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CLINICAL RESEARCH ARTICLE

Comparison of the effectiveness of female voice, male voice, and hybrid voice-tone smoke alarms for sleeping children

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BACKGROUND: To test whether children awaken from slow wave sleep and perform an escape procedure better in response to a smoke alarm that uses a male voice, female voice, combination of a low-frequency tone plus a female voice (hybrid alarm), or high-frequency tone.
METHODS: Using a randomized, non-blinded, repeated-measures design, 188 children aged 5–12 years were exposed during stage 4 slow wave sleep to four smoke alarms.
RESULTS: Among study subjects, 84.6%, 87.2%, 88.8%, and 56.4% awakened and 84.0%, 86.7%, 88.8%, and 55.3% successfully performed the escape procedure within 5 min of alarm onset in response to the male voice, female voice, hybrid, and high-frequency tone alarms, respectively, while the median time-to-escape was 12.0, 12.0, 13.0, and 96.5 s for these four alarms, respectively. All pairwise comparisons between the high-frequency tone alarm and each of the other three alarms were statistically significant for the proportions of subjects who awakened or escaped and for time-to-awaken and time-to-escape. There were no significant differences in these outcome measures between the latter three alarms.
CONCLUSIONS: Use of the male or female voice or hybrid alarms in children's sleep areas may reduce residential fire-related injuries and deaths among children old enough to perform self-rescue.

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IMPACT:

- The male voice, female voice, and hybrid alarms were each significantly more effective than a high-frequency tone alarm in awakening children aged 5–12 years from slow wave sleep and prompting their performance of an escape procedure.
- There were no significant differences in the effectiveness of the male voice, female voice, and hybrid alarms when compared with each other.
- Use of these alarms in children's sleep areas may reduce residential fire-related injuries and deaths among children old enough to perform self-rescue.

INTRODUCTION

Smoke alarms are vital for the primary prevention of residential fire-related injury and death. They have been shown to awaken most sleeping adults,[1,2] but the high-frequency tone alarms found in many households are not effective in awakening children.[3–6] This is problematic because the rate of fire-related mortality is three times higher during sleep and about half of residential fire fatalities are nocturnal among sleeping individuals.[7,8] Children are at greater risk for residential fire-related injury and death while sleeping than adults because they sleep longer than adults and spend proportionally more time in slow wave sleep, which is the sleep stage that requires the loudest auditory stimulus to awaken an individual. In addition, the average auditory stimulus intensity to awaken a child is greater than that for an adult during each stage of sleep, making children less likely to arouse to a smoke alarm in a fire.[4] Despite recognition of the importance of this problem and initial research indicating that an effective smoke alarm for children is achievable, there is a critical gap in knowledge regarding the key characteristics of a smoke alarm that will awaken children and prompt their escape.[5,6]

Our previous research demonstrated that alarms using a female voice significantly outperformed a residential high-frequency tone alarm; however, personalizing the voice alarm signal by using the child's first name or the voice of the child's mother did not increase alarm effectiveness.[5,6,9] The effectiveness of a male voice alarm has been tested among sleeping older adults but not among children.[10] Although a female voice has been demonstrated to be perceived as more urgent than that of a male voice among awake adult listeners,[11] it is unclear whether this is relevant to awakening a child from slow wave sleep or prompting escape once awakened. Therefore, research is needed to evaluate the relative effectiveness of a smoke alarm using a female vs a male voice among children. In addition, our previous research showed that a low-frequency tone alarm and a female stranger's voice alarm each performed better than comparator alarm signals. The low-frequency tone was marginally better at awakening

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children but had a somewhat longer time-to-escape than the female stranger's voice alarm; therefore, there may be advantages to combining these signals into one alarm.[9] In addition, the content of the voice alarm may provide valuable instructions regarding life-saving escape behaviors to a child during the period of confusion associated with sleep inertia upon awakening.[12] A hybrid alarm that combines the low-frequency tone and female voice merits further research.

