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ARTICLE

Comparison of a Personalized Parent Voice Smoke Alarm With a Conventional Residential Tone Smoke Alarm for Awakening Children

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ABSTRACT

BACKGROUND. Conventional residential tone smoke alarms fail to awaken the majority of children during slow wave sleep. With the objective of identifying a more effective smoke alarm for children, we compared a personalized parent voice smoke alarm with a conventional residential tone smoke alarm, both presented at 100 dB, with respect to their ability to awaken children 6- to 12-years-old from stage 4 sleep and prompt their performance of a simulated self-rescue escape procedure.

METHODS. Using a randomized, nonblinded, clinical research design, a volunteer sample of healthy children 6- to 12-years-old was enrolled in the study. Children were trained how to perform a simulated self-rescue escape procedure when they heard a smoke alarm. Each child's mother recorded a voice alarm message, "First name! First name! Wake up! Get out of bed! Leave the room!" For each child, either the voice or tone smoke alarm was randomly selected and triggered during the first cycle of stage 4 sleep, and then the other alarm was triggered during the second cycle of stage 4 sleep. Children's sleep stage was monitored by electroencephalography, electro-oculography, and chin electromyography. The 4 main outcome measures included the number of children who awakened, the number of children who escaped, the time to awakening, and the time to escape.

RESULTS. Twenty-four children were enrolled. The median age was 9 years, and 11 (46%) were boys. One half of the children received the parent voice alarm first, and one half received the tone alarm first; however, the order that the alarm stimuli were presented was not statistically associated with awakening or escaping. Twenty-three (96%) of the 24 subjects awakened to the parent voice alarm compared with 14 (58%) to the tone alarm. One child did not awaken to either stimulus. Nine children awakened to their parent's voice but not to the tone, whereas none awakened to only the tone and not the voice. Twenty (83%) of the subjects in the parent voice alarm group successfully performed the escape pro-

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Key Words
fire, smoke alarm, sleep, children, injury, trauma, prevention

Abbreviations
S4—stage 4 sleep
EEG—electroencephalography
REM—rapid eye movement
SWS—slow wave sleep

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cedure within 5 minutes of alarm onset compared with 9 (38%) in the tone alarm group. The median time to awaken was 20 seconds in the voice alarm group compared with 3 minutes in the tone alarm group. The median time to escape was 38 seconds in the voice alarm group compared with the maximum allowed 5 minutes in the tone alarm group. When exposed to the tone alarm, older children were more likely to awaken and were more likely to escape than younger children. There was no association between child's age and awakening or escaping for children exposed to the parent voice alarm. There was no association between child's gender and awakening or escaping for either alarm type.

CONCLUSIONS. To our knowledge, this study is the first to compare the ability of different types of smoke alarms to awaken children while monitoring sleep stage. The personalized parent voice smoke alarm at 100 dB successfully awakened 96% of children 6- to 12-years-old from stage 4 sleep with 83% successfully performing a simulated self-rescue escape procedure, significantly outperforming the 100-dB conventional residential tone smoke alarm. These findings suggest a clear direction for future research, as well as important fundamental changes in smoke alarm design, that address the unique developmental needs of children. The development of a more effective smoke alarm for use in homes and other locations where children sleep provides an opportunity to reduce fire-related morbidity and mortality among children.

BEING ASLEEP AT the time of a residential fire is an important risk factor for fire-related death. Approximately half of residential fire deaths occur at night, with the victims asleep at the time of the fire.[1] Even in daytime fires, many deaths occur as a result of the victim being asleep at the time of the emergency.[2] Indeed, being asleep at the time of a residential fire is a greater risk factor for fire-related mortality than time of day.[3] An important factor contributing to fire-related death and disability among children is that children usually do not awaken to conventional residential smoke alarms.[4,5] Auditory smoke alarms are a core component of the current national public health strategy to prevent residential fire-related mortality and morbidity. To be effective, smoke alarms must be capable of consistently awakening sleeping individuals and signaling the existence of a fire/smoke emergency to them, requiring rapid escape. However, auditory arousal thresholds are age dependent, and children can be remarkably resistant to awakening by sound when asleep.[5] Although home fire safety professionals have expressed significant concerns regarding the ineffectiveness of conventional smoke alarms for sleeping children, relatively little research has been done on this important issue.[6] Moreover, the research that has been completed has not considered important information, such as stage of sleep.[7–9]

Previous studies suggest that mother's voice[10–14] and the sound of one's own first name[15–25] elicit a differential human response as early as infancy and, therefore, may be more effective than other sounds at awakening children. We compared a personalized parent voice smoke alarm with a conventional residential tone smoke alarm, with respect to their ability to awaken children 6- to 12-years-old from stage 4 sleep (S4) and prompt performance of a simulated self-rescue escape procedure. We compared these smoke alarm stimuli while monitoring children's sleep stage, which is a critically important methodologic approach that no other research team, to our knowledge, has attempted. The findings of this study will contribute to the development of a more effective smoke alarm for use in homes and other locations where children sleep, which will provide an opportunity to reduce fire-related morbidity and mortality among children.

METHODS

The comparative effectiveness of a personalized parent voice smoke alarm and a conventional residential tone smoke alarm to awaken children 6- to 12-years-old from S4 and prompt their escape was evaluated using a randomized, nonblinded, clinical research design. Children 6- to 12-years-old, who were sons or daughters of Columbus Children's Hospital employees or who were patients receiving primary care in 1 of the 9 primary care clinics of Children's Hospital, were eligible for enrollment in this study. One e-mail to hospital employees and word-of-mouth yielded the 24 children, who served as subjects in this study, without the need for other methods of recruitment. Complete eligibility criteria are found in Table 1.

