Hearing Loss Among World Trade Center Firefighters and Emergency Medical Service Workers

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Objective: To determine if World Trade Center (WTC) exposure is associated with hearing loss. **Methods:** Logistic regression to evaluate the immediate impact of WTC exposure and parametric survival analysis to assess longitudinal outcomes. **Results:** Those arriving on the morning of September 11, 2001 had elevated odds of low-frequency (odds ratio [OR]: 1.24; 95% confidence interval [CI]: 1.04 to 1.47) and high-frequency (OR: 1.16; 95% CI: 1.02 to 1.31) hearing loss at their first post-September 11, 2001 examination. Longitudinally, participants arriving before September 13, 2001 and spending more than or equal to 6 months at the WTC-site had greater risk of hearing loss in the low frequencies (risk ratio [RR]: 1.31; 95% CI: 1.05 to 1.60) and high frequencies (RR: 1.37; 95% CI: 1.22 to 1.54). By 2016, 3194 (37%) had abnormal hearing sensitivity in either ear and 1751 (20%) in both ears. **Conclusions:** More heavily WTC-exposed workers were at increased risk of hearing loss, and group differences persisted for at least 15 years. Those with abnormal hearing sensitivity may benefit from interventions such as hearing aids and other rehabilitation.

Keywords: hearing conservation, hearing sensitivity, longitudinal hearing loss, occupational exposures, World Trade Center

Nearly 16,000 Fire Department of the City of New York (FDNY) rescue/recovery personnel responded to the terrorist attack on the World Trade Center (WTC). Approximately 2,200 were on site when the twin towers collapsed on the morning of September 11, 2001, and 343 firefighters and emergency medical services workers (EMS) were killed in the disaster.[1] The emergency response transitioned to a rescue/recovery mission that continued for FDNY until July 24, 2002. To date, 200 of these workers have since succumbed to WTC-related illnesses.

Firefighters are routinely exposed to multiple chemical and physical hazards such as noise and heat during regular duties.[2] Excess rates of hearing impairment have been observed in firefighters and EMS,[3–6] although changes in equipment over time and methodological challenges[7] could limit the generalizability of findings from these earlier studies.

Following the WTC disaster, higher rates of hearing difficulty have been self-reported by community members and FDNY rescue/recovery workers exposed to the noise and dust cloud produced by the collapsing towers, but to date we could find no published peer-reviewed, objective measurements after this or any other major disaster.[8–10] The noise environment included the sounds of sirens, impacts from falling debris, and the sounds of the collapsing buildings, which produced seismic vibrations over 2.1 on the Richter scale.[11] During the collapse, atypically high exposures to these hazards can be assumed given the extraordinary circumstances of the WTC tragedy. During recovery operations, exposures were exacerbated by limited enforcement of typical worker safety standards and sub-optimal use of effective personal protective equipment including respirators and hearing protection. Recovery and cleanup operations involved exposures to noises from generators, trucks, heavy equipment, and power tools.

It is known that excessive noise exposure is hazardous to hearing and it is becoming clearer that a metabolic mechanism is most commonly involved in the injury pathway.[12] The metabolic process leading to hearing damage from noise can also be initiated by exposures to some chemical agents, and combined exposures to noise and ototoxic chemical agents can have synergistic deleterious effects.[13] Although the concentrations are unknown, the hazardous constituents of the dust cloud included pulverized building components, including concrete, glass, gypsum, spray-applied fire resistive materials (comprised of Portland cement, mineral glass fibers, asbestos, silicon dioxide),[1] aerosolized jet fuel, and other agents such as lead, cadmium, antimony and polycyclic aromatic hydrocarbons (PAHs) that are known to induce inflammatory responses.[14] In addition to the chemical exposures from the dust cloud on September 11, the remnants that settled over the site were repeatedly

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Clinical significance: Audiometric evidence of increased hearing loss among persons exposed to the World Trade Center (WTC) attacks may inform disaster planning and clinical practice following similar exposures. Given the levels of disproportionate hearing impairment in this cohort, regular auditory surveillance should be considered.
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disturbed during recovery and cleanup operations, some of which was mitigated by the rains on September 14th and water spraying operations thereafter.[15]

Emergency responders need to communicate and coordinate responses, listen for signals from people requiring rescue, and to traverse hazardous environments as safely as possible. Inadequate mitigation of hazards can compromise worker effectiveness, survival, and could lead to premature retirement or mandatory transfer to another work assignment. Hearing impairment also has major impacts on quality of life in non-work settings. Routine audiometric tests on FDNY firefighters and EMS, pre- and post-September 11, present a unique opportunity to determine whether exposures from this event led to increased long-term risk of significant hearing loss. Moreover, given the absence of any large, long-term study of hearing loss following natural or unnatural disasters, our findings should be an important addition to the scientific literature and to disaster-related public health planning. The aims of this study were to evaluate the immediate impact of the WTC collapse on hearing impairment and to determine if an effect persisted over the following 15 years.