This study tests whether children awaken from slow wave sleep and perform an escape procedure better in response to a smoke alarm that uses a female voice, male voice, or a combination of a low-frequency tone plus a female voice. The findings of this study will contribute to the development of a more effective smoke alarm for children, which may reduce residential fire-related injuries and deaths among children old enough to perform self-rescue.

METHODS

Study population

The study population consisted of children aged 5–12 years, who were recruited via institution-wide emails in a large academic children's hospital and study announcements via the hospital's Facebook account. Children were eligible to participate if (1) they spoke English, and they did not (2) have a clinical diagnosis and were not taking a medication that might affect sleep, arousal, or their ability to perform the escape procedure, (3) have an acute illness at the time of the study, or (4) have a hearing impairment. Children received a pure tone hearing screening test on the first study night using a Maico MA25 portable audiometer; to participate in the study, children had to successfully respond to all tested frequencies of 500, 1000, 2000, and 4000 Hertz (Hz) at ≤30 decibels (dB) in both ears.

The study population was restricted to children aged 5–12 years because adolescents, like adults, generally respond well to smoke alarms and do not experience the same difficulty as younger children in awakening to a high-frequency residential smoke alarm. In addition, children aged <5 years are too immature to reliably rescue themselves in a residential fire and therefore must rely on adult rescue.[4]

The target number of children completing the study was determined to be a minimum of 176, based on the sample size used in our previous studies employing the same study design,[5] which had demonstrated adequate statistical power. All children meeting enrollment criteria were entered into the study; none were excluded for other reasons. Among the 230 children initially enrolled, 37 withdrew because they were unable to fall asleep, 4 withdrew because they were nervous or frightened by the alarms, and 1 subject was excluded because of a sound system malfunction on the first study night. This yielded a final study enrollment of 188 children.

Study design

This study used a randomized, non-blinded, repeated-measures design, in which children aged 5–12 years were each exposed during stage 4 slow wave sleep (S4S) to four smoke alarm signals: (1) female voice, (2) male voice, (3) a hybrid voice-tone alarm, consisting of a low-frequency tone plus female voice, and (4) high-frequency tone. The voice message used in the male voice, female voice, and hybrid alarms was "Fire! Fire! Wake up! Get out of bed! Leave the room!" Study alarms were assessed regarding their ability to awaken the children and prompt their performance of a simulated escape procedure. An auditory arousal threshold (AAT) is the intensity level in dB of an auditory stimulus required to induce arousal from sleep. The repeated-measures design is important because it avoids potential confounding due to variation of AATs among individuals (inter-subject variability can be high) and takes advantage of the stability of AATs for an individual across sleep cycles (intra-subject variability is low).[13–15]

Table 1. Latin Square showing the four alarm signal sequences.

Alarm sequences	Night 1		Night 2	
	Sleep cycle 1	Sleep cycle 2	Sleep cycle 1	Sleep cycle 2
1	B	C	A	D
2	A	B	D	C
3	D	A	C	B
4	C	D	B	A

A, B, C, and D represent the four alarm signals used in the study.

The NFPA 72 National Fire Alarm Code requires that fire alarms use the Temporal-Three (T-3) pattern as defined by ISO 8201.[16] Although a low-frequency T-3 tone alarm was adopted as the United States standard for sleeping areas in 2014,[17] a high-frequency (approximately 3200 Hz) T-3 tone alarm was also included in this study because it is the alarm type currently found in many homes. The low-frequency (500 Hz square wave) T-3 alarm used in this study was a Simplex 1996, 4100 Fire Alarm and is the same alarm previously used in studies by Proulx and Laroche[18] and Bruck et al.[19] Four sequences of alarm signals were used, based on the Latin Square shown in Table 1, to minimize the possibility of a sequence effect. Block randomization (in blocks of four) of these sequences within each of the four age groups (5–6, 7–8, 9–10, 11–12 years) was performed and then placed in sequentially numbered sealed envelopes by a research assistant, who was not involved with study enrollment or conducting the study. Children received the next available envelope for their age group upon arrival for their first night of the study, and only study staff knew the assigned alarm sequence after the envelope was opened. Voice and tone alarm signals were amplified through small, smoke alarm-size speakers in the study bedrooms to provide consistent signals at 85 dB when measured at the pillow. Study rooms simulated realistic residential decor and conditions.