The children were trained how to perform a simulated self-rescue escape procedure when they heard either of the 2 types of smoke alarms. This procedure was to get out of bed, walk to the door of the room, open the

TABLE 1 **Study Subject Eligibility Criteria**

Child is ≥6 years of age and has not yet had his/her 13th birthday.
Child is son or daughter of a Columbus Children's Hospital employee or receives primary care in a Columbus Children's Hospital primary care clinic.
Child does not have a clinical diagnosis that may affect sleep, arousal or ability to perform the escape procedure.
Child does not have a hearing impairment.
Child is not taking medication that may affect sleep, arousal, or ability to perform the escape procedure.
Child does not have an acute illness at the time of the sleep study.
Child and child's caretaker speak English (2000 US Census data indicate that <5% of the population >5 years of age in Franklin County speaks English less than "very well").
Family is able to be contacted by telephone (to obtain prestudy information, to remind family about study appointment, and to confirm that the child is in normal state of health on day of study).

door, and exit. Children then practiced this procedure until they demonstrated that they could do it correctly twice in a row. Each child's mother recorded a voice alarm message using the child's first name (ie, "First name! First name! Wake up! Get out of bed! Leave the room!"). The tone alarm stimulus was a recording of a smoke alarm meeting current National Fire Protection Association (NFPA 72–11, National Fire Alarm Code, chapter 11) smoke alarm standards.[26] Children slept in 1 of 4 comfortably furnished hospital rooms that were wired for the study and set up with 2 beds. The second bed was for the parent's use if having the parent in the same room allowed the child to fall asleep more easily. Parents were provided with earplugs and were instructed not to interact with the child after an alarm was triggered. Parents were told ahead of time that the child could bring a favorite pillow, stuffed animal, or other transitional object to the sleep study if he/she desired. Families arrived at the sleep laboratory at 7 PM, and "lights out" typically occurred at 9 to 10 PM, depending on the child's sleepiness and normal bedtime. Electroencephalography (EEG), electro-oculography, and chin electromyography electrodes were applied to each subject by an EEG technician to monitor the child's stage of sleep, and once "lights out" occurred, continuous monitoring was conducted. The EEG montage included the C3, C4, O1, O2, A1, and A2 electrodes.

Children were allowed to go to sleep and be in S4 for 5 minutes before an alarm was triggered. S4 is defined as high voltage (>75 μV), slow wave (<2 cycles/second) EEG activity accounting for $>50\%$ of a 30-second EEG epoch. For each child, 1 of the 2 smoke alarm stimuli was randomly selected and triggered during the first cycle of S4. After awakening, the child was resettled in bed and allowed to fall asleep again, and then the other alarm stimulus was triggered during the second cycle of S4. Both alarms were sounded at 100 dB until the child escaped from the room or for a maximum of 5 minutes if the child did not complete the escape procedure. Any child who did not awaken after 5 minutes of the alarm was manually awakened by a study staff member and the parent. A child was defined as awake based on the EEG tracing.

When the alarm was triggered, a stopwatch was started, which was then stopped when the child opened the bedroom door to exit. This time was recorded as the child's "time to escape." The EEG technician also marked the onset of the alarm on the EEG recording, which was used to calculate the time from alarm initiation to EEG-defined awakening. This time was recorded as the child's "time to awaken." The 4 study outcome measures were: whether a child awakened (yes or no), whether the child escaped (yes or no), the time to awaken, and the time to escape.

When the family arrived at the sleep laboratory on the night of the study, health and hearing screens were completed on each child by study personnel. Historical information was collected from the parent and child regarding the absence of exclusion criteria (Table 1) and factors that could influence the likelihood of arousal from S4, including confirmation that no caffeine or other stimulants had been taken after 2 PM that day. Pure tone hearing screening included the frequencies 500, 1000, 2000, and 4000 Hz using a Beltone model 120 portable audiometer (Beltone Electronics Corp, Chicago, IL) calibrated to American National Standards Institute standards. Subjects passed the hearing screening if they responded to all of the tested frequencies at 20 dB in both ears. These frequencies encompass those of conventional residential tone smoke alarms and human speech.

Alarm stimuli were generated by a sound system designed in consultation with a professional sound company. The system included a recording station, using an Alesis Adat XT 8-track digital recorder (Alesis, Cumberland, RI), where the child's mother recorded her personalized voice alarm message. A Crown CTs 1200 amplifier (Crown Audio, Inc, Elkhart, IN) and Mackie 1604 VLZ mixer (LOUD Technologies, Inc, Woodinville, WA) were used to play back this message and the tone alarm through an ElectroVoice Sx300 speaker (Telex Communications, Inc, Burnsville, MN) placed in the child's bedroom, which provided a consistent sound intensity of 100 dB measured at the study subject's pillow. At the time of playback, the voice message or tone alarm was repeated for 60 seconds, then there was a 10-second pause, and then the alarm was repeated for another 60 seconds. These cycles were continued until the child awakened and exited the room or ≤ 5 minutes maximum.

