Evaluation of a Surgical Staff's Noise Exposures during Total Knee Replacement Surgeries

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The cover photo is a close-up image of sorbent tubes, which are used by the HHE Program to measure airborne exposures. This photo is an artistic representation that may not be related to this Health Hazard Evaluation. Photo by NIOSH.

Highlights of this Evaluation

The Health Hazard Evaluation Program received a request from a medical and surgical hospital. An employer representative was concerned about the surgical staff's exposure to noise during total knee replacement surgeries.

What We Did

- We measured surgical staff's noise exposures in January and July 2015.
- We observed work practices and spoke informally with employees about their work activities and noise.
- We estimated the surgeons' potential noise exposures as a function of the number and length of surgeries in a work day.

What We Found

- Noise exposures were highest during surgeries. Most of the noise was caused by powered surgical tools.
- One surgeon's noise exposure was above the National Institute for Occupational Safety and Health recommended exposure limit on one of the days we measured noise. None of the other noise exposures were above the limit.
- None of the surgical staffs' noise exposures were above the Occupational Safety and Health Administration noise exposure limits.
- We estimated that surgeons' noise exposures could exceed the recommended exposure limit, depending on the number and length of surgeries and noise levels during surgeries.

What the Employer Can Do

- Purchase powered surgical tools that generate the least amount of noise when replacing or buying new surgical tools.
- Include orthopedic surgeons in a hearing loss prevention program that includes annual hearing tests, appropriate hearing protection, training, and noise exposure assessments.
- Offer flat-attenuation ear plugs or noise cancelling earmuffs for surgeons' use during knee replacement surgeries.

We measured surgical staff's noise exposures during total knee replacement surgeries. One surgeon was overexposed to noise on one day. The other surgeon and the rest of the surgical staff were not overexposed to noise. We estimated the potential range of noise exposures for surgeons and found that they could be overexposed to noise depending on the noise level during surgeries, and length and number of surgeries. We recommended including orthopedic surgeons in a hearing loss prevention program, using quieter surgical tools, and providing hearing protection.

What Employees Can Do

- Wear hearing protection devices during surgery.
- Keep the volume of music in the operating room low to limit background noise levels and minimize the potential for speech interference.

Abbreviations

ACGIH®	American Conference of Governmental Industrial Hygienists
AL	Action level
CFR	Code of Federal Regulations
dB	Decibels
dBA	Decibels, A-weighted
Hz	Hertz
NIHL	Noise-induced hearing loss
NIOSH	National Institute for Occupational Safety and Health
OEL	Occupational exposure limit
OSHA	Occupational Safety and Health Administration
PEL	Permissible exposure limit
REL	Recommended exposure limit
TLV®	Threshold limit value
TWA	Time-weighted average
WEEL™	Workplace environmental exposure level

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Introduction

The Health Hazard Evaluation Program received a request from employer representatives at a hospital. They were concerned about the potential for noise-induced hearing loss (NIHL) among operating room employees performing total knee replacement surgeries, also known as knee arthroplasty. We visited the hospital in January 2015 and July 2015 to observe total knee replacement surgeries, learn more about the equipment and tools used during surgeries, and measure noise exposures of surgical staff. A typical surgical team for total knee replacement surgeries included a surgical assistant, anesthesiologist, circulating nurse, scrub nurse, and surgeon. A surgical fellow may also be present to assist the surgeon.

Methods

The objectives of this health hazard evaluation were to (1) measure full-shift time-weighted average (TWA) personal noise exposures among operating room personnel during total knee replacement surgeries and compare exposures to occupational exposure limits (OELs) for noise, (2) compute task-based TWA noise exposures during surgeries, (3) compare noise exposure measurements taken on the surgeons' right and left sides, and (4) model surgeons' range of noise exposures using numbers of surgeries, length of surgeries, and noise levels during surgeries as variables.

Personal Noise Monitoring

We measured operating room staff's full-shift TWA noise exposures using Larson Davis Spark™ model 706RC integrating noise dosimeters. The dosimeters integrated noise at a 50-hertz (Hz) sampling rate and data-logged 1-second averaged noise levels for the duration of the measurement period. We measured noise exposure for three job titles: surgeons, surgical assistants, and anesthesiologists. We manually tracked the time that surgeons spent in surgery versus the time they spent outside surgery. Surgical staff wore dosimeters on the waistband of their medical scrubs; we attached the dosimeter microphone in an upright position midway between the neck and the end of the shoulder on the outside of the surgical gown. We covered the microphone with a windscreen to reduce artifact noise caused by accidental bumping or rubbing. Each surgeon wore two dosimeters, with one microphone clipped to each shoulder. At the end of the work shift, we downloaded the noise measurement data from the dosimeters using the PCB Piezotronics Blaze™ program.

The dosimeters simultaneously collected noise data using three settings to allow comparison of noise measurement results with three different noise exposure limits, the Occupational Safety and Health Administration (OSHA) permissible exposure limit (PEL), the OSHA action level (AL), and the National Institute for Occupational Safety and Health (NIOSH) recommended exposure limit (REL). For noise dosimeter measurements, OSHA uses a 90 decibel, A-weighted (dBA) threshold and a 5-decibel (dB) exchange rate for the PEL measurements and an 80 dBA threshold and 5-dB exchange rate for the AL measurements. NIOSH uses an 80 dBA threshold and a 3-dB exchange rate for the REL measurements. Noise below the threshold level is not integrated by the noise dosimeter for the TWA measurement results. The exchange rate refers to the amount of dB by which the sound level may increase if the exposure time is halved, or decrease if exposure time is doubled. NIOSH considers noise measured using the 3-dB exchange rate to more accurately relate noise exposures to hearing loss risk [NIOSH 1998]. Additional information on noise exposure limits and health effects is provided in Appendix A.

Comparing Left and Right Ear Noise Exposures

To compare whether differences occurred between the surgeons' right and left ear noise exposures during surgeries, we took separate personal noise dosimetry measurements on the surgeons' right and left sides. For analysis, we performed two-sided, paired Student's t-test and determined the *P* value to examine the statistical relationship between the surgeons' right side versus left side noise measurements.

Modeling Surgeon Noise Exposures

We modeled surgeons' TWA noise exposures on the basis of the following variables: number of surgeries, surgical noise level, nonsurgical noise level, surgery duration, and shift length. Equation 1 shows how we calculated surgeons' TWA noise exposures.

Equation 1. Surgeons' estimated TWA noise exposures

$$Surgeons'\ TWA\ noise\ exposures = 10\log_{10}\left[\left(\frac{1}{W}\right)\left(\left((N*T)\left(10^{S_{avg}/10}\right)\right)+\left((W-(N*T))\left(10^{NS_{avg}/10}\right)\right)\right)\right]$$

Where:

W = length of workshift (minutes)
N = number of surgeries performed
T = time per surgery (minutes)
S_{avg} = measured TWA noise level during surgery (dBA)
NS_{avg} = measured TWA noise level during nonsurgical periods (dBA)

Results and Discussion

Observations

During the evaluation, each surgical team performed three or four total knee replacements on each day of noise monitoring. During one of our days of monitoring, a surgical fellow assisted the surgeon. A knee implant vendor representative was also present to help select the proper joint replacement components. Surgeries were performed across three operating rooms. The rooms were similar in size and design. The operating rooms had vinyl floors and drywall ceilings and walls. Surgical procedures required establishing a sterile field around the patient to reduce the patient's risk of acquiring infections. The sterile field included the area from the patient's shoulder to slightly past the patient's foot and extending about 5 feet on either side of the patient. The sterile field was separated from the nonsterile field by plastic sheeting at the shoulder of the patient. Personnel movement between the sterile and nonsterile fields during surgeries was limited to reduce the patient's risk of infection. On the days we monitored, the surgical staff worked 8-hour work shifts. However, surgeons or surgical staff reported during informal conversations that they sometimes worked longer shifts.