METHODS

FDNY Study Population

The base population included 11,627 active-duty male firefighters and EMS who were FDNY employees on September 11, 2001. All participants responded to the WTC-attacks between September 11 and 24, 2001. Participants without audiometric records within 2 years prior to the attacks were excluded to minimize the influence of earlier occupational or environmental exposures. Additionally, study participants had at least one audiogram within 2 years after September 11. The final analytic cohort included 8,623 participants (Fig. 1). Demographic data (age, race/ethnicity, and sex) were obtained from the FDNY employee database. This study was approved by the Institutional Review Board of the Albert Einstein College of Medicine/Montefiore Medical Center (#07–09–320); written informed consent was obtained from all participants.

WTC Exposure Measures

Exposure was characterized jointly on time of initial arrival and the number of months working at the WTC-site, as ascertained at the participants' first post-September 11 medical monitoring examination. Participants reported if they were first present at the WTC-site on the morning of September 11 (considered the highest exposure since they were present during or immediately after the collapse); the afternoon of September 11; September 12; or September 13 through September 24.[16] Participants also reported which months they were present from September through July 2002. Values were assigned representing the number of months in which a participant reported working at the site for more than or equal to 1 day.[16,17] The number of months working at the WTC-site was considered a time-dependent exposure variable and the quantity of months increased every month a participant reported working at the site. After July 2002, when the site closed, the participant's total number of months was used for the rest of follow-up as the measure of duration at the WTC-site.

Audiometric Measurements

The FDNY Bureau of Health Services conducts medical monitoring examinations on its workforce every 12 to 18 months. These examinations include pure-tone threshold audiograms conducted by trained technicians using audiometers calibrated to report thresholds in hearing threshold level (HL) using supra-aural earphones[18] in sound booths meeting the requirements of ANSI S3.1–1999.[19] Thresholds were measured at stimulus frequencies of 0.5, 1, 2, 3, 4, 6, and 8 kHz in 5 dB steps using a modified Hughson-Westlake technique.[20] Data were reviewed for quality assurance. During this review, individual frequencies were flagged if thresholds differed by greater than 40 dB between ears (suggesting signal crossover) or differed by more than 70 dB between neighboring frequencies in the same ear (suggesting an unlikely audiogram slope). Flagged thresholds were removed from all analyses and if thresholds for more than two frequencies were flagged for a given examination, that examination was removed. Examinations were discarded if an electronic data transfer error was suspected (ie, all thresholds recorded were 0 dB HL and the resultant thresholds for that test were markedly inconsistent with other results; if all thresholds were recorded as −10 dB HL; or if more than two thresholds were missing). Any material hearing impairment is defined as recording mean hearing thresholds of at least 20 dB HL for either ear in the 1, 2, 3, and 4 kHz frequencies. Bilateral material hearing loss is defined as requiring both ears to meet the aforementioned criterion.

Statistical Analysis

Trans-9/11 Analyses

The trans-September 11 analyses were conducted to evaluate the extent to which exposures from the collapse of the towers were associated with rapid auditory changes. Pure-tone thresholds from baseline (last pre-September 11 examination 2 years prior to September 11, 2001) were subtracted from the earliest post-September 11 thresholds (at most 2 years after September 11, 2001) for each frequency. A 15-dB or greater threshold increase (ie, worsening) from baseline was defined as the outcome. In a secondary analysis, we required a persistent 5-dB shift from baseline[21] to assess the influence of sporadic changes. Logistic regression was used to evaluate the degree to which arriving at the WTC-site on the morning of September 11 was associated with these outcomes. Neighboring frequencies were combined into sets to establish a more robust marker of hearing impairment than evaluating individual frequencies. The groups included two sets of three-frequency averages (0.5, 1, and 2 kHz; 3, 4, and 6 kHz) and all adjacent frequency pairs (0.5 and 1 kHz, 1 and 2 kHz, etc). In our primary analysis, one such shift qualified as a positive outcome. All models were adjusted for age on September 11, race and class on September 11 (firefighter or EMS). Race (non-Hispanic white, non-Hispanic black, Hispanic, Asian, and other) was dichotomized as non-Hispanic black versus other to be consistent with national reference rates.[22,23]

We also conducted a sensitivity analysis to assess if there was a differing exposure effect for those who had poorer hearing at baseline, we repeated the analyses with each frequency set by comparing those with baseline thresholds 15 dB HL or worse to those with thresholds 15 dB HL or better.

Longitudinal Time-to-Event Analyses

In an unadjusted analysis, baseline median, 10th and 90th percentiles pure-tone thresholds were plotted by frequency (0.5, 1, 2, 3, 4, 6, and 8 kHz) and stratified by ear laterality. We then calculated change from baseline for each successive 3-year time interval, using the last measurement recorded in each period.