All of the study data forms were carefully inspected by research staff at the time of collection and testing, allowing for immediate correction and/or clarification of recorded data. All of the data were reexamined at the time of data coding and entry to detect any problems not noticed at the time of testing. EEG recordings were reviewed by 1 of the authors (M.S.), who is board-certified in sleep medicine, while blinded to the type of alarm used. The EEG readings were scored in a standard manner for sleep stage at 30-second intervals. The EEG reviewer documented the subject's EEG response to the alarm and verified that the sleep study was conducted by study personnel according to protocol, including that the alarm was triggered at the appropriate time during the sleep cycle.

A χ^2 test was used to assess whether the order that alarm stimuli were presented was associated with awakening or escaping. Somer's D was used to assess the effect of age on awakening and escaping to the tone alarm or parent voice alarm. A 2-sided McNemar's test based on the binomial distribution was used to calculate an exact P value when testing the difference in success

between the 2 alarm stimuli for awakening and escaping. Median times to awakening with 15th and 85th percentile intervals were calculated, and time to awakening was compared for the 2-alarm groups using a Wilcoxon signed rank test. Survival analysis was used to assess the time from alarm activation to EEG-defined awakening. Kaplan-Meier curves demonstrated the different responses to the 2 alarm stimuli with respect to the probability of awakening. Survival analysis was also used to assess the time from alarm activation to completion of the escape procedure. Median escape times with 15th and 85th percentile intervals were calculated, and escape times were compared for the 2 alarm groups using a Wilcoxon signed rank test. Kaplan-Meier curves were also used to illustrate the different responses to the 2-alarm stimuli with respect to the probability of escaping.

SPSS version 13.0 statistical software (SPSS Inc, Chicago, IL) was used to perform statistical analyses.[27] This study was approved by the Columbus Children's Hospital Institutional Review Board. Written informed consent for participation in the study was obtained from the parent. Written informed assent was also obtained from the child if the child was ≥9 years of age, which is the policy of the Columbus Children's Hospital Institutional Review Board. Each participant family received $100 on completion of the study to reimburse them for their time participating in the study.

RESULTS

Twenty-four children 6 to 12 years old were enrolled. The median age was 9 years, and 11 (46%) were boys. One half of the children received the parent voice alarm first, and one half received the tone alarm first; however, the order that the 2 alarm stimuli were presented was not statistically associated with awakening or escaping (χ^2, $P = .73$ and $P = .77$, respectively). Twenty-three (96%) of the 24 subjects awakened to the parent voice alarm compared with 14 (58%) who awakened to the tone alarm. One child did not awaken to either stimulus. Nine children awakened to their parent's voice but not to the tone, whereas none awakened to only the tone and not the voice (McNemar, $P = .004$). Twenty (83%) of the subjects in the parent voice alarm group successfully performed the escape procedure within 5 minutes of alarm onset, compared with 9 (38%) in the tone alarm group (McNemar, $P = .001$). The median time to awaken was 20 seconds (15th to 85th percentile interval: 12 to 86 seconds) in the voice alarm group compared with 180 seconds (15th to 85th percentile interval: 26 to 300 seconds) in the tone alarm group (Wilcoxon signed rank, $P < .001$). The median time to escape was 38 seconds (15th to 85th percentile interval: 16 to 300 seconds) in the voice alarm group compared with the maximum allowed 300 seconds (15th to 85th percentile interval: 40 to 300 seconds) in the tone alarm group (Wilcoxon signed rank, $P < .001$).

Because many authorities in the fire safety community consider 3 minutes as the desired escape time in the event of a residential fire, the 2 alarm stimuli were also compared with respect to their ability to prompt escape within this shortened time frame. Two children in the tone alarm group had escape times between 3 and 5 minutes, but all of the children who escaped in the parent voice alarm group had escape times <3 minutes. Therefore, when 3 minutes was used as the cutoff time defining successful completion of the escape procedure, 2 children were recategorized as unsuccessful in the tone alarm group. This made the relative superiority in performance of the parent voice alarm compared with the tone alarm even greater (McNemar, $P < .001$). Using 3 minutes as the cutoff did not affect the comparison of median escape times between the 2 alarm groups. Survival analysis comparing the 2 alarm types was performed on awakening and escape times, and Figs 1 and 2 illustrate the resulting Kaplan-Meier curves.

The association between age and awakening and between age and escape for the 2 alarm types was assessed (Table 2). There was an increased likelihood of awakening with increasing age for the tone alarm (Somer's D, $P < .001$). Few (2 of 10) children <9 years awakened to the tone alarm compared with almost all (12 of 14) of the children ≥9 years. There was no association between age and awakening for the parent voice alarm (Somer's D, $P = .29$), because children of all ages consistently awakened to the parent voice alarm, with the exception of 1 child. The only child who did not awaken to the parent's voice was a 6-year-old boy, who remained in S4 through both alarm episodes. He was difficult to manually arouse after each alarm trial, and exhibited marked

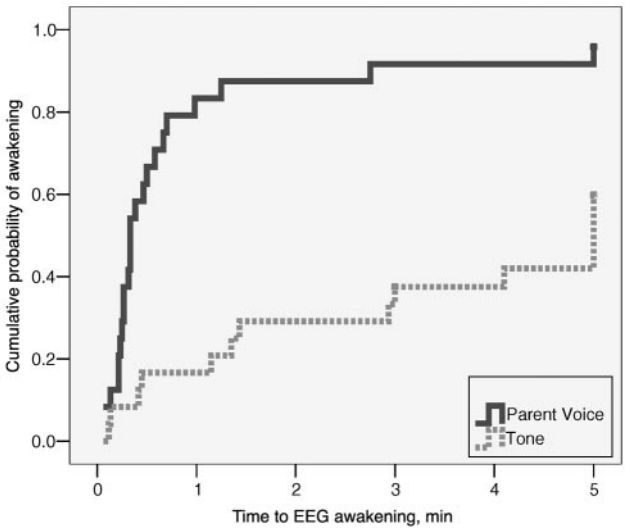

FIGURE 1
Cumulative probability of awakening by time to awakening for parent voice smoke alarm and tone smoke alarm stimuli.