Surgeon A performed four surgeries on each of 2 days of monitoring. On the first day, he performed surgeries on one 58-year-old male and three females (aged 45, 65, and 71 years). On the second day, he performed surgery on three males (aged 58, 67, 73 years) and one 83-year-old female. We monitored surgeon B's noise exposure for one day. He performed surgeries on two males (aged 61 and 65) and one female (aged 74). The surgeons reported that noise levels seemed higher during knee replacements on patients with greater bone density; younger, male, and larger patients tended to have greater bone density than older, female, or smaller patients.

Surgical staff, including the scrub nurse, circulating nurse, surgical assistant, and anesthesiologist, prepared the room, equipment, tools, and the patient for surgery. During surgeries, the surgeon exposed the knee joint, then removed portions of the tibia and femur bones using a surgical saw. The knee was measured for the correct implants, which were then fixed to the tibial head and implanted into the femoral head using surgical drills, a hammer, and adhesive implant cement. After the implant cement cured, the incision was closed. Following surgery, operating room staff disposed of waste, prepared used surgical equipment for sterilization, and transported the patient to the recovery room. Between procedures, surgeons spoke with patients, typed or dictated post-op notes, prepared for upcoming surgeries, and completed other administrative duties.

The use of pneumatically powered surgical tools (saws and drills) and hammers were the primary noise sources in the operating room. Other sources of noise included placing or moving surgical equipment and tools on metal surgical trays; noise from vitals sign monitors, anesthesia equipment, and lavage equipment; background music; and talking. The surgical tool and knee implant vendor representative noted that approximately 6 months before our first visit the hospital had begun using a sharper, thinner blade on the surgical saw, which reportedly reduced noise during orthopedic surgeries.

Most surgeries were performed with a surgeon and one surgical assistant on either side of the knee undergoing replacement. During two surgeries, an orthopedic surgery fellow also worked on the knee. An anesthesiologist worked at the head of the patient, outside the sterile field. At the foot of the patient in the sterile field, a scrub nurse provided and collected surgical tools and mixed resin for implantation. The circulating nurse recorded surgical notes on a computer in the corner of the operating room. Saws and hammers were used during every knee replacement. The surgical team used the Stryker® System 6 tool system, equipped with a 1.19 millimeter Attune® sawblade.

Employees did not wear hearing protection devices. One employee inserted pieces of paper that had been rolled into balls into the ear canals as protection against noise exposure. The employee reported doing this for every orthopedic surgery. The hospital did not provide hearing protection devices in the surgical staff locker room, the employee break room, the surgical suite hand wash area, or the operating rooms.

Personal Noise Exposure Measurements

A summary of TWA personal noise exposure measurements is provided in Table 1. Detailed exposure results are in Appendix B, Table B1. Surgeons and surgical fellows used the surgical tools and were closest to noise sources during surgeries, and had the highest noise exposures. In contrast, the anesthesiologists were further from noise sources and had the lowest noise exposures. Surgical assistants' and the anesthesiologists' full-shift TWA noise exposures were below NIOSH and OSHA 8-hour TWA noise exposure limits. NIOSH reported similar results for surgical staff (registered nurses and surgical technicians) during orthopedic surgeries in a previous evaluation [NIOSH 2010a].

Table 1. Summary of surgical staff full-shift TWA noise exposure measurements

Job title	Number of measurements	NIOSH REL criterion (dBA)	OSHA AL criterion (dBA)	OSHA PEL criterion (dBA)
Surgeon (right shoulder measurement)	3	81.4–86.8	76.5–83.5	68.1–78.2
Surgeon (left shoulder measurement)	3	77.9–83.2	71.3–77.9	62.3–73.0
Surgical fellow (right shoulder measurement)	1	81.5	74.3	70.4
Surgical fellow (left shoulder measurement)	1	83.0	75.6	72.5
Surgical assistant	3	76.0–78.7	64.2–70.8	58.2–65.4
Anesthesiologist	2	67.8–71.8	58.2–75.8	38.4–46.1
Noise exposure limits (8-hour work shift)		85	85	90

On one of the days we monitored noise, one of the surgeons was exposed to a TWA noise level that was above the NIOSH REL, but below the OSHA AL and PEL on his right side measurement. All the other TWA noise measurements on surgeons were below noise exposure limits.

Using the NIOSH REL noise measurement criterion, both surgeons' TWA noise measurement results taken on their right side were significantly higher than those taken on their left side. The noise measurement results for surgeon A were 1.4–5.0 dBA higher on the right side than the left side, with a mean difference of 3.0 dBA. For surgeon B the noise measurement results were 0.2–1.6 dBA higher on the right side than the left side, with a mean difference of 0.9 dBA. Using a two-sided, paired Student's t-test for statistical analysis, we found that results of noise exposure measurements taken on the surgeon's right side using NIOSH REL noise measurement criterion were significantly higher than exposures measured on the left side ($P = 0.04$).

Surgeons' right side noise measurements were most likely higher because both surgeons were right handed and held the powered surgical tools and hammers on their right sides. As a result, their right ears were closer to the noise sources. In contrast, the surgical fellow had higher noise measurements on the left side for the first two surgeries, ranging 2.2–2.9 dBA higher on the left side versus the right side. We noted that sometimes the fellow stood on the surgeon's right side during surgeries; therefore, the left ear was closer to the surgical tools used by the surgeon. In contrast, the fellow's right side measurement during the third surgery was 2.3 dBA higher than the left side measurement.

Figure 1 shows the time history profile for surgeon A on the first day of noise monitoring. The surgeon completed four surgeries during the work shift. Noise levels were above 85 dBA, the NIOSH REL, for a greater proportion of time during the surgeries than during the time outside surgeries. Additionally, noise exposures were sometimes 90–100 dBA during surgeries, and fluctuated substantially because of intermittent surgical tool use. During knee replacements, surgeons used reciprocating saws, drills, and hammers multiple times for periods generally ranging from 1–30 seconds. We measured sound levels approximately 6 feet from the surgeon; those levels ranged from 80–93 dBA when the surgeon or surgical assistant was using saws and hammers. Because sound decreases with distance according to the inverse square law, the sound levels at the surgeon's ear during tool use are likely to be several decibels higher than we measured. Researchers have previously measured noise levels ranging from 90–110 dBA near surgeons during use of reciprocating saws [Dodenhoff 1995; Fritsch et al. 2010; Kamal 1982; Mullett et al. 1999; Nott and West 2003; Willett 1991].

