14. Franks JR. The role of audiometric data management in hearing loss prevention: audiometric data management. In: Proceedings: Best practices in hearing loss prevention. Cincinnati, OH: U.S. Department of Health and Human Services, Centers for Disease Control and Prevention, National Institute for Occupational Safety and Health, DHHS (NIOSH) Publication No. 2001-157; 1999
15. Heyer N, Morata TC, Pinkerton LE, et al. Use of historical data and a novel metric in the evaluation of the effectiveness of hearing conservation program components. Occup Environ Med 2011;68 (07):510–517
16. Masterson EA, Tak S, Themann CL, et al. Prevalence of hearing loss in the United States by industry. Am J Ind Med 2013;56(06):670–681
17. Arslan E, Orzan E. Audiological management of noise induced hearing loss. Scand Audiol Suppl 1998;48:131–145
18. Rivin E. Noise abatement of industrial production equipment. In: Crocker M, ed. Handbook of Noise and Vibration Control. Hoboken, NJ: John Wiley and Sons; 2007:987–994
19. Lam YW, Hodgson DC. The prediction of ringing noise of a drop hammer in a rectangular enclosure. J Acoust Soc Am 1993;93(02):875–884
20. Kamal AA, Mikael RA, Faris R. Follow-up of hearing thresholds among forge hammering workers. Am J Ind Med 1989;16(06):645–658
21. Saidur R, Rahim NA, Hasanuzzaman M. A review on compressed-air energy use and energy savings. Renew Sustain Energy Rev 2010;14(04): 1135–1153
22. Beamer B, McCleery T, Hayden C. Buy quiet initiative in the USA. Acoust Aust 2016;44(01): 51–54
23. U.S. EPA Environmental Protection Agency, 40 CFR 211 Subpart B, Hearing Protection Device Labeling, Sept 29, 1978. Code of Federal Regulations. Washington, DC: U.S. Government Printing Office, Office of the Federal Register; 1978
24. Murphy WJ, Stephenson MR, Byrne DC, Witt B, Duran J. Effects of training on hearing protector attenuation. Noise Health 2011;13(51):132–141
25. Berger EH, Franks JR, Lindgren F. International review of field studies of hearing protection attenuation. In: Axelsson A, Borchgrevink H, Hamernik RP, eds. Scientific Basis of Noise-Induced Hearing Loss. New York: Thieme Medical Publishers; 1996:361–377
26. Berger EH, Franks JR, Behar A, et al. Development of a new standard laboratory protocol for estimating the field attenuation of hearing protection devices. Part III. The validity of using subject-fit data. J Acoust Soc Am 1998;103(02): 665–672
27. Franks JR, Murphy WJ, Johnson JL, Harris DA. Four earplugs in search of a rating system. Ear Hear 2000;21(03):218–226
28. Joseph A, Punch J, Stephenson M, Paneth N, Wolfe E, Murphy WJ. The effects of training format on earplug performance. Int J Audiol 2007;46(10):609–618

29. Rabinowitz PM, Galusha D, Ernst CD, Slade MD. Audiometric "early flags" for occupational hearing loss. J Occup Environ Med 2007;49(12): 1310–1316
30. Masterson EA, Sweeney MH, Deddens JA, Themann CL, Wall DK. Prevalence of workers with shifts in hearing by industry: a comparison of OSHA and NIOSH Hearing Shift Criteria. J Occup Environ Med 2014;56(04):446–455
31. International Standard Organization 1999 (ISO 1999). Acoustics—Estimation of Noise-Induced Hearing Loss, Annex B3 U.S. Population from the NHANES Survey. Geneva, Switzerland: International Standards Organization; 2013
32. Pfander F, Bongartz H, Brinkmann H, Kietz H. Danger of auditory impairment from impulse noise: a comparative study of the CHABA damage-risk criteria and those of the Federal Republic of Germany. J Acoust Soc Am 1980;67(02): 628–633
33. Sulkowski WJ. Hearing impairment caused by impulse noise: survey in the drop forging industry. Scand Audiol Suppl 1980;12(Suppl 12):307–317
34. 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(04):265–271
35. Zhao YM, Qiu W, Zeng L, et al. Application of the kurtosis statistic to the evaluation of the risk of hearing loss in workers exposed to high-level complex noise. Ear Hear 2010;31(04):527–532
36. Davis RI, Qiu W, Heyer NJ, et al. The use of the kurtosis metric in the evaluation of occupational hearing loss in workers in China: implications for hearing risk assessment. Noise Health 2012;14(61): 330–342
37. Qiu W, Murphy WJ, Suter A. Kurtosis: a new tool for noise analysis. Acoust Today 2020;16(04): 39–47
38. Kryter KD, Ward WD, Miller JD, Eldredge DH. Hazardous exposure to intermittent and steady-state noise. J Acoust Soc Am 1966;39(03):451–464
39. Ryan AF, Kujawa SG, Hammill T, Le Prell C, Kil J. Temporary and permanent noise-induced threshold shifts: a review of basic and clinical observations. Otol Neurotol 2016;37(08):e271–e275
40. Davies H, Marion S, Teschke K. The impact of hearing conservation programs on incidence of noise-induced hearing loss in Canadian workers. Am J Ind Med 2008;51(12):923–931