Then, to evaluate the association between WTC exposure and longitudinal hearing loss, we fit piecewise exponential time-to-event (ie, survival analysis) models with quarterly increments as the time interval. The goal of this analysis was to test for an exposure–response relationship. Piecewise exponential time-to-event models typically result in similar rate ratios as Cox regression models but have the advantage of permitting rigorous parametric estimation of baseline incidence. More detailed methodology for this approach is outlined by Glaser et al.[24] In these models we also included age at

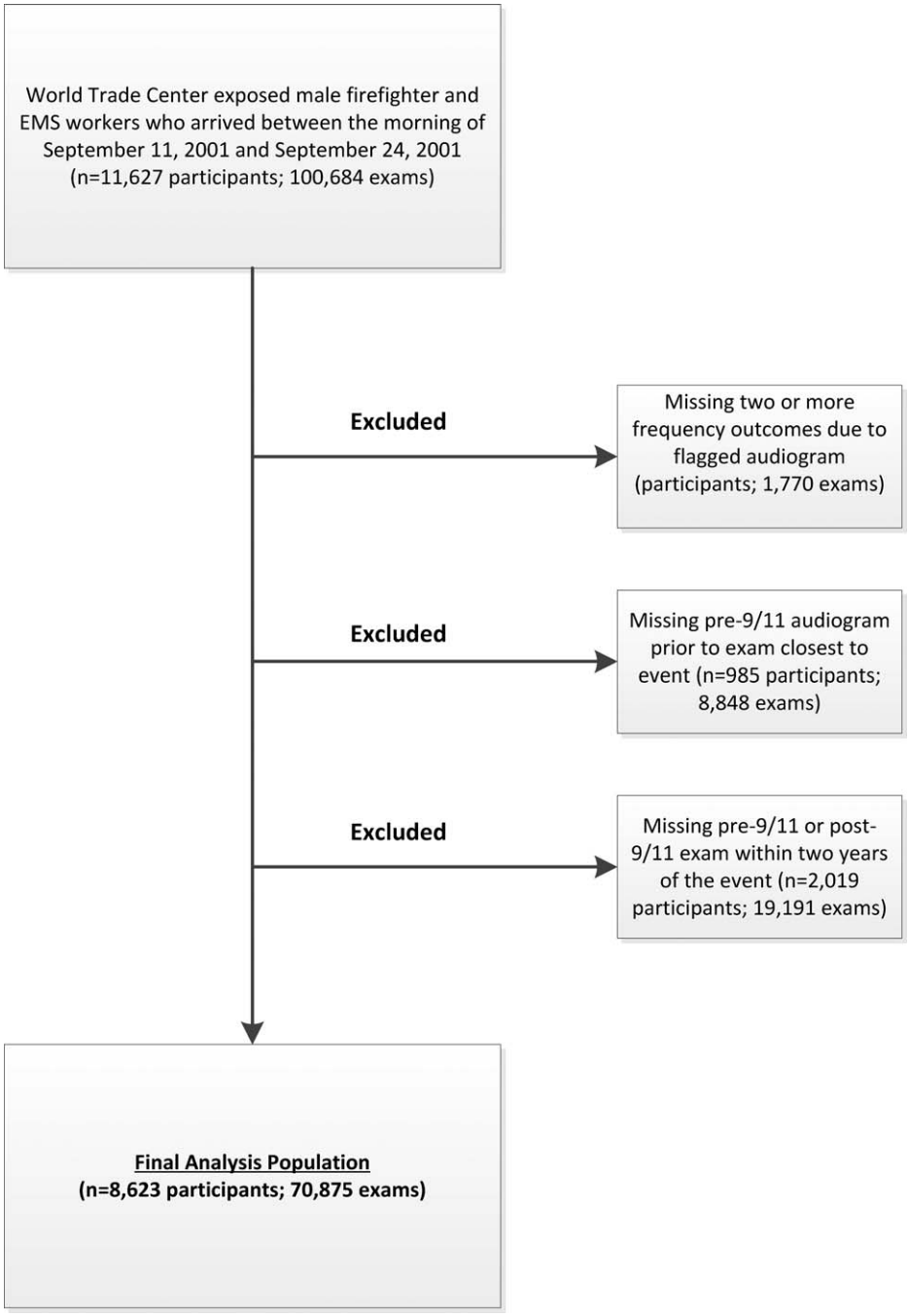


FIGURE 1. Flow of participants into analytic cohort.

the time of audiogram, race/ethnicity (non-Hispanic black vs other), and job title on September 9, 2011 (firefighter vs EMS).

We evaluated both the independent and cumulative effects of arrival time and duration on hearing impairment. For arrival time, those who first arrived at the WTC-site between the morning of September, 11 and September 12 were considered the most highly exposed and those who arrived between September 13 and September 24 the least exposed. For duration, those who spent at least 6 months at the WTC-site were considered to be most highly exposed; 2 to 5 months, moderately exposed; and a maximum of 1 month, the least exposed. When combining these two measures (arrival and duration), there were six levels of exposure intensity, with those who arrived at the WTC-site latest and spent the least amount of time as the referent category.

An event was defined as a 15-dB threshold shift (or greater) from baseline (last pre-September 11 audiogram) that was confirmed on the next test as a 15-dB or greater threshold shift at the same frequency and ear (ie, ''15-dB twice criterion'').[21] Events were then combined into ''low'' (0.5, 1, and 2 kHz) and ''high'' (3, 4, and 6 kHz) frequency sets; if an individual met the definition of an event for more than one frequency within ''low'' or ''high,'' the first event was used in analyses. Each set of events was then evaluated separately. Since medical monitoring examinations began in October 2001, we removed September 2001 from baseline hazard

calculations. Individuals were censored at their final examination prior to September 11, 2016.