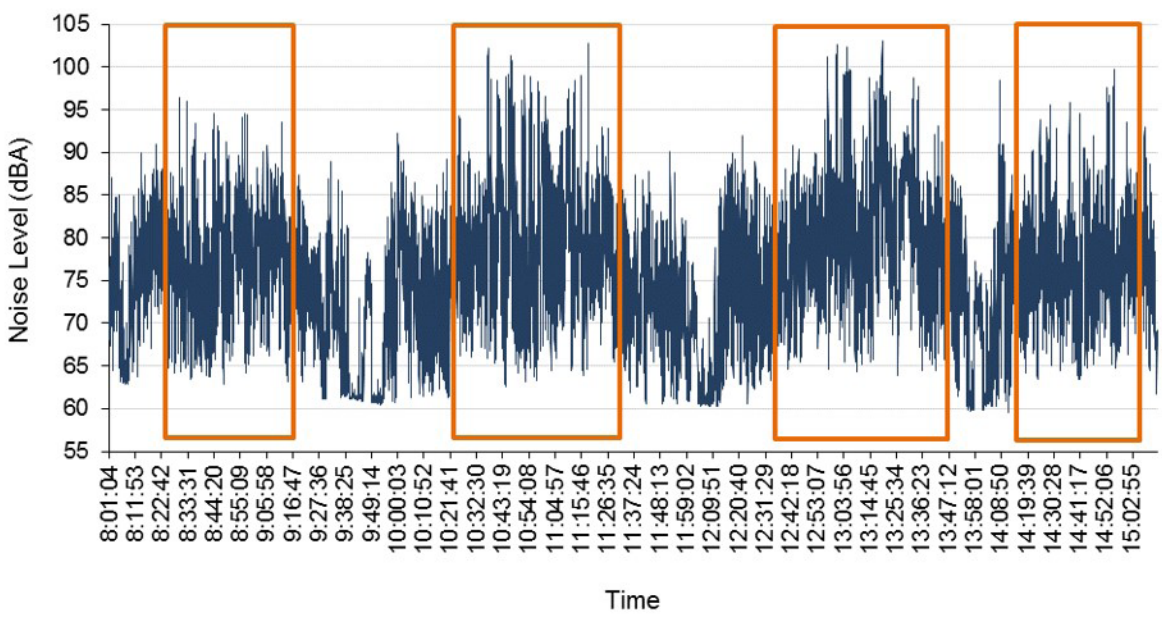

Figure 1. Time history profile showing surgeon A's noise exposure (outlined in boxes in figure) during four knee replacements on January 13, 2015, using NIOSH noise measurement criterion.

Figure 2 provides a histogram showing the surgeons' percent time exposed to various sound levels during surgeries. Most of the time the surgeons' and surgical fellow's noise exposures were below 80 dBA during surgeries. During the two work shifts we monitored, surgeon A's noise exposure was above 85 dBA for 18% of the time on the first day of monitoring and 15% of the time on the second day of monitoring. The surgical fellow and surgeon B spent about 10%–12% of their time during surgeries exposed to sound levels above 85 dBA. Both surgeons and the surgical fellow spent a comparable percent of time (5%–7%) during surgery exposed to noise levels above 90 dBA; this noise was primarily from surgical tools. Similarly, Willett [1991] found that powered instrument use accounted for 4% of the time of an operation. Although powered surgical instrument use comprised only a small proportion of time, it contributed significantly to total noise exposures according to our noise exposure measurements. Overall, the TWA noise measurements for surgeons during surgeries were slightly greater than those reported by Love [2003] in a study of surgeons' noise exposures during total knee and total hip replacements. In that study, noise exposures during total knee replacements were 79.7 and 82.1 dBA.

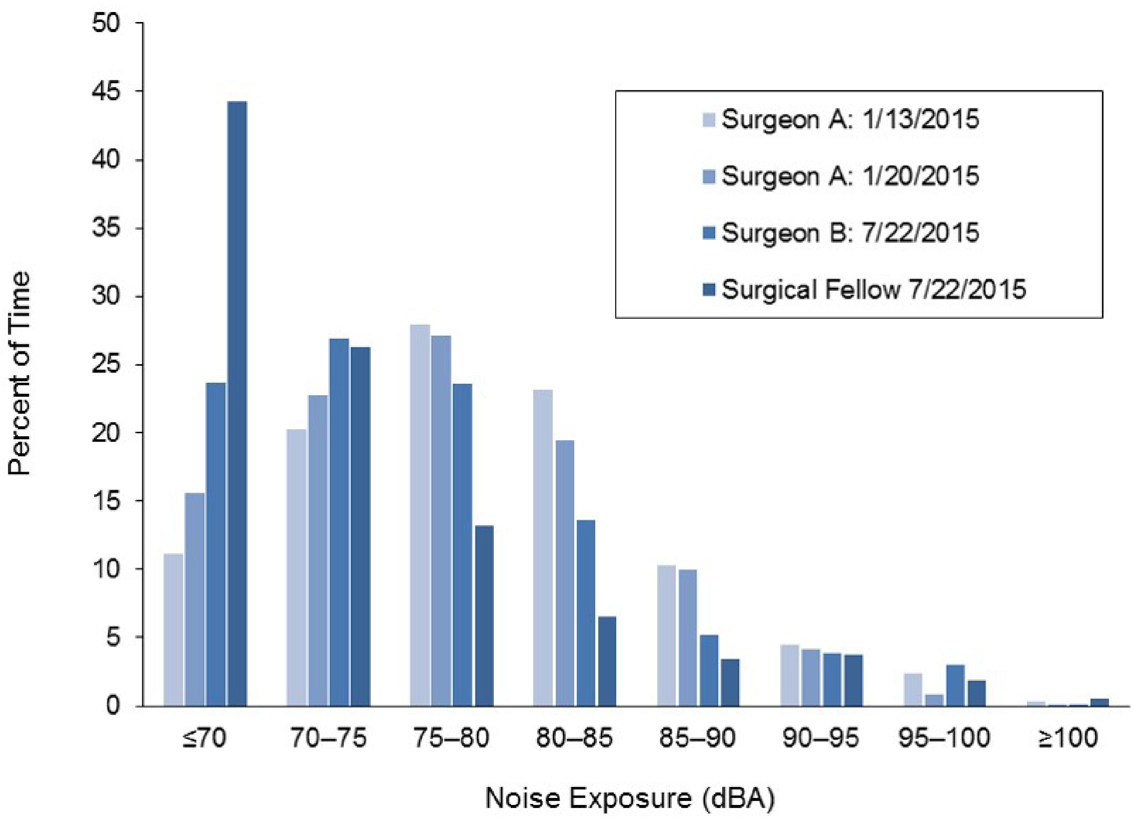

Figure 2. Histogram of the surgeons' and surgical fellow's noise exposures during surgeries.

We computed the surgeons' task-based TWA noise exposures during surgeries and during the time outside surgeries, on the basis of the time they spent in each task. The duration of each surgery ranged from 49–113 minutes and varied with the complexity of each surgery and surgeons' individual techniques. The total time in surgery accounted for 49%–53% of each surgeon or the surgical fellow's 8-hour work shift. Reducing the total time in surgery during a shift of fixed length would reduce TWA noise exposures.

Table 2 shows the task-based range of TWA noise exposure levels during surgeries and during the time outside surgeries. As expected, noise exposures were higher during surgeries than during the time between surgeries. Surgeons have very little exposure to high noise levels outside of surgeries. Surgeon A's noise exposure during surgeries on the first day of monitoring was higher than his exposures on the second day of monitoring, and higher than surgeon B's noise exposures. These differences in noise exposures are most likely related to differences in complexity of the surgeries, tool use, bone densities of patients, length of surgeries, and surgeons' techniques.