Subjects were taught an escape procedure on the night of the study, which was to get out of bed when awakened by an alarm, walk to the bedroom door, and exit. Sleep stage was monitored to ensure that comparisons among alarm signals were not influenced by the variability of AATs among stages of sleep. To achieve this, scalp and facial electrodes were attached to each child by a polysomnography (PSG) technician. The electroencephalography (EEG) montage included C3, C4, O1, O2, A1, and A2 electrodes. After bedroom lights were turned off, continuous EEG, electro-oculography, and chin electromyography via telemetry with synchronized low-light video monitoring were conducted.

Testing protocol and measurements

Each child was allowed to progress into S4S and remained there for 5 min before an alarm was triggered. S4S is a deep stage of slow wave sleep and is defined as high voltage (>75 microvolts), slow wave (<2 cycles/s) EEG activity accounting for >50% of a 30-s EEG/PSG epoch.[20] Alarm signals were tested during S4S because it is the sleep stage with the highest AAT and therefore the most refractory to arousal.[4] The child was alone in the bedroom when the alarm sounded. "Time-to-awaken" is the interval from the triggering of the alarm to the initiation of at least a 3-s arousal associated with movement and subsequent awake EEG. The interval from when the alarm was triggered until the child opened the bedroom door is the "time-to-escape". If an alarm failed to awaken the subject after 5 min, the child was awakened by research staff and the parent. This procedure was conducted during the first and second sleep cycles on two separate study nights at least 6 days apart, resulting in each child being exposed to four different alarm signals (two different signals each night). Testing on consecutive nights was not done to avoid possible confounding effects of sleep deprivation and altered sleep architecture. A senior certified PSG technician determined the "time-to-awaken" from EEG video recordings, which was later reviewed and verified by one of the authors (M.S.), who is board-certified in sleep medicine, while blinded to the alarm used. This review did not reveal any discrepancies.

Statistical analysis
Statistical analyses were performed using SAS Enterprise Guide 7.15 (SAS Institute Inc., Cary, NC). Cochran's Q test, which extends McNemar's test for matched pairs to three or more treatments, was used to assess equality of proportions of subjects who awakened and escaped within 5 min. If significant differences were found, exact pairwise McNemar's tests were performed to assess the equality of proportions of children who awakened and escaped. The Kaplan–Meier estimator was used to estimate the probability functions for time-to-awaken and time-to-escape, which were censored after 5 min. The generalized Wilcoxon test was used to assess the overall equality and pairwise comparison of time-to-awaken and time-to-escape probability functions. Hazard ratios (HRs) with Wald's 95% confidence intervals (CIs) were calculated only for each pair of alarm signals where there was a statistically significant difference using the generalized Wilcoxon test. Cochran–Armitage test for trend was used to assess the trend between child age and the proportion of children who awakened and escaped. Statistical significance was determined using $\alpha = 0.05$.

This study was approved by the institutional review board of the Research Institute at Nationwide Children's Hospital. Written informed consent was obtained from children's parents, and assent was obtained from children aged ≥9 years.

RESULTS

A total of 188 subjects completed the study. The median age was 9.0 years and 53.7% ($n = 101$) were boys. Overall, 53.7% ($n = 101$) of children awakened to all four alarms, and 5.9% ($n = 11$) did not awaken to any of the alarms. In addition, 49 (26.1%) children awakened to three of the four alarms, including 46 (24.5%) children who awakened to the hybrid alarm and both voice alarms but not to the high-frequency tone alarm. Eighteen (9.6%) children awakened to two of the four alarms, including 13 (6.9%) who awakened to the hybrid alarm and one voice alarm but not to the high-frequency tone alarm. An additional 9 (4.8%) children awakened to only one of the four alarms, including 4 (2.1%) children who awakened to only the male voice alarm, 3 (1.6%) children who awakened to only the hybrid alarm, and 2 (1.1%) children who awakened to only the female voice alarm. The proportions of subjects who awakened (Cochran–Armitage: all $p < 0.001$) and escaped (Cochran–Armitage: all $p < 0.001$) increased with increasing age group for each of the 4 alarms (Table 2). There were no significant differences in the proportions of boys and girls who awakened (χ^2: all $p > 0.050$) or escaped (χ^2: all $p > 0.050$) within 5 min for each alarm type (Table 2).