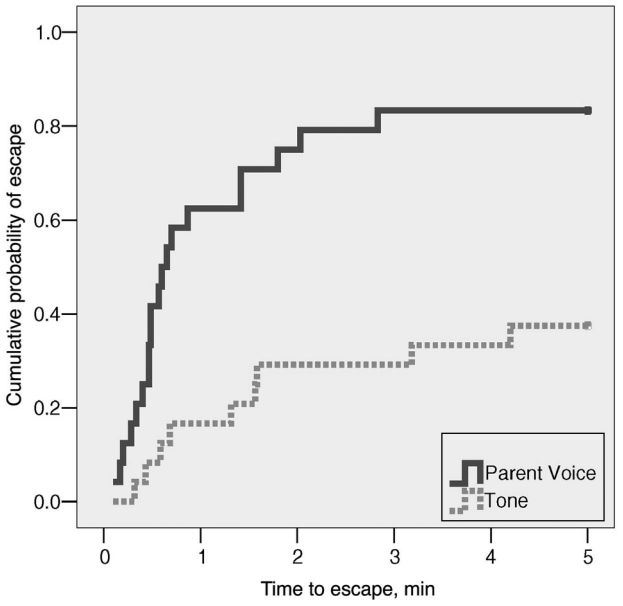

FIGURE 2
Cumulative probability of escape by time to escape for parent voice smoke alarm and tone smoke alarm stimuli.

sleep inertia after awakening. When the association between age and escape was assessed, a strong association was observed for the tone alarm (Somer's D, $P < .001$) but not for the parent voice alarm (Somer's D, $P = .053$). None (0 of 10) of the children <9 years escaped to the tone alarm compared with most (9 of 14) of the children ≥9 years. Most (20 of 24) children of all ages escaped to the parent voice alarm; the 4 children who did not escape included two 6-year-olds, one 8-year-old, and one 9-year-old. There were no statistically significant associations between gender and awakening and between gender and escape for either of the 2 alarm types (Table 2).

DISCUSSION

According to data from the WISQARS database of the Centers for Disease Control and Prevention, during the decade 1991–2000, there were >33 000 deaths from residential fires in the United States, of which ~8000, or 24%, were children <15 years of age.[4] About half of the residential fire deaths occur at night, with the victims asleep at the time of the fire.[1] Even in daytime fires, many deaths occur as a result of the victim being asleep at the time of the emergency.[2] To be effective, smoke alarms must be capable of consistently awakening sleeping individuals and signaling to them the existence of a fire/smoke emergency requiring rapid escape. Conventional residential smoke alarms generally produce a tone of 85 dB, which will awaken most sleeping adults.[28,29] However, children often do not awaken to conventional smoke alarms, because children have much higher auditory arousal thresholds than adults.[5] Despite recognition of the magnitude and importance of this problem, there has been a critical gap in knowledge regarding whether a smoke alarm can be designed that will effectively and consistently awaken children and prompt their escape.

Sleep consists of several stages that cycle throughout the night. One complete sleep cycle lasts ~90 to 100 minutes; therefore, during an average sleep period, a person will experience 4 to 5 complete sleep cycles. The sleep cycle begins with 4 stages of nonrapid eye movement (non-REM) sleep, with each consecutive stage (stages 1–4) characterized by increased slowing of the frequency of EEG wave patterns. Stages 3 and 4 sleep are collectively referred to as slow wave sleep (SWS). Stages of sleep can be identified by EEG, electro-oculography, and chin electromyography monitoring.

Several factors associated with sleep place children at greater risk for fire-related injury and death. First, children sleep longer than adults and are, therefore, more likely to be sleeping when a fire occurs. Furthermore, during each stage of sleep, the average auditory stimulus intensity required to elicit an arousal in children is much higher than in adults. Children also have disproportionately more SWS than adults, which has a higher arousal threshold than other stages of sleep. Most SWS occurs during the early sleep cycles, and, unfortunately, house fires also are more common during the early hours of the night. Hence, children are more likely than adults to be in a stage of sleep that is refractory to arousal at the time of a nocturnal residential fire.[4]

Many children do not awaken even to extremely loud sounds. In 1 study of boys 8 to 12 years of age, the frequency of awakenings was only 4.5% during SWS, 34% during stage 2 sleep, and 50% during REM sleep, even at intensities ≤123 dB, that is, 90 to 100 dB above normal background noise.[30] It is important to note that decibels are measured on a logarithmic scale. Normal speech is in the 40- to 60-dB range; loud sounds are considered to be 80 to 100 dB; jet engines are 125 dB; and danger of acute acoustic trauma occurs at levels >140 dB, although hearing damage depends on the duration of exposure in addition to the intensity of sound.