Table 2. Surgeons' TWA noise exposures during surgical and nonsurgical periods

		Task duration (minutes)	NIOSH REL criterion (dBA)	OSHA AL criterion (dBA)	OSHA PEL criterion (dBA)
Surgeon A January 13, 2015	Surgery (n = 4)	50–69	86.2–89.2	83.6–86.4	76.8–82.8
	Not in surgery	199	81.6	78.0	66.2
	TWA noise exposure	432	86.8	83.5	78.2
Surgeon A January 20, 2015	Surgery (n = 4)	49–74	81.9–84.0	76.6–80.7	70.6–72.9
	Not in surgery	190	76.2	70.5	48.3
	TWA noise exposure	444	81.4	76.5	68.1
Surgeon B July 22, 2015	Surgery (n = 3)	64–113	84.0–85.3	78.6–79.9	74.9–76.7
	Not in surgery	100	77.5	72.4	53.1
	TWA noise exposure	357	83.8	78.0	74.0
Surgical fellow July 22, 2015	Surgery (n = 3)	64–113	81.3–86.1	74.4–79.0	71.2–77.6
	Not in surgery	140	75.1	68.5	47.1
	TWA noise exposure	397	83.0	75.6	72.5

Noise Exposure Estimates Based on Number of Surgeries

We used the noise exposure data that we collected during our three site visits to model an expected range of surgeons' full-shift TWA noise exposures by shift length, number of surgeries, surgery duration, and noise exposure levels during and outside of surgeries. Figures 3 through 8 show the estimated TWA noise exposure ranges for 8-, 10-, and 12-hour shifts using the shortest and the longest surgery durations we documented and the range of noise exposures we measured during surgeries (on the basis of NIOSH measurement criterion). NIOSH adjusts the REL for longer works shifts. The REL is 84.0 dBA for 10-hour work shifts and 83.2 dBA for 12-hour work shifts. Surgeons' noise exposure levels could exceed the REL, depending on the number, duration, and noise exposure levels during surgeries.

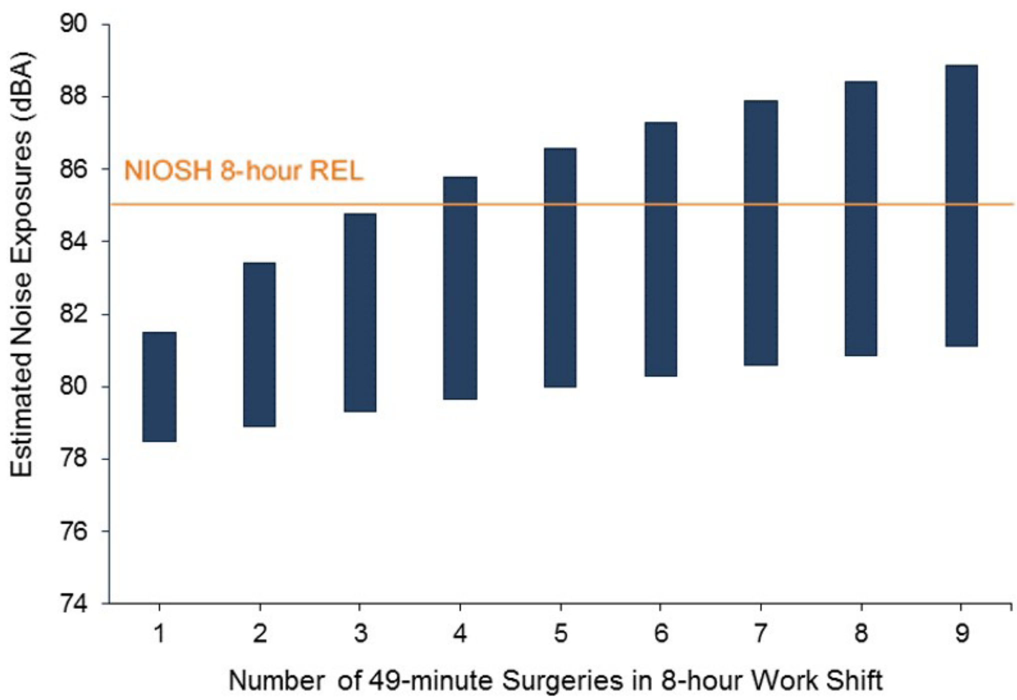

Figure 3. Range of surgeons' estimated noise exposures for an 8-hour work shift on the basis of the range of noise levels during surgeries and number of surgeries with a 49-minute duration.

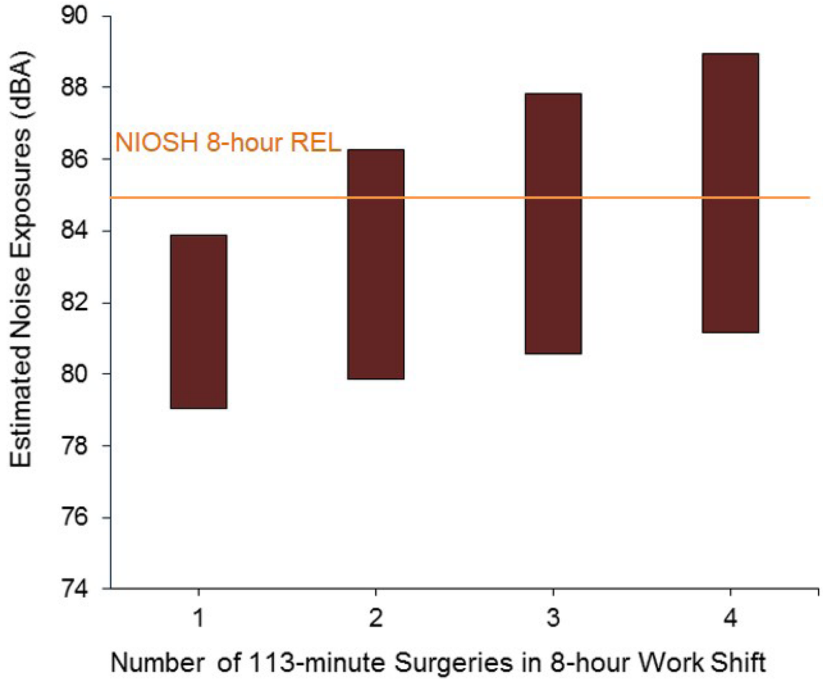

Figure 4. Range of surgeons' estimated noise exposures for an 8-hour work shift on the basis of the range of noise levels during surgeries and number of surgeries with a 113-minute duration.