To assess the impact of potential loss to follow-up in the last few years of the study, we performed sensitivity analyses, censoring outcomes at an artificial end of study date of September, 2012 for comparison with the results obtained through September, 2016. We also conducted a sensitivity analysis in which we stratified models used in the primary analysis by those who, at baseline, recorded 15 dB or greater at any frequency versus those who recorded less than 15 dB on all frequencies. SAS version 9.4 (SAS Institute, Cary, NC) was used for all analyses.

RESULTS

Cohort Characteristics

About 95% of the cohort was a race other than non-Hispanic black, with the vast majority white. Most participants were firefighters on September 11 (85%) and were active-duty employees at their final examination (72%). Among firefighters and EMS, average total years of service as an FDNY employee was 22 and 20 years, respectively. The mean age on September 11 was 40 years for firefighters and 36 years for EMS. At baseline, pre-9/11, the preponderance (89%; $n = 7{,}640$) of participants had mean hearing thresholds (1, 2, 3, 4 kHz) better than 20 dB HL in both ears, indicating hearing sensitivity generally within normal limits. This percentage declined to 63% ($n = 5{,}429$) at the final audiometric examination. Conversely, the proportion of bilateral hearing impairment increased from 4% ($n = 334$) at baseline to 20% ($n = 1{,}751$) at the final examination. Other demographic characteristics are presented in Table 1.

Baseline audiometric examinations revealed median hearing threshold levels consistent with good hearing sensitivity at stimulus frequencies through 2 kHz and, at most, a slight hearing impairment at higher stimulus frequencies (Fig. 2A). The distributions of hearing threshold levels around the median were asymmetric, with approximately 10% of participants having baseline thresholds around 20 dB HL at stimulus frequencies of 2 kHz and below and 35 to 40 dB HL at 4 and 6 kHz.

Changes in hearing sensitivity, calculated by subtracting subsequent hearing thresholds from baseline thresholds, were examined in 3-year intervals, beginning with the 2002 to 2004 interval (Fig. 2). Subtle changes were observed during the 2002 to 2004 interval, with median changes of 0 dB and 10th to 90th percentile ranges extending from ±10 dB through 2 kHz and from −20 to +25 dB at 4 and 6 kHz and intermediate values at 3 and 8 kHz (Fig. 2B).

The asymmetry in the distribution of changes from baseline in the direction of worse hearing progressed through follow-up period. Median changes at and below the 2 kHz stimulus frequency remained at 0 dB throughout the follow-up period, and the distribution of differences around the median indicated a compressed range of observations in the direction of better hearing (−5 to −10 dB) and an expanded range of observations above the median (15 to 20 dB), indicating an increased likelihood of declines in hearing sensitivity. A similar but larger trend was observed at stimulus frequencies above 2 kHz, with improvements from baseline in the −5 to −10 dB range and apparent decrements from baseline in the 30 to 50 dB range (Fig. 2C through F).

Trans-September 11 Analyses

When the outcome of a single 15-dB shift was evaluated, comparing those who arrived on the morning of September 11 to those who arrived later, odds ratios (OR) were 1.24 (95% CI: 1.04 to 1.47; P-value = 0.02) for low frequencies (0.5, 1, and 2 kHz) and 1.16 (95% CI: 1.02 to 1.31; P-value = 0.02) for high frequencies (3, 4, 6 kHz) (Fig. 3) in logistic regression models also including age, race/ethnicity, and occupational group. For the first sensitivity analysis, which required a confirmatory 5-dB

TABLE 1. Selected Demographic Characteristics

	Arrival Time to the World Trade Center (WTC) Site				
	Morning of 9/11 ($n = 1{,}484$)	**Afternoon of 9/11 ($n = 4{,}334$)**	**9/12 ($n = 1{,}493$)**	**9/13–9/24 ($n = 1{,}312$)**	**Total ($n = 8{,}623$)**
Race/Ethnicity (n, %)					
Non-Hispanic black	87 (5.86)	150 (3.46)	63 (4.22)	114 (8.69)	414 (4.80)
Other races*	1,397 (94.14)	4,184 (96.54)	1,430 (95.78)	1,198 (91.31)	8,209 (95.20)
Work assignment on 9/11/01 (n, %)					
Firefighter	1,180 (79.51)	3,919 (90.42)	1,318 (88.28)	943 (71.88)	7,360 (85.35)
EMS†	304 (20.49)	415 (9.58)	175 (11.72)	369 (28.12)	1,263 (14.65)
Retirement status at final examination (n, %)					
Active	1,026 (69.14)	3,113 (71.83)	1,083 (72.54)	956 (72.87)	6,178 (71.65)
Retired	458 (30.86)	1,221 (28.17)	410 (27.46)	356 (27.13)	2,445 (28.35)
Total duration at WTC site (n, %)					
1 month	468 (31.54)	1,145 (26.42)	426 (28.53)	430 (32.77)	2,469 (28.63)
2–5 months	601 (40.50)	2,036 (46.98)	743 (49.77)	669 (50.99)	4,049 (46.96)
6–10 months	415 (27.96)	1,153 (26.60)	324 (21.70)	213 (16.23)	2,105 (24.41)
Other characteristics (mean ± SD)					
Age at final examination	49.05 ± 6.98	49.62 ± 6.76	49.69 ± 6.81	49.93 ± 7.39	49.58 ± 6.91
Age on 9/11/01	39.38 ± 7.51	39.48 ± 7.55	39.74 ± 7.39	40.22 ± 8.27	39.62 ± 7.64
Number of examinations	8.05 ± 3.98	8.26 ± 3.82	8.10 ± 3.81	8.43 ± 4.27	8.22 ± 3.92
Years of follow-up	9.67 ± 4.06	10.14 ± 3.97	9.95 ± 4.06	9.71 ± 4.27	9.96 ± 4.05
Person-time in years (low frequencies)	8.69 ± 4.57	9.10 ± 4.51	8.99 ± 4.55	8.88 ± 4.70	8.97 ± 4.56
Person-time in years (high frequencies)	6.33 ± 4.43	6.55 ± 4.41	6.31 ± 4.34	6.55 ± 4.56	6.47 ± 4.43