Findings of enhanced sleep-sustaining processes during the first sleep cycle in children are expected because of a general absence of cortical or behavioral arousals associated with various parasomnias, such as sleepwalking, that may occur during this time. The intensity of the sleep-protective process is such that it is difficult to affect behavioral or EEG arousals during the first sleep cycle in children. Arousals from SWS are very difficult to elicit during the first, as well as subsequent, sleep cycles.

This difficulty awakening sleeping children with sound can lead to tragedy when children do not respond

TABLE 2 **Percentage of Children Who Awakened and Escaped by Type of Smoke Alarm, Child Age, and Child Gender**

Child Age, y	*N*	Percent Awakened		Percent Escaped	
		Tone, *n* (%)	Parent Voice, *n* (%)	Tone, *n* (%)	Parent Voice, *n* (%)
6	5	1 (20)	4 (80)	0 (0)	3 (60)
7	2	1 (50)	2 (100)	0 (0)	2 (100)
8	3	0 (0)	3 (100)	0 (0)	2 (67)
9	5	4 (80)	5 (100)	1 (20)	4 (80)
10	2	2 (100)	2 (100)	2 (100)	2 (100)
11	4	3 (75)	4 (100)	3 (75)	4 (100)
12	3	3 (100)	3 (100)	3 (100)	3 (100)
Somer's D *P*		<.001	.29	<.001	.053
Younger (<10 y) vs older (≥10 y) *P*		.02	.30	<.001	.02
Child gender					
Female	13	7 (54)	13 (100)	4 (31)	12 (92)
Male	11	7 (64)	10 (91)	5 (45)	8 (73)
χ^2 *P*		.63	.27	.46	.20

to residential smoke alarms. This has created significant concern in the home fire safety industry.[6] However, despite this concern, relatively little research has been done on this important issue. To our knowledge, besides our research team, only 1 investigator has evaluated arousals from sleep to actual smoke alarms among children. Bruck[7] used actigraphy to document arousal in response to a 3-minute exposure to 60-dB alarms among 20 children 6 to 17 years old and compared the responses of these children to the responses of their parents, who were 30 to 59 years of age. All of the adults awakened compared with 31% of children who awakened at least once and only 15% who awakened consistently in response to the alarms. Importantly, because EEG monitoring was not performed, the author was not able to comment on the effect of sleep stage, which is a critically influential factor in determining arousal from sleep among children. In a second study, Bruck and Bliss[8] reported that only 29% of children age 6 to 10 years awakened consistently to the alarm compared with 71% of children age 11 to 15 years. Again, EEG monitoring was not done, and, therefore, the influence of sleep stage was unknown.

In 2004, Bruck et al[9] published results of 3 studies involving children 6 to 10 years old. They compared mother's and a female actor's voice (study 1, $N = 20$), a low-pitch (500–2500 Hz) tone smoke alarm (study 2, $N = 14$), and an Australian standard (high pitch, ~4000 Hz) smoke alarm (study 3, $N = 14$), all presented at 89 dB ± 3dB. In these studies, 100% of children awakened to mother's voice, 94% to the female actor's voice, 96% to the low-pitch alarm, and 57% to the standard alarm. Because the low-pitch tone alarm was as effective as the voice alarms, the authors concluded that the lower frequency of the alarm signal was the important factor in successfully arousing the children and not the use of a voice or the message urgency or content. There were several important limitations to these studies, including that they were 3 separate studies done at different times with variation in methods. The lack of a repeated-measures design is a critical weakness because of the potential large variation in auditory arousal thresholds known to exist among individuals.[3,31] Alarms were triggered at 1 AM or 1 AM and 3 AM without monitoring sleep stage, and, in fact, 2 patients were excluded from study 1, because they were awake at the time that the alarm sounded. In addition, actigraphy was used to determine awakening rather than EEG-defined awakening. This can be an issue, because partial arousals may mimic wakeful behavior. Indeed, in our study, 1 child sat up in bed in response to an alarm, whereas his EEG showed him to still be in stage 2 sleep. Escape completion and time to escape were also not addressed in these 3 studies by Bruck and colleagues.[9]

A second problem inherent in relying on smoke alarms to save lives is that on awakening from sleep, many adults have been found to have difficulty with sleep inertia, which is a performance impairment in decision-making that occurs immediately after awakening. In a study of 12 adults monitored in a sleep laboratory for 1 night and twice awakened by fire alarms, Bruck[32] found that decision-making performance was as little as 51% of optimum (ie, baseline) during the first few minutes after awakening. The initial effects of sleep inertia were significantly greater after SWS arousal than after REM arousal. To survive an actual house fire using self-rescue, children not only need to awaken but also must be able to perform escape behaviors that require decision-making and action. For this reason, this study evaluated not only children's awakening to smoke alarms but also their ability to perform a simulated escape procedure on awakening from S4, which evaluates the effect of sleep inertia.