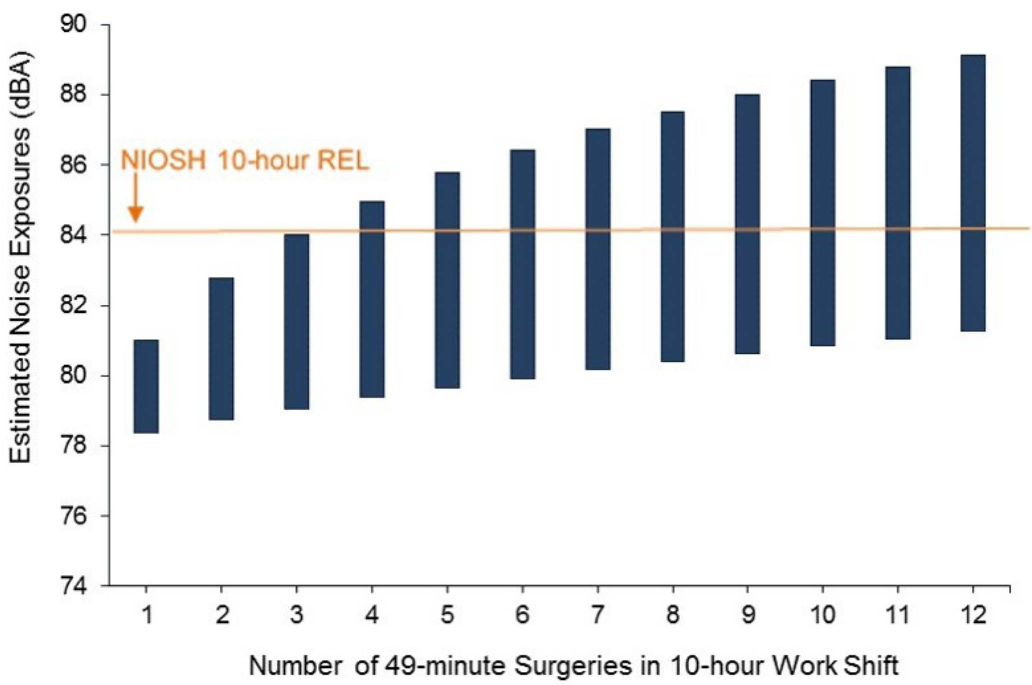

Figure 5. Range of surgeons' estimated noise exposures for a 10-hour work shift on the basis of the range of noise levels during surgeries and number of surgeries with a 49-minute duration.

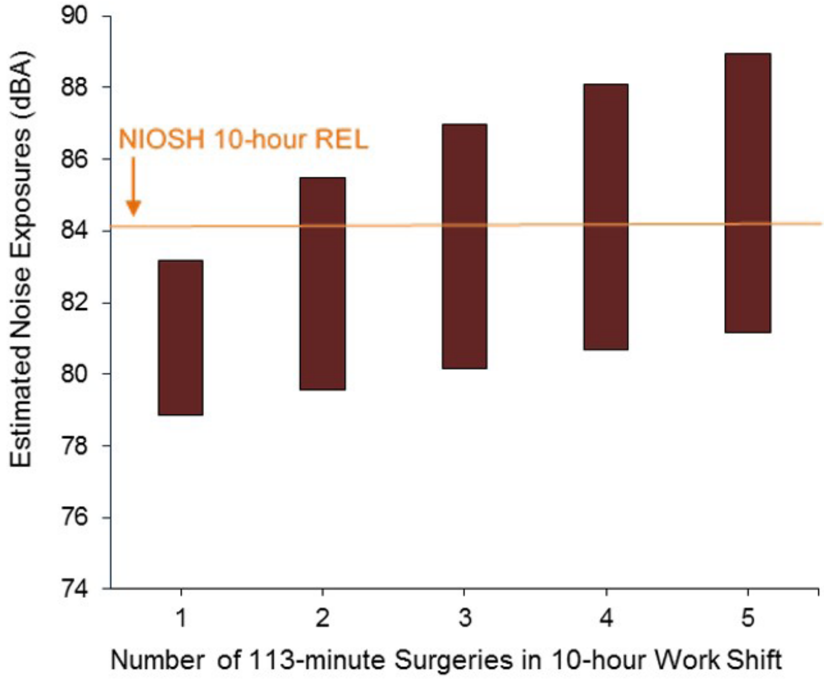

Figure 6. Range of surgeons' estimated noise exposures for a 10-hour work shift on the basis of the range of noise levels during surgeries and number of surgeries with a 113-minute duration.

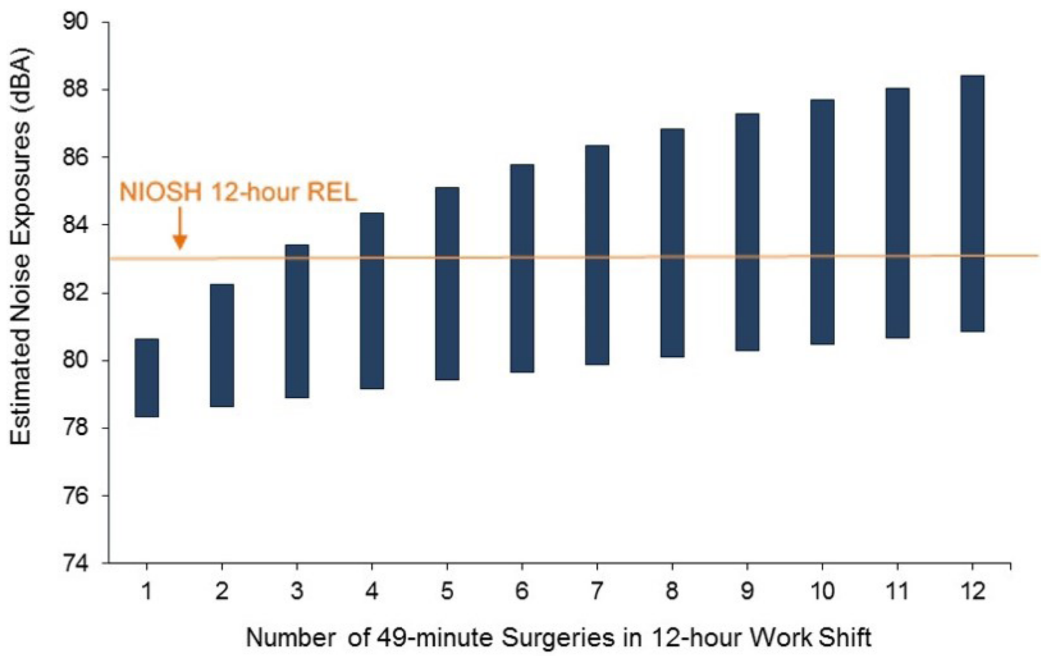

Figure 7. Range of surgeons' estimated noise exposures for a 12-hour work shift on the basis of the range of noise levels during surgeries and number of surgeries with a 49-minute duration.

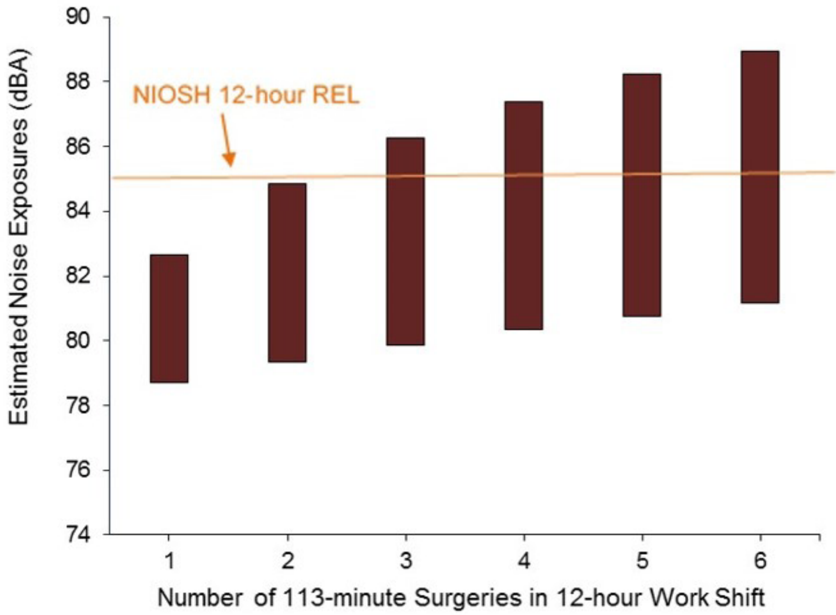

Figure 8. Range of surgeons' estimated noise exposures for a 12-hour work shift on the basis of the range of noise levels during surgeries and number of surgeries with a 113-minute duration.