*Includes non-Hispanic white ($n = 7{,}634$), Hispanic ($n = 414$), Asian ($n = 41$), and other ($n = 7$).
†Emergency medical services workers.

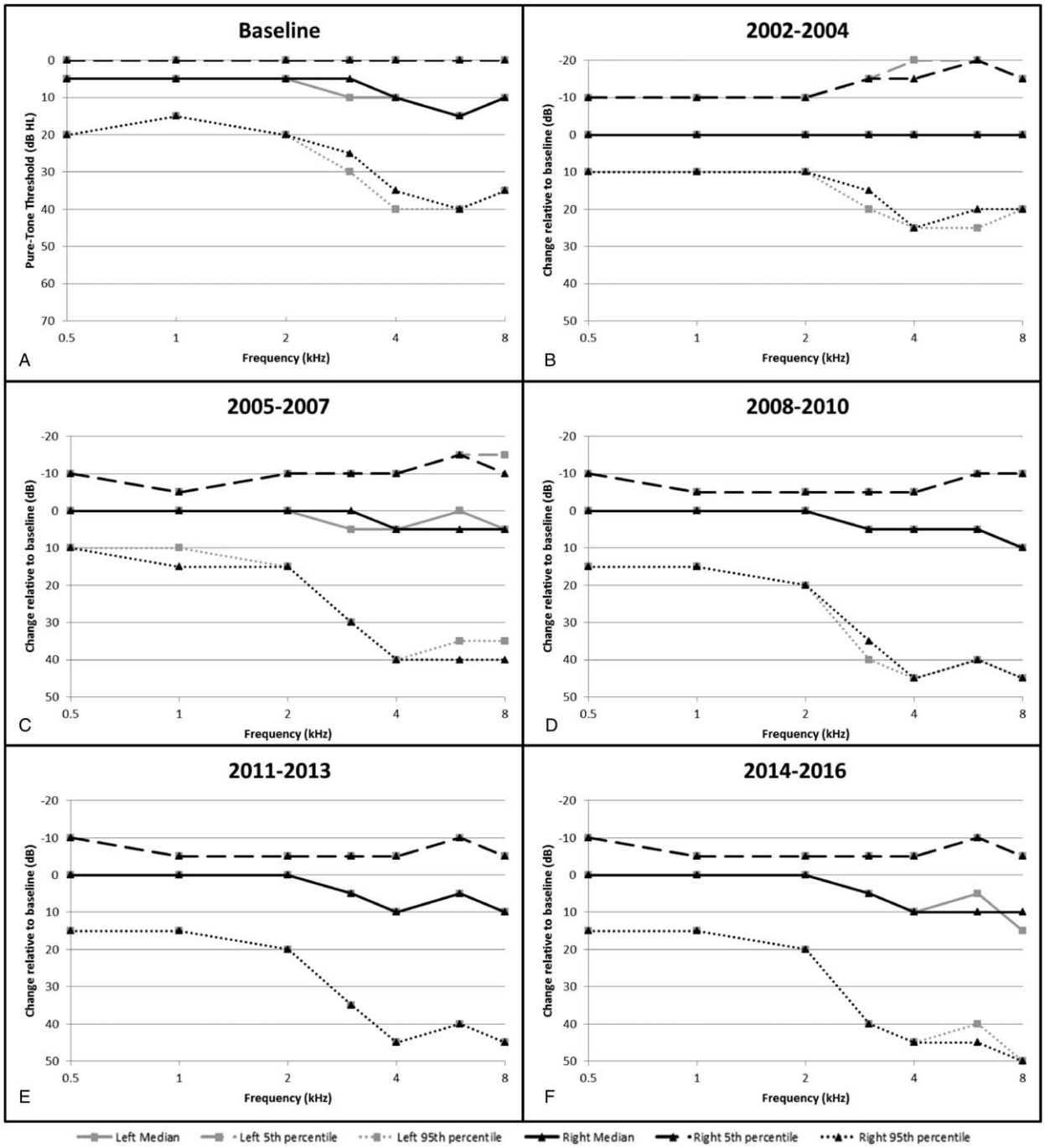


FIGURE 2. Baseline pure-tone thresholds (db HL) by frequency (hHz) and changes relative to baseline in 3 years increments. A. Thresholds at baseline (ie, before September 11, 2001). B. Change in thresholds from baseline to 2002 to 2004. C. Change in thresholds from baseline to 2005 to 2007. D. Change in thresholds from baseline to 2008 to 2010. E. Change in thresholds from baseline to 2011 to 2013. F. Change in thresholds from baseline to 2014 to 2016. Grey lines and squares correspond with the left ear; black lines and triangles correspond with right ear. Patterns describing the median and 5th/95th percentiles are described below the figure.

threshold shift after the initial 15-dB threshold shift, ORs were similar (OR = 1.13 [95% CI: 0.99 to 1.30; *P*-value = 0.07] and 1.29 [95% CI: 1.06 to 1.57; *P*-value = 0.01] for high and low, respectively). In a second sensitivity analysis comparing those who recorded thresholds of 15 dB or greater at baseline to those with no impairment revealed no obvious differences, indicating that the observed effect was not driven by regression to the mean.