Response to Mother's Voice

A child may respond differently to a smoke alarm using his/her mother's voice than one using an unfamiliar voice. Using this strategy, a new, but unproven, parent voice alarm (KidSmart) recently became available on the market. The scientific literature on maternal voice recognition is limited and focuses on infancy. A child's recognition of mother's voice occurs early in life. Indeed, evidence suggests that this recognition begins in the womb as a fetus. An elegant study of newborns 1 to 3 days old demonstrated their ability to discriminate mother's voice from other unfamiliar female voices, as well as their preference for mother's voice. Infants, who had been operantly trained, altered their nonnutritive sucking patterns to gain exposure to their mother's voices.[10] In another study, newborns tested with this same operant choice procedure did not display any preference for their father's voice over the voice of an unfamiliar male.[33] Querleu et al[11] showed that neonates <2 hours old and without postnatal auditory exposure preferred their mother's voice compared with other female voices. Hepper et al[12] conducted experiments at 36 weeks' gestation that examined fetal movements in the womb in response to mother's voice. These third-trimester fetuses showed a differential response to their mother speaking compared with tape recordings of the voice of their mother or of a female stranger played through a speaker at the abdomen. Another study demonstrated an increase in heart rate among term fetuses in response to mother's voice compared with a decrease in fetal heart rate in response to a stranger's voice.[13] These studies and others conclude that there is a unique prenatal priming of maternal recognition by the newborn and that a child's preference for his/her mother's voice is based on exposure to her voice in the womb.

In a study of 4-month-old infants, Purhonen et al[14] demonstrated a differential change in the amplitude of auditory event-related potentials among infants exposed to mother's voice compared with infants exposed to the voice of a female stranger, suggesting a different cerebral processing of maternal voice stimuli than other voice stimuli. These findings support the existence of neurophysiologic mechanisms associated with a child's preference for his/her mother's voice.

Response to One's Own First Name

The "cocktail party" phenomenon is a common experience, where a person's attention is suddenly drawn by the sound of his/her name from across a noisy room. It takes a powerful stimulus to capture one's attention and elevate that stimulus into awareness. Moray[15] first studied this phenomenon, showing that approximately one third of those tested reported hearing their name in an unattended auditory channel but did not remember details of what was said in that unattended channel. These findings were corroborated by Howarth and Ellis,[16] who demonstrated a differential threshold of intelligibility for one's own name compared with other names. Infants 4 to 5 months old are capable of recognizing their own name, as demonstrated by Mandel et al[17] using a modified version of the head-turn preference procedure. Response to one's own name is so potent that it persists during altered states of consciousness, even when reactivity to other powerful stimuli has disappeared. For example, reactivity to one's name occurs before reactivity to pain or noise after general anesthesia.[18] Individuals with severe dementia, who have lost recognition of time and place, continue to respond to their name.[19] Importantly, the sound of one's own name also remains a potent stimulus during sleep.

Although a functional disconnection between the external world and the cerebral cortex of a sleeping person is supported by a lack of behavioral response and memory of stimuli presented during sleep, detection and discrimination of important stimuli do persist during sleep. Event-related potential studies have demonstrated a differential response to one's own first name, compared with response to other names, during stage 2 sleep and REM sleep.[20–22] Using combined EEG and functional MRI monitoring during non-REM sleep, the left amygdala and the left prefrontal cortex were more activated by the sound of a subject's own first name than by a pure tone beep matched for intensity and duration.[23] The sound of one's name has also been shown to evoke behavioral responses during sleep.[24] Langford et al[25] demonstrated that young adults awaken more quickly to the sound of a tape recording of their own name than to that of nonsensical speech. These studies argue that one's own first name is an intrinsically significant stimulus, eliciting a differential human response as early as infancy, and is so potent that it persists during sleep, even when reactivity to other stimuli has disappeared.

Current smoke alarm technology (installed per current NFPA 72–11, National Fire Alarm Code, chapter 11) consists of an 85-dB tone alarm at 500 to 4000 Hz with a 3-pulse repeating temporal pattern.[4,26] However, 100 dB was chosen as the intensity of the alarms in our study, because existing literature, although limited, indicated that <5% of children would be expected to awaken during S4 to a conventional tone alarm at the standard 85 dB.[30] We did not want to conduct a "straw man" comparison when testing the new voice alarm. We wanted to compare the parent voice alarm to a louder tone alarm stimulus that would have the potential for a higher success rate.

The study population was restricted to children 6 to 12 years of age for several reasons. Adolescents do not experience the same difficulty in awakening from SWS as do younger children. Therefore, adolescents are more similar to adults in their response to smoke alarm stimuli than they are to younger children. Children ≤5 years of age are generally regarded by the fire safety community

as being too developmentally immature to reliably be able to perform self-rescue in a house fire.[4] For this age group, the only logical escape plan in the case of a residential fire is based on an adult rescuing the child. The choice of the 6- to 12-year-old age group as the study population permitted study of a more homogeneous group at high risk of failure to respond to smoke alarm stimuli. A smoke alarm stimulus identified as capable of awakening and prompting escape among this age group would be expected to be at least as effective in less alarm-resistant age groups.

Alarm stimuli were tested during S4 in this study, because this is the deepest stage of sleep and is when an individual is the most refractory to arousal.[4] If an alarm stimulus is successful in awakening children from S4 and prompting them to escape, then this stimulus would be expected to be at least as successful during other stages of sleep. An effective smoke alarm should provide an adequate stimulus for sleeping children, who are at highest risk of nonresponse.

Not only did the parent voice smoke alarm significantly outperform the conventional residential tone smoke alarm, but the results were dramatic. The personalized parent voice alarm using the mother's voice at 100 dB successfully awakened 96% of children from S4 and prompted 83% of them to perform a simulated self-rescue escape procedure. Directly witnessing the responses to the 2 types of alarms was revealing. Many of the children who slept through 5 minutes of the tone alarm bolted upright in bed almost immediately when the mother's voice alarm was used.