Noise Exposure and Hearing Loss in Surgeons

With the exception of one TWA full-shift noise measurement, surgeons' noise exposures were below OELs. However, exposures are variable, and our estimate of potential noise exposures show that, at times, noise exposures could exceed the NIOSH REL. NIOSH research has shown that workers exposed to average daily noise levels of 80–85 dBA have a 1%–8% risk of material hearing impairment over a 40-year working lifetime, demonstrating that noise exposure should be limited as possible, even to levels below the REL [NIOSH 1998]. Furthermore, previous studies have shown that up to 50% of orthopedic operating room personnel exposed to noise from powered instruments experienced low-level NIHL, and that the severity correlates with duration of employment [Kamal 1982; Willett 1991].

Because powered surgical tools generate the highest noise levels in the operating room, noise reduction efforts should focus on using surgical instruments that generate the least amount of noise. Research has shown that the saw blade design for reciprocating surgical saws can affect noise levels [Sydney et al. 2007]. A "Buy Quiet" strategy should be used when purchasing or replacing surgical tools or tool components. Specifically, the amount of noise generated by the new equipment should be considered as part of the purchasing decision.

Until noise levels from surgical equipment are reduced, offering and encouraging the use of hearing protection can help protect surgeons from long-term risk of hearing loss. However, hearing protection must be chosen carefully, because hearing protectors that excessively attenuate noise may substantially interfere with vital surgical staff communication or the ability to hear patient monitoring equipment. On the basis of the surgeons' noise exposures and their need for communication, hearing protection that attenuates noise evenly across all frequencies (i.e., flat attenuation earplugs) and has a low noise reduction rating would be an appropriate option. Noise cancellation earmuffs provide another option for hearing protection [Fritch et al. 2010].

Conclusions

Powered surgical tools were the primary sources of noise in the orthopedic operating room and noise levels were highest during surgical procedures. One of the surgeon's personal noise exposure exceeded the NIOSH REL on one of the days we did noise monitoring, but the other personal noise exposure measurements for surgeons and other surgical staff were below all OELs. On the basis of our noise measurements and our estimates of potential noise exposures, surgeons' noise exposures may exceed the NIOSH REL, depending on surgery length, shift length, and number of surgeries in a shift. Surgeons can reduce their risk of hearing loss by using flat attenuation ear plugs or noise cancellation earmuffs.

Recommendations

On the basis of our findings, we recommend the actions listed below. We encourage the hospital to use a labor-management health and safety committee or working group to discuss our recommendations and develop an action plan. Those involved in the work can best set priorities and assess the feasibility of our recommendations for the specific situation at the hospital.

Our recommendations are based on an approach known as the hierarchy of controls. This approach groups actions by their likely effectiveness in reducing or removing hazards. In most cases, the preferred approach is to eliminate hazardous materials or processes and install engineering controls to reduce exposure or shield employees. Until such controls are in place, or if they are not effective or feasible, administrative measures and personal protective equipment may be needed.

Engineering Controls

Engineering controls reduce employees' exposures by removing the hazard from the process or by placing a barrier between the hazard and the employee. Engineering controls protect employees effectively without placing primary responsibility of implementation on the employee.

1. Replace the current blades in the reciprocating surgical saws with blades designed to generate less noise, if available.

Administrative Controls

The term administrative controls refers to employer-dictated work practices and policies to reduce or prevent hazardous exposures. Their effectiveness depends on employer commitment and employee acceptance. Regular monitoring and reinforcement are necessary to ensure that policies and procedures are followed consistently.

1. Ensure that powered surgical tools are operating as quietly as possible and are maintained regularly. A change in volume of an instrument may indicate that the

instrument needs service or replacement.

2. Use a "Buy Quiet" strategy to identify and purchase surgical tools and equipment that generate the least amount of noise. Investigate whether newer models of powered surgical tools or blades, or equipment from other manufacturers produces less noise. Information about Buy Quiet programs can be found at https://www.cdc.gov/niosh/topics/buyquiet/.
3. Reduce the likelihood of surgeons' noise exposures exceeding the NIOSH REL by taking into account the number of surgeries, duration of surgeries, and length of shift when preparing each surgeon's daily surgical schedule.
4. Establish a hearing loss prevention program for orthopedic surgeons. The program should include annual audiometric exams, provide hearing protection, provide training on hearing loss and use of hearing protection, and include periodic noise exposure assessments. For additional information on noise and guidance on developing a hearing loss prevention program, refer to the NIOSH document, Occupational Noise Exposure, at https://www.cdc.gov/niosh/docs/98-126/default.html.
5. Keep the volume of music played in the operating room low to limit background noise and minimize the potential for speech interference.

Personal Protective Equipment

Personal protective equipment is the least effective means for controlling hazardous exposures. Proper use of personal protective equipment requires a comprehensive program and a high level of employee involvement and commitment. The right personal protective equipment must be chosen for each hazard. Supporting programs such as training, change-out schedules, and medical assessment may be needed. Personal protective equipment should not be the sole method for controlling hazardous exposures. Rather, personal protective equipment should be used until effective engineering and administrative controls are in place.

1. Offer and encourage surgeons to use flat attenuation ear plugs or noise cancelling earmuffs during knee replacement surgeries. These types of hearing protectors attenuate noise, but have less effect on speech comprehension.

Appendix A: Occupational Exposure Limits and Health Effects of Noise

NIOSH investigators refer to mandatory (legally enforceable) and recommended OELs for chemical, physical, and biological agents when evaluating workplace hazards. OELs have been developed by federal agencies and safety and health organizations to prevent adverse health effects from workplace exposures. Generally, OELs suggest levels of exposure that most employees may be exposed to for up to 10 hours per day, 40 hours per week, for a working lifetime, without experiencing adverse health effects. However, not all employees will be protected if their exposures are maintained below these levels. Some may have adverse health effects because of individual susceptibility, a pre-existing medical condition, or a hypersensitivity (allergy). In addition, some hazardous substances act in combination with other exposures, with the general environment, or with medications or personal habits of the employee to produce adverse health effects. Most OELs address airborne exposures, but some substances can be absorbed directly through the skin and mucous membranes.

Most OELs are expressed as a TWA exposure. A TWA refers to the average exposure during a normal 8- to 10-hour workday. Some chemical substances and physical agents have recommended short-term exposure limits or ceiling values. Unless otherwise noted, the short-term exposure limit is a 15-minute TWA exposure. It should not be exceeded at any time during a workday. The ceiling limit should not be exceeded at any time.

In the United States, OELs have been established by federal agencies, professional organizations, state and local governments, and other entities. Some OELs are legally enforceable limits; others are recommendations.