Longitudinal Time-to-Event Analyses

Results from the time-to-event models for both low and high frequencies are presented in Fig. 4. Among 8,623 participants in the

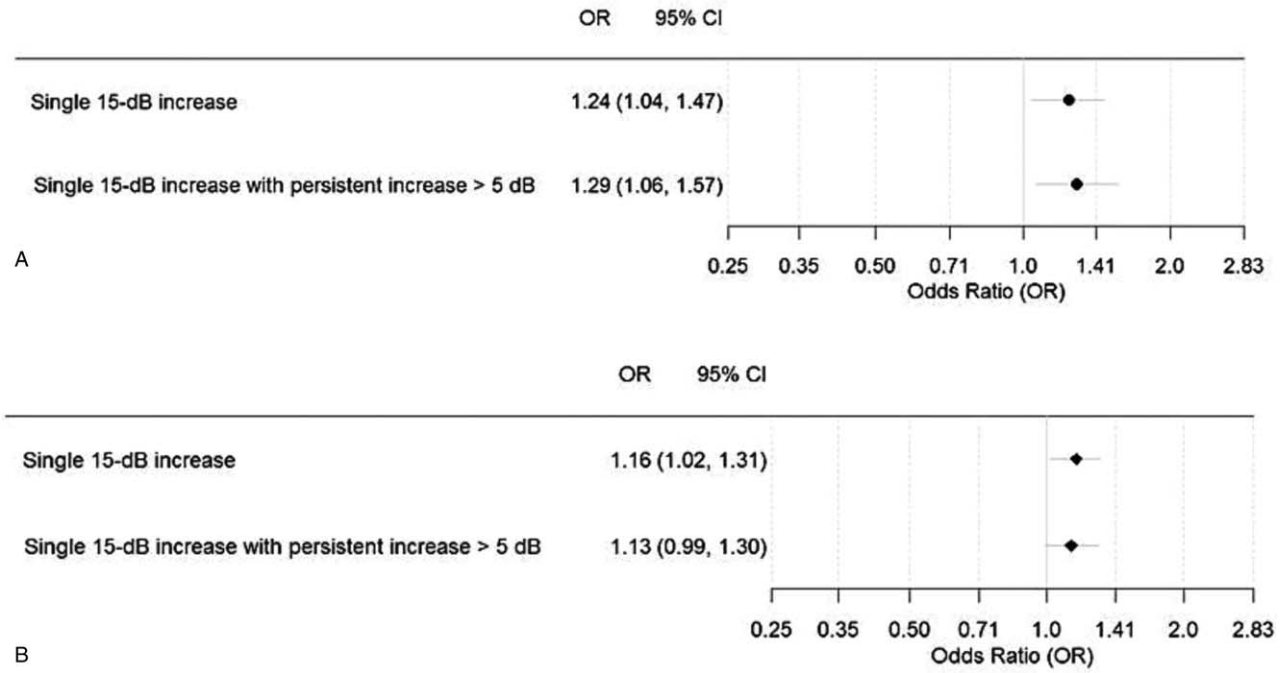


FIGURE 3. Logistic regression evaluating the association of WTC-exposure and hearing loss directly after September 11, 2001 to Trans-September 11 analysis ($N = 8{,}623$). Low frequencies (0.5, 1, and 2 kHz). High frequencies (3, 4, and 6 kHz). These models adjust for age on September 11, 2001, non-Hispanic black race, and work assignment on September 11, 2001.