The high (100-dB) intensity of the alarm stimuli also seemed to have an effect. The conventional residential tone alarm at 100 dB awakened 58% of children from S4 and prompted 38% of them to perform the simulated self-rescue escape procedure. Although the scientific literature is limited, these are higher success rates than would be expected based on previous studies. There was also a statistically significant association between child's age and escaping for the tone alarm, manifested by a lower success rate among younger children, especially children <9 years. A similar trend was noted for the association between child's age and awakening to the tone alarm, but this did not achieve statistical significance. Child's gender was not associated with awakening or escaping for either type of alarm.

To survive an actual house fire using self-rescue, children not only need to awaken but also must be able to perform behaviors that require decision-making and action. The behavior commands included in the message content of the parent voice smoke alarm (ie, "Wake up! Get out of bed! Leave the room!") may be important for prompting children to perform predetermined, prerehearsed, appropriate, life-saving, escape behaviors. The commands and behaviors used in this study are not necessarily the same as those that parents would choose in the real world. The voice alarm message could include other instructions, such as to feel the bedroom door and open it only if it is not hot.

Various factors may have been important to the success of the parent voice smoke alarm, including the stimulus intensity, the characteristics of the sound system used (ie, use of a large speaker with wide dynamic range), the use of the child's first name in the alarm message, and the child's recognition of his/her mother's voice. However, the relative contribution of each of these factors is unknown.

Although this study demonstrated the success of the parent voice smoke alarm, several factors may limit its adoption for general use. For example, the 100-dB stimulus used in this study is much louder than a standard 85-dB smoke alarm, and, therefore, it may not be acceptable to the general public for household use. Currently, a major cause of nonoperational residential smoke alarms in the United States is intentional deactivation because of nuisance alarms. Nuisance alarms are false alarms triggered by cooking smoke, steam, or other causes. A nuisance alarm at 100 dB may be more likely to result in intentional alarm deactivation than a standard 85-dB alarm because of the human discomfort that its much higher sound intensity would cause. The 100-dB level also may be unnecessary for the voice alarm to be effective. In addition, the influence of the use of a large speaker on study results is uncertain, but clearly, a speaker of this size is not feasible for a residential smoke alarm. Finally and importantly, requiring the parent to record an alarm message before installing a smoke alarm will increase the parental effort involved and, therefore, will likely be a deterrent to its use, based on established injury prevention theory.[34] A generic, prerecorded voice message may be just as effective as a personalized parent voice message.

Research on smoke alarm stimuli that will awaken children and prompt their escape has several potential future directions. In addition to auditory stimuli, stimuli based on other senses may be effective in awakening children. Various types and combinations of tactile/vibratory, temperature, and light stimuli await investigation. In real life, when we attempt to awaken a sleeping child, we use multiple stimulus modalities. We generally turn on the light in the child's room, gently shake or rock a shoulder or leg, call the child's name, and ask him/her to wake up. Ideally, we would like to recreate these stimulus conditions, which are known to work, in a smoke alarm. In addition, a smoke alarm that incorporates effective nonauditory stimuli would have clear application in preventing fire-related mortality and morbidity among the deaf and hard-of-hearing population.

A couple of factors may potentially limit the number of children's lives saved by a more effective smoke alarm. Fire play is an important cause of residential fire-related deaths to children, especially among chil-

dren <5 years.[35] In addition, a study by Fahy and Molis[36] evaluated fatalities in residential fires where smoke alarms operated and concluded that children 6 to 15 years old did not represent a disproportionate share of these deaths. Those considerations notwithstanding, our research findings may contribute to Objective 15–25 of Healthy People 2010 to reduce residential fire-related deaths in the United States from 1.2 deaths per 100 000 in 1998 to 0.2 deaths per 100 000 by 2010.[37]

CONCLUSIONS

To our knowledge, this study is the first to compare the ability of different types of smoke alarms to awaken children while monitoring sleep stage. The personalized parent voice smoke alarm at 100 dB successfully awakened 96% of children 6 to 12 years old from S4 with 83% successfully performing a simulated escape procedure, significantly outperforming the 100-dB conventional residential tone smoke alarm.

These findings suggest a clear direction for future research, as well as important fundamental changes in smoke alarm design, that address the unique developmental needs of children. The development of a more effective smoke alarm for use in homes and other locations where children sleep provides an opportunity to reduce fire-related morbidity and mortality among children.