- The U.S. Department of Labor OSHA PELs (29 CFR 1910 [general industry]; 29 CFR 1926 [construction industry]; and 29 CFR 1917 [maritime industry]) are legal limits. These limits are enforceable in workplaces covered under the Occupational Safety and Health Act of 1970.
- NIOSH RELs are recommendations based on a critical review of the scientific and technical information and the adequacy of methods to identify and control the hazard. NIOSH RELs are published in the *NIOSH Pocket Guide to Chemical Hazards* [NIOSH 2010b]. NIOSH also recommends risk management practices (e.g., engineering controls, safe work practices, employee education/training, personal protective equipment, and exposure and medical monitoring) to minimize the risk of exposure and adverse health effects.
- Other OELs commonly used and cited in the United States include the threshold limit values (TLVs), which are recommended by the American Conference of Governmental Industrial Hygienists, a professional organization, and the workplace environmental exposure levels (WEELs), which are recommended by the American Industrial Hygiene Association, another professional organization. The TLVs and WEELs are developed by committee members of these associations from a review of the published, peer-reviewed literature. These OELs are not consensus standards. TLVs are considered

voluntary exposure guidelines for use by industrial hygienists and others trained in this discipline "to assist in the control of health hazards" [ACGIH 2016]. WEELs have been established for some chemicals "when no other legal or authoritative limits exist" [AIHA 2016].

Outside the United States, OELs have been established by various agencies and organizations and include legal and recommended limits. The Institut für Arbeitsschutz der Deutschen Gesetzlichen Unfallversicherung (Institute for Occupational Safety and Health of the German Social Accident Insurance) maintains a database of international OELs from European Union member states, Canada (Québec), Japan, Switzerland, and the United States. The database, available at http://www.dguv.de/ifa/GESTIS/GESTIS-Internationale-Grenzwerte-für-chemische-Substanzen-limit-values-for-chemical-agents/index-2.jsp, contains international limits for more than 2,000 hazardous substances and is updated periodically.

OSHA requires an employer to furnish employees a place of employment free from recognized hazards that cause or are likely to cause death or serious physical harm [Occupational Safety and Health Act of 1970 (Public Law 91–596, sec. 5(a)(1))]. This is true in the absence of a specific OEL. It also is important to keep in mind that OELs may not reflect current health-based information.

When multiple OELs exist for a substance or agent, NIOSH investigators generally encourage employers to use the lowest OEL when making risk assessment and risk management decisions. NIOSH investigators also encourage use of the hierarchy of controls approach to eliminate or minimize workplace hazards. This includes, in order of preference, the use of (1) substitution or elimination of the hazardous agent, (2) engineering controls (e.g., local exhaust ventilation, process enclosure, dilution ventilation), (3) administrative controls (e.g., limiting time of exposure, employee training, work practice changes, medical surveillance), and (4) personal protective equipment (e.g., respiratory protection, gloves, eye protection, hearing protection). Control banding, a qualitative risk assessment and risk management tool, is a complementary approach to protecting employee health. Control banding focuses on how broad categories of risk should be managed. Information on control banding is available at http://www.cdc.gov/niosh/topics/ctrlbanding/. This approach can be applied in situations where OELs have not been established or can be used to supplement existing OELs.

Noise

NIHL is an irreversible condition that progresses with noise exposure. It is caused by damage to the nerve cells of the inner ear and, unlike some other types of hearing disorders, cannot be treated medically [Berger et al. 2003]. More than 22 million U.S. workers are estimated to be exposed to workplace noise levels above 85 dBA [Tak et al. 2009]. 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. This excess risk increases to 25% for an average daily noise exposure of 90 dBA [NIOSH 1998]. NIOSH defines material hearing impairment as an average of the hearing threshold levels for both ears that exceeds 25 dB at frequencies of 1,000 Hz, 2000 Hz, 3000 Hz, and 4000 Hz.

Although hearing ability commonly declines with age, exposure to excessive noise can increase the rate of hearing loss. In most cases, NIHL develops slowly from repeated exposure to noise over time, but the progression of hearing loss is typically the greatest during the first several years of noise exposure. NIHL can also result from short duration exposures to high noise levels or even from a single exposure to an impulse noise or a continuous noise, depending on the intensity of the noise and the individual's susceptibility to NIHL [Berger et al. 2003]. Noise exposed workers can develop substantial NIHL before it is clearly recognized. Even mild hearing losses can impair one's ability to understand speech and hear many important sounds. In addition, some people with NIHL also develop "tinnitus." Tinnitus is a condition in which a person perceives hearing sound in one or both ears, but no external sound is present. Persons with tinnitus often describe hearing ringing, hissing, buzzing, whistling, clicking, or chirping like crickets. Tinnitus can be intermittent or continuous and the perceived volume can range from soft to loud. Currently, no cure for tinnitus exists.

The preferred unit for reporting of noise measurements is the decibel, A-weighted. A-weighting is used because it approximates the "equal loudness perception characteristics of human hearing for pure tones relative to a reference of 40 dB at a frequency of 1,000 Hz" and is considered to provide a better estimation of hearing loss risk than using unweighted or other weighting measurements [Earshen 2003]. The dB unit is dimensionless, and it represents the logarithmic ratio of the measured sound pressure level to an arbitrary reference sound pressure (20 micropascals, which is defined as the threshold of normal human hearing at a frequency of 1,000 Hz). Decibels are used because of the very large range of sound pressure levels audible to the human ear. Because the dB is logarithmic, an increase of 3 dB is a doubling of the sound energy, an increase of 10 dB is a 10-fold increase, and an increase of 20 dB is a 100-fold increase in sound energy. Noise exposures expressed in decibels cannot be averaged by taking the arithmetic mean.

Workers exposed to noise should have baseline and yearly hearing tests to evaluate their hearing thresholds and determine whether their hearing has changed over time. Hearing testing should be done in a quiet location, such as an audiometric test booth where background noise does not interfere with accurate measurement of hearing thresholds. In workplace hearing conservation programs, hearing thresholds must be measured at 500 Hz, 1,000 Hz, 2,000 Hz, 3,000 Hz, 4,000 Hz, and 6,000 Hz. Additionally, NIOSH recommends that 8000 Hz should also be tested [NIOSH 1998]. The OSHA hearing conservation standard requires analysis of changes from baseline hearing thresholds to determine if the changes are substantial enough to meet OSHA criteria for a standard threshold shift. OSHA defines a standard threshold shift as a change in hearing threshold relative to the baseline hearing test of an average of 10 dB or more at 2,000 Hz, 3,000 Hz, and 4,000 Hz in either ear [29 CFR 1910.95]. If a standard threshold shift occurs, the company must determine if the hearing loss also meets the requirements to be recorded on the OSHA Form 300 Log of Work-Related Injuries and Illnesses [29 CFR 1904.1]. In contrast to OSHA, NIOSH defines a significant threshold shift as an increase in the hearing threshold level of 15 dB or more, relative to the baseline audiogram, at any test frequency in either ear measured twice in succession [NIOSH 1998].

Hearing test results are often presented in an audiogram, which is a plot of an individual's hearing thresholds (y-axis) at each test frequency (x-axis). Hearing threshold levels are plotted such that fainter sounds are shown at the top of the y-axis, and more intense sounds are plotted below. Typical audiograms show hearing threshold levels from −10 or 0 dB to about 100 dB. Lower frequencies are plotted on the left side of the audiogram, and higher frequencies are plotted on the right. NIHL often manifests itself as a "notch" at 3,000 Hz, 4,000 Hz, or 6000 Hz, depending on the frequency spectrum of the workplace noise and the anatomy of the individual's ear [ACOM 1989; Osguthorpe and Klein 2001; Schlaucha and Carneya 2011; Suter 2002]. A notch in an individual with normal hearing may indicate early onset of NIHL. For health hazard evaluations, a notch is defined as the frequency where the hearing threshold level is preceded by an improvement of at least 10 dB at the previous test frequency and followed by an improvement of at least 5 dB at the next test frequency.