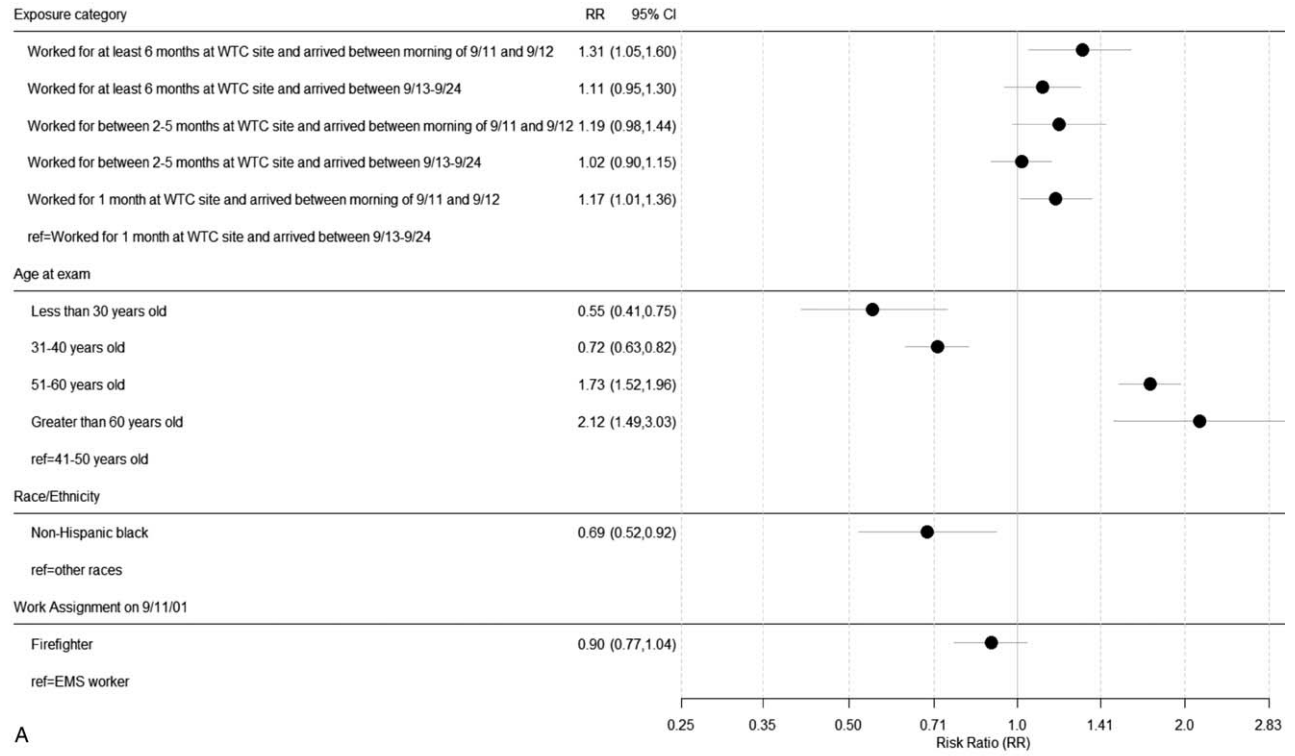
final analytic cohort, there were 1,524 (18%) events in the low frequency set during the first 15 years of follow-up. The most highly exposed group had an elevated risk of incident hearing loss (risk ratio [RR] = 1.31; 95% CI: 1.05 to 1.60; P-value = 0.01) in the low frequencies. In the high frequency set, there were 4,740 (55%) events during the first 15 years of follow-up, and the most highly exposed group was also more likely to have an event compared with the least exposed (RR = 1.37; 95% CI: 1.22 to 1.54; P-value < 0.01). The effect of WTC initial arrival time was more noticeable in the low frequencies, and WTC duration effects were most noticeable in the high frequencies. As expected, age at time of examination was positively related to hearing threshold shift events, and non-Hispanic Black race/ethnicity was protective against hearing threshold shift events for both frequency sets. Firefighters on September 11 had a slightly elevated risk of incident hearing loss when compared with EMS for the high frequency set, only (RR = 1.10; 95% CI: 1.00 to 1.20; P-value = 0.04). Sensitivity analyses did not reveal important differences from the results presented in Fig. 4, indicating that these findings are robust to baseline hearing sensitivity and increased loss to follow-up in later years (2012 to 2016).

DISCUSSION

FDNY responders with high levels of exposure to the WTC rescue/recovery operations were at greater risk of reductions in hearing sensitivity. Increased odds of reduced hearing sensitivity were observed during the 2-year period immediately following the disaster, and time-to-event analyses revealed that WTC exposures increased the risk of persistent reductions in hearing sensitivity over the subsequent 15 years, even after adjusting for aging. Participants arriving on the morning of the WTC disaster had greater odds of significant hearing loss during the 2 years following the event, and those who arrived earlier and were exposed to the WTC-site for longer periods had a greater risk of decreased hearing sensitivity in the long-term. Further, by the end of follow-up, 3,194 (37%) study participants had abnormal hearing sensitivity, indicated by hearing thresholds consistent with an increased risk of self-reported hearing difficulty (ie, average thresholds worse than 20 dB HL in either ear). Additionally, over half of the 3,194 and 20% of the overall study population had bilateral hearing impairment. Some of these participants may benefit from interventions such as hearing aids and other rehabilitation.

The presence of significant declines in hearing sensitivity in both low and high frequency sets is inconsistent with effects solely due to noise exposure, which would be expected to affect only the high-frequency set.[25] In addition to noise, particulate matter, solvents, and metal fumes were present at the WTC-site during both the rescue and recovery operations, and reductions in low-frequency hearing sensitivity could be associated with exposure to these agents. It remains unclear whether the elevated risk is an acceleration of sensorineural impairment[6] or due to an increased risk of middle ear disorders accompanying the increased risk of upper respiratory inflammation (chronic rhinosinusitis) documented in this population.[26,27] This warrants further exploration in future work. Although additional analyses of current data can provide limited insight, the assessment of middle ear immittance via tympanometry or wideband absorbance[28] would be a valuable adjunct to pure-tone threshold audiometry in future studies.