Among the 188 subjects, 84.6%, 87.2%, and 88.8% awakened and 84.0%, 86.7%, and 88.8% successfully performed the escape procedure within 5 min of alarm onset in response to the male voice, female voice, and hybrid alarms, respectively. In comparison, 56.4% of children awakened and 55.3% successfully performed the escape procedure within 5 min of high-frequency tone alarm onset (Table 2). The type of alarm had a significant effect on the proportion of subjects who awakened (Cochran's Q: $p < 0.001$) and escaped (Cochran's Q: $p < 0.001$) within 5 min. For pairwise comparisons, there were significant differences in the proportions of subjects who awakened (McNemar: all $p < 0.001$) or escaped (McNemar: all $p < 0.001$) between the high-frequency tone alarm and each of the other three alarms. Each pairwise comparison between the male voice alarm, female voice alarm, and hybrid alarm indicated no significant differences in the proportions of subjects who awakened (McNemar: all $p > 0.050$) or escaped (McNemar: all $p > 0.050$). Among children who awakened within 5 min, most also performed the escape procedure within 5 min (100.0% also escaped for the hybrid alarm, 99.4% for the female voice alarm, 99.4% for the male voice alarm, and 98.1% for the high-frequency tone alarm).

The Kaplan–Meier cumulative probabilities of time-to-awaken and time-to-escape for the four alarms are given in Figs. 1 and 2. Overall, the probability functions for time-to-awaken were significantly different (Wilcoxon: $p < 0.001$) for the 4 alarms. Compared with the high-frequency tone alarm, there were significant differences in the probability functions for time-to-awaken for the hybrid alarm (Wilcoxon: $p < 0.001$; HR: 2.63, 95% CI: 2.06–3.37), female voice alarm (Wilcoxon: $p < 0.001$; HR: 2.67, 95% CI: 2.09–3.42), and male voice alarm (Wilcoxon: $p < 0.001$; HR: 2.45, 95% CI: 1.91–3.14) (Table 3). The median time-to-awaken was 42.5 s for the high-frequency tone alarm and 2.0 s for the hybrid and each of the voice alarms (Table 2). Similarly, the probability functions for time-to-escape were significantly different for the 4 alarms overall (Wilcoxon: $p < 0.001$). Time-to-escape probability functions for the hybrid alarm (Wilcoxon: $p < 0.001$; HR: 2.77, 95% CI: 2.16–3.54), female voice alarm (Wilcoxon: $p < 0.001$; HR: 2.75, 95% CI: 2.14–3.52), and male voice alarm (Wilcoxon: $p < 0.001$; HR: 2.50, 95% CI: 1.95–3.21) were significantly different than the probability function for the high-frequency tone alarm (Table 3). The median time-to-escape for the high-frequency tone alarm was 96.5 s compared with 13.0 s for the hybrid alarm and 12.0 s each for the female and male voice alarms (Table 2). Pairwise comparisons of the probability functions for time-to-awaken and time-to-escape between the hybrid alarm, female voice alarm, and male voice alarm indicated no statistically significant differences between each of these pairs (Table 3).

DISCUSSION

The male, female, and hybrid alarms all performed equally well in this study, awakening 85%, 87%, and 89% and prompting 84%, 87%, and 89% of children to escape, respectively. Pairwise comparisons between each of these alarms did not reveal any statistically significant differences in the proportions of subjects who awakened or escaped. Consistent with previous studies,[5,6,9] the high-frequency tone alarm was not as successful in awakening (56%) and prompting children to escape (55%). There were statistically significant differences between the high-frequency alarm and each of the other three alarms with respect to the proportions of subjects who awakened or escaped. The inclusion of an escape procedure is a unique feature and a strength of our study design compared to other studies because a child not only needs to awaken but also needs to escape in the event of a fire. The median time-to-escape was essentially the same among the male voice (12 s), female voice (12 s), and hybrid (13 s) alarms but was higher for the high-frequency alarm (96 s). Pairwise comparisons of the probability functions for time-to-awaken and time-to-escape between the male voice, female voice, and hybrid alarms indicated no statistically significant differences. However, the time-to-awaken and time-to-escape probability functions for each of the male voice, female voice, and hybrid alarms were significantly different than these probability functions for the high-frequency tone alarm.