NIOSH has an REL for noise of 85 dBA, as an 8-hour TWA. For calculating exposure limits, NIOSH uses a 3-dB time/intensity trading relationship, or exchange rate. Using this criterion, an employee can be exposed to 88 dBA for no more than 4 hours, 91 dBA for 2 hours, 94 dBA for 1 hour, 97 dBA for 0.5 hours, etc. Exposure to impulsive noise should never exceed 140 dBA. For extended work shifts NIOSH adjusts the REL to 84.5 dBA for a 9-hour shift, 84.0 dBA for a 10-hour shift, 83.6 dBA for an 11-hour shift, and 83.2 dBA for a 12-hour work shift. When noise exposures exceed the REL, NIOSH recommends the use of hearing protection and implementation of a hearing loss prevention program [NIOSH 1998].

The OSHA noise standard specifies a PEL of 90 dBA and an AL of 85 dBA, both as 8-hour TWAs. OSHA uses a less conservative 5-dB exchange rate for calculating the PEL and AL. Using the OSHA criterion, an employee may be exposed to noise levels of 95 dBA for no more than 4 hours, 100 dBA for 2 hours, 105 dBA for 1 hour, 110 dBA for 0.5 hours, etc. Exposure to impulsive or impact noise must not exceed 140 dB peak noise level. OSHA does not adjust the PEL for extended work shifts. However, the AL is adjusted to 84.1 dBA for a 9-hour shift, 83.4 dBA for a 10-hour shift, 82.7 dBA for an 11-hour shift, and 82.1 dBA for a 12-hour work shift. OSHA requires implementation of a hearing conservation program when noise exposures exceed the AL [29 CFR 1910.95].

An employee's daily noise dose, based on the duration and intensity of noise exposure, can be calculated according to the formula: Dose = 100 x (C1/T1 + C2/T2 + ... + Cn/Tn), where Cn indicates the total time of exposure at a specific noise level and Tn indicates the reference exposure duration for which noise at that level becomes hazardous. A noise dose greater than 100% exceeds the noise exposure limit.

To calculate the noise dose using NIOSH criteria, the reference duration (Tn) for each time period must be calculated using the following formula: T (minutes) = 480/2(L−85)/3, where L = the measured noise exposure level for each time period. To calculate noise dose using OSHA criteria, the reference duration (Tn) for each time period must be calculated using a slightly different formula: T (minutes) = 480/2(L−90)/5, where L = the measured noise exposure level for each time period.

Appendix B: Individual Exposure Results

Table B1. Surgical staff time-weighted average personal noise exposure measurement results

Job title	Date	Duration (minutes)	NIOSH REL criterion (dBA)	OSHA AL criterion (dBA)	OSHA PEL criterion (dBA)
Anesthesiologist A	1/13/2015	355	71.8	62.8	46.1
Anesthesiologist B	1/20/2015	476	68.7	58.2	38.4
Surgeon A (right shoulder measurement)	1/13/2015	297*	86.8	83.5	78.2
Surgeon A (left shoulder measurement)	1/13/2015	432	83.2	77.9	71.8
Surgeon A (right shoulder measurement)	1/20/2015	444	81.4	76.5	68.1
Surgeon A (left shoulder measurement)	1/20/2015	444	77.8	71.2	62.6
Surgeon B (right shoulder measurement)	7/22/2016	357	83.8	78.0	74.0
Surgeon B (left shoulder measurement)	7/22/2016	357	82.9	75.9	73.0
Surgical fellow (right shoulder measurement)	7/22/2016	397	81.5	74.3	70.4
Surgical fellow (left shoulder measurement)	7/22/2016	397	83.0	75.6	72.5
Surgical assistant A	1/13/2015	459	78.7	70.8	65.4
Surgical assistant B	1/13/2015	49†	75.3	68.1	52.8
Surgical assistant C	1/20/2015	386	76.0	67.8	58.2
Surgical assistant C (right shoulder measurement)	7/22/2016	465	78.2	64.2	65.4
Surgical assistant C (left shoulder measurement)	7/22/2016	465	71.9	61.3	51.4

*Surgeon did not wear dosimeter on right side until after the first surgery had been completed.

†Dosimeter only operated for 31 minutes at beginning of work shift and 18 minutes at the end of the work shift.

Table B2. Full shift and task-based time-weighted average personal noise exposure measurement results for surgeons

		Surgery time	Duration (min)	Right ear measurement NIOSH REL criterion (dBA)	Left ear measurement NIOSH REL criterion (dBA)	Right ear measurement OSHA AL criterion (dBA)	Left ear measurement OSHA AL criterion (dBA)	Right ear measurement OSHA PEL criterion (dBA)	Left ear measurement OSHA PEL criterion (dBA)
Surgeon A January 13, 2015	Surgery 1	8:25–9:18	56	NA	80.7	NA	76.7	NA	64.6
	Surgery 2	10:23–11:32	69	88.9	86.7	86.1	82.7	82.2	78.9
	Surgery 3	12:50–13:48	58	89.2	87.8	86.4	84.2	82.8	79.9
	Surgery 4	14:14–15:04	50	86.2	81.9	83.6	77.3	76.8	69.4
	No surgery	—	199	81.6	75.7	78.0	69.8	66.2	48.8
	TWA		432	86.8	83.2	83.5	77.9	78.2	71.8
Surgeon A January 20, 2015	Surgery 1	7:56–9:10	74	81.9	80.0	76.6	74.0	70.6	67.5
	Surgery 2	10:17–11:17	60	83.6	81.0	79.9	76.4	71.9	67.0
	Surgery 3	11:50–12:39	49	84.0	78.9	80.7	73.6	72.9	62.5
	Surgery 4	13:27–14:38	71	83.2	79.6	78.8	73.5	72.1	65.4
	No surgery	—	190	76.2	68.7	70.5	59.4	48.3	18.7
	TWA		444	81.4	77.9	76.5	71.3	68.1	62.3
Surgeon B July 22, 2015	Surgery 1	9:07–10:27	80	84.9	83.4	79.2	76.5	76.2	74.4
	Surgery 2	11:16–13:09	113	85.3	85.1	79.9	78.9	76.7	76.4
	Surgery 3	13:41–14:45	64	84.0	83.0	78.6	76.3	74.9	73.7
	No surgery	—	100	77.5	73.3	72.4	66.2	53.1	37.7
	TWA		357	83.8	82.9	78.0	75.9	74.0	73.0
Surgical fellow July 22, 2015	Surgery 1	9:07–10:27	80	83.8	86.1	76.5	79.0	77.6	77.6
	Surgery 2	11:16–13:09	113	81.7	84.6	75.0	78.2	75.7	75.7
	Surgery 3	13:41–14:45	64	83.6	81.3	76.9	74.4	71.2	71.2
	No surgery	—	140	75.8	75.1	69.0	68.5	47.1	47.1
	TWA		397	81.5	83.0	74.2	75.6	70.4	72.5

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