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REFERENCES

1. Runyan C, Bangdiwala S, Linzer M, Sacks J, Butts J. Risk factors for residential fires. *N Engl J Med.* 1992;327:859–863
2. Brennan P. Victims and survivors in fatal residential building fires. In: Shields J, ed. *Human Behavior in Fire: Proceedings of the First International Symposium*. Belfast, Northern Ireland: Fire SERT Centre, University of Ulster; 1995:157–166
3. Bruck D. The who, what, where and why of waking to fire alarms: a review. *Fire Safety J.* 2001;36:623–639
4. Underwriters Laboratories Committee on Children and Smoke Alarms. *Report From the UL Smoke Alarm STP Research Group on Childhood Awakening in Response to Smoke Alarms*. Northbrook, IL: Underwriters Laboratories; 2003
5. Busby K, Mercier L, Pivik R. Ontogenic variations in auditory arousal threshold during sleep. *Psychophysiology.* 1994;31:182–188
6. Bandla H, Splaingard ML. Sleep problems in children with common medical disorders. *Pediatric Clin N Am.* 2004;51:203–227
7. Bruck D. Non-awakening in children in response to a smoke detector alarm. *Fire Safety J.* 1999;32:369–376
8. Bruck D, Bliss RA. Sleeping children and smoke alarms. In: Yamada T, ed. *Proceedings of the Fourth Asia-Oceania Symposium on Fire Science and Technology*. Tokyo, Japan: Asia-Oceania Symposium on Fire Science and Technology; 2000:602–613
9. Bruck D, Reid S, Kouzma J, Ball M. The effectiveness of different alarms in waking sleeping children. *Proceedings from the Third International Symposium on Human Behaviour in Fire.* Belfast, Ireland: Third International Symposium on Human Behaviour in Fire; 2004:279–289
10. DeCasper AJ, Fifer WP. Of human bonding: newborns prefer their mother's voices. *Science.* 1980;208:1174–1176
11. Querleu D, Lefebvre C, Renard X, Titran M, Morillion M, Crepin G. Reaction of the newborn infant less then 2 hours after birth to the maternal voice. *J Gynecol Obstet Biol Reprod.* 1984;13:409–420
12. Hepper PG, Scott D, Shahidullah S. Newborn and fetal response to maternal voice. *J Reprod Infant Psychol.* 1993;11:147–153
13. Kisilevsky BS, Hains SMJ, Lee K, et al. Effects of experience on fetal voice recognition. *Psychol Sci.* 2003;14:220–224
14. Purhonen M, Kilpelainen-Lees R, Valkonen-Korhonen M, Karhu J, Lehtonen J. Cerebral processing of mother's voice compared to unfamiliar voice in 4-month-old infants. *Int J Psychophysiol.* 2004;52:257–266
15. Moray N. Attention in dichotic listening: Affective cues and the influence of instructions. *Q J Exp Psychol.* 1959;11:56–60
16. Howarth CI, Ellis K. The relative intelligibility threshold for one's own name versus other names. *Q J Exp Psychol.* 1961;13:236–240
17. Mandel DR, Jusczyk PW, Pisoni DB. Infants' recognition of the sound patterns of their own names. *Psychol Sci.* 1995;6:314–317
18. Kurtz D, Trapp C, Kieny MT, et al. Study of recovery and the post-anaesthetic period. *Rev Electroencephalogr Neurophysiol Clin.* 1977;7:62–69
19. Fishback DB. Mental status questionnaire for organic brain syndrome, with a new visual counting test. *J Am Geriatr Soc.* 1977;25:167–170
20. Pratt H, Berlad I, Lavie P. 'Oddball' event-related potentials and information processing during REM and not RE sleep. *Clin Neurophysiol.* 1999;110:53–61
21. Perrin F, Garcia-Larrea L, Mauguiere F, Bastuji H. A differential brain response to the subject's own name persists during sleep. *Clin Neurophysiol.* 1999;110:2153–2164
22. Perrin F, Bastuji H, Mauguiere F, Garcia-Larrea L. Functional dissociation of the early and late portions of human K-complexes. *Neuroreport.* 2000;11:1637–1640
23. Portas CM, Krakow K, Allen P, Josephs O, Armony JL, Frith CD. Auditory processing across the sleep-wake cycle: simultaneous EEG and fMRI monitoring in humans. *Neuron.* 2000;28:991–999
24. Oswald I, Taylor AM, Trisman M. Discriminative responses to stimulation during human sleep. *Brain.* 1960;80:440–453
25. Langford GW, Meddis R, Pearson AJ. Awakening latency from sleep for meaningful and non-meaningful stimuli. *Psychophysiol.* 1974;11:1–5
26. National Fire Protection Association. *NFPA 72–2002: National*

Fire Alarm Code. 2002 ed. Quincy, MA: National Fire Protection Association; 2002
27. *SPSS for Windows* [computer program]. Release 13.0. Chicago, IL: SPSS, Inc; 2004
28. Nober EH, Pierce H, Well A. Waking effectiveness of household smoke and fire detection devices. *Fire J.* 1981;75:86–130
29. Bruck D, Horasan M. Non-arousal and non-action of normal sleepers in response to a smoke detector alarm. *Fire Safety J.* 1996;25:125–139
30. Busby K, Pivik RT. Auditory arousal thresholds during sleep in hyperkinetic children. *Sleep.* 1985;8:332–341
31. Zepelin H, McDonald CS, Zammit GK. Effects of age on auditory awakening. *J Gerontol.* 1984;39:294–300
32. Bruck D, Pisani DL. The effects of sleep inertia on decision-making performance. *J Sleep Res.* 1999;8:95–103
33. DeCasper AJ, Prescott PA. Human newborns' perception of male voices: Preference, discrimination, and reinforcing value. *Dev Psychobiol.* 1984;17:481–491
34. Baker SP. Childhood injuries: the community approach to prevention. *J Public Health Policy.* 1981;2:235–246
35. Istre GR, McCoy M, Carlin DK, McClain J. Residential fire related deaths and injuries among children: fireplay, smoke alarms, and prevention. *Inj Prev.* 2002;8:128–132
36. Fahy RF, Molis JL. Fatalities in home fires where smoke alarms operated. *Proceedings from the Third International Symposium on Human Behaviour in Fire.* Belfast, Ireland: Third International Symposium on Human Behaviour in Fire; 2004:57–66
37. US Department of Health and Human Services. *Healthy People 2010*, Volume 2, 2nd ed. Washington, DC: US Government Printing Office; 2000

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