Children aged 5–12 years have a higher residential fire fatality rate than teenagers and adults up to age 35 years.[21] Although they are potentially capable of self-rescue in a residential fire, they are unlikely to awaken to the high-frequency tone smoke alarm found in many homes.[3–5] Despite the importance of this issue,

Table 2. Awakening and escaping by type of alarm, age group, and sex.

Type of alarm, age group, and sex	Number of children n	Number awakened n (%)	Time-to-awaken (s) Median (IQR)	Number escaped n (%)	Time-to-escape (s) Median (IQR)
Hybrid[a]					
Age (years)					
5–6	41	29 (70.7)	4.0 (2.0 to >300.0)	29 (70.7)	28.0 (13.0 to >300.0)
7–8	51	44 (86.3)	2.0 (1.0 to 8.0)	44 (86.3)	13.0 (7.0 to 29.0)
9–10	48	47 (97.9)	2.0 (1.0 to 7.5)	47 (97.9)	11.0 (7.0 to 21.0)
11–12	48	47 (97.9)	2.0 (1.0 to 4.0)	47 (97.9)	10.5 (7.0 to 14.5)
Sex					
Male	101	86 (85.2)	2.0 (1.0 to 7.0)	86 (85.2)	13.0 (8.0 to 27.0)
Female	87	81 (93.1)	2.0 (1.0 to 7.0)	81 (93.1)	13.0 (8.0 to 25.0)
Subtotal	188	167 (88.8)	2.0 (1.0 to 7.0)	167 (88.8)	13.0 (8.0 to 25.0)
Female voice					
Age (years)					
5–6	41	27 (65.9)	3.0 (1.0 to >300.0)	27 (65.9)	20.0 (10.0 to >300.0)
7–8	51	46 (90.2)	1.0 (1.0 to 6.0)	45 (88.2)	12.0 (7.0 to 23.0)
9–10	48	44 (91.7)	2.0 (1.0 to 5.5)	44 (91.7)	11.0 (7.0 to 23.5)
11–12	48	47 (97.9)	2.0 (1.0 to 4.0)	47 (97.9)	10.0 (7.0 to 15.0)
Sex					
Male	101	88 (87.1)	2.0 (1.0 to 7.0)	87 (86.1)	12.0 (7.0 to 30.0)
Female	87	76 (87.4)	2.0 (1.0 to 5.0)	76 (87.4)	12.0 (8.0 to 23.0)
Subtotal	188	164 (87.2)	2.0 (1.0 to 5.5)	163 (86.7)	12.0 (7.0 to 27.5)
Male voice					
Age group					
5–6	41	25 (61.0)	5.0 (2.0 to >300.0)	25 (61.0)	54.0 (13.0 to >300.0)
7–8	51	43 (84.3)	2.0 (1.0 to 6.0)	42 (82.4)	12.0 (8.0 to 43.0)
9–10	48	43 (89.6)	2.0 (1.0 to 5.0)	43 (89.6)	11.0 (7.0 to 20.5)
11–12	48	48 (100.0)	2.0 (1.0 to 5.0)	48 (100.0)	10.5 (8.0 to 14.0)
Sex					
Male	101	82 (81.2)	3.0 (1.0 to 10.0)	81 (80.2)	12.0 (8.0 to 56.0)
Female	87	77 (88.5)	2.0 (1.0 to 5.0)	77 (88.5)	12.0 (9.0 to 27.0)
Subtotal	188	159 (84.6)	2.0 (1.0 to 6.0)	158 (84.0)	12.0 (8.0 to 40.5)
High-frequency tone					
Age (years)					
5–6	41	14 (34.2)	>300.0 (19.0 to >300.0)	14 (34.2)	>300.0 (86.0 to >300.0)
7–8	51	26 (51.0)	80.0 (2.0 to >300.0)	25 (49.0)	>300.0 (13.0 to >300.0)
9–10	48	28 (58.3)	40.0 (2.0 to >300.0)	28 (58.3)	68.5 (12.5 to >300.0)
11–12	48	38 (79.2)	13.0 (4.0 to 105.0)	37 (77.1)	35.0 (14.0 to 189.5)
Sex					
Male	101	51 (50.5)	215.0 (5.0 to >300.0)	50 (49.5)	>300.0 (16.0 to >300.0)
Female	87	55 (63.2)	27.0 (4.0 to >300.0)	54 (62.1)	59.0 (15.0 to >300.0)
Subtotal	188	106 (56.4)	42.5 (4.0 to >300.0)	104 (55.3)	96.5 (15.5 to >300.0)