One limitation of the current study is that these results could have been biased toward the null due to the lack of an unexposed comparison group and the coarse measurement of exposure duration. Nearly all FDNY firefighters and EMS were engaged in rescue/recovery operations at the WTC-site and therefore, even the reference group still had some level of WTC exposure.[16] Duration of work at the site was calculated based on which months the participant reported being at the site. The amount of time spent on site during each month was not ascertained. Finally, we observed trends toward declining hearing sensitivity that were not uniform across participants (Fig. 2). The interpretation of these results must be tempered by the complexities of longitudinal observations with



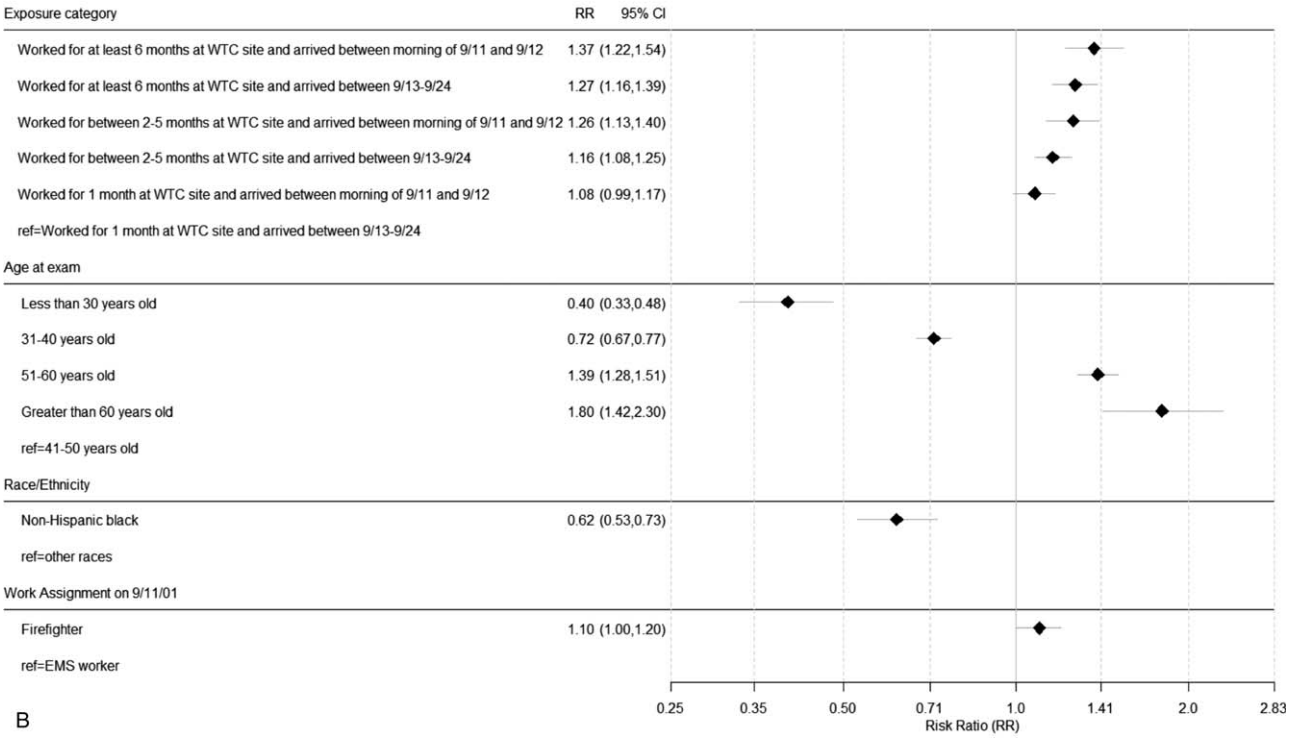


FIGURE 4. Survival analysis evaluating the longitudinal association between WTC-exposure and noise induced hearing loss in the first 15 years after September 11 ($N = 8,623$). Low frequencies (0.5, 1, and 2 kHz). High frequencies (3, 4, and 6 kHz).

humans. Examination intervals varied across participants, and cumulative attrition yielded declining sample sizes over time. Further, it is reasonable to assume that attrition did not occur at random and could have been influenced by factors associated with the exposure (eg, retirement, disability, morbidity, and mortality). Time-to-event analyses, also known as survival analyses, are robust to these complexities and were used to examine the association between exposures and hearing outcomes. We believe these limitations would reduce effect sizes, indicating that the observed effects are underestimates.

Despite these limitations, this is the first longitudinal study to analyze audiometric measurements in WTC-exposed first responders or for that matter after any large-scale disaster. Additionally, our measurements included pre- and post-WTC exposure audiometry enabling us to determine the association with hearing using pre-exposure hearing levels as baseline. Finally, our outcome measures were well-defined, credible and generalizable, and were informed by NIOSH recommendations.[21]

These findings provide audiometric evidence that supports reports of increased hearing difficulty by workers and community members exposed to the WTC disaster.[8–10] Although the opportunity to conduct extensive audiometric monitoring of additional groups has passed, the current study demonstrates the importance of hearing conservation programs in this worker group. It also illustrates the need to include exposure assessment, risk mitigation (eg, engineering and administrative controls, personal protective equipment) and health monitoring of exposed persons in disaster plans. Furthermore, health monitoring, including audiometry, should extend well beyond the end of recovery operations and should be regularly evaluated to optimize early detection and for those with significant hearing loss, intervention.

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