IQR interquartile range.
[a]The hybrid alarm consists of a low-frequency tone plus a female voice.

relatively few studies have been conducted on the effectiveness of different types of alarm signals to awaken children.[19,22–25] Furthermore, these studies have had methodological limitations, including small sample sizes, not monitoring and controlling for sleep stage, not including escape completion or time-to-escape as study outcomes, and not utilizing a repeated-measures design to mitigate the potential effects of inter-subject variation in AATs.[14,15]

The findings of this study add important information to our previous studies and the work of others, which will help to develop an effective and practical smoke alarm for children as well as older individuals.[5,6,9,22,24,25] Our initial research demonstrated that a maternal voice alarm was more effective than a high-frequency tone alarm in awakening children and prompting their performance of an escape procedure.[6] However, it was unclear which components of that alarm were responsible for its success. In a follow-up study, we showed that the use of the child's first name in the alarm message was not necessary for its effectiveness.[5] We then showed that the use of the mother's voice in the alarm message was not an essential factor; indeed, in that study, a low-frequency tone alarm and a female stranger's

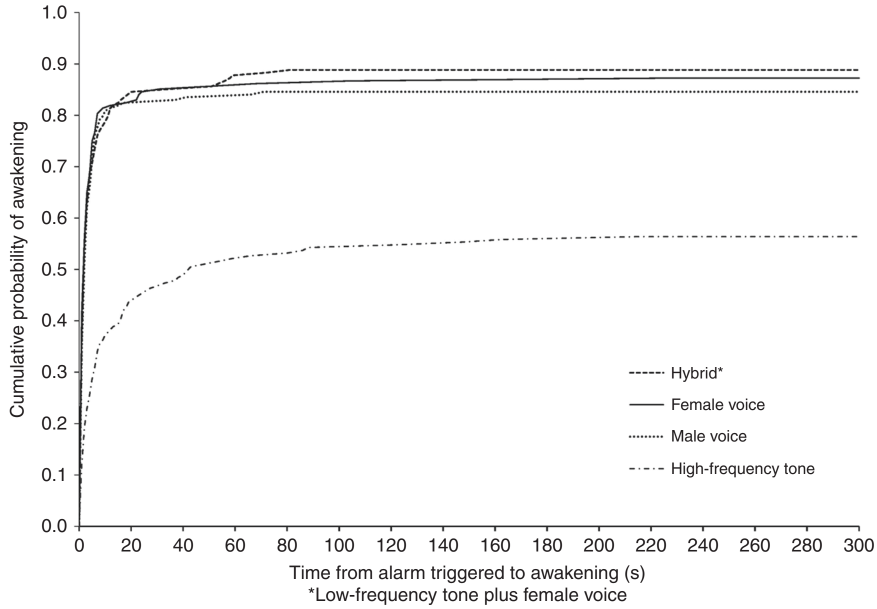

Fig. 1 Cumulative probability of awakening by type of alarm. The hybrid alarm consists of a low-frequency tone plus a female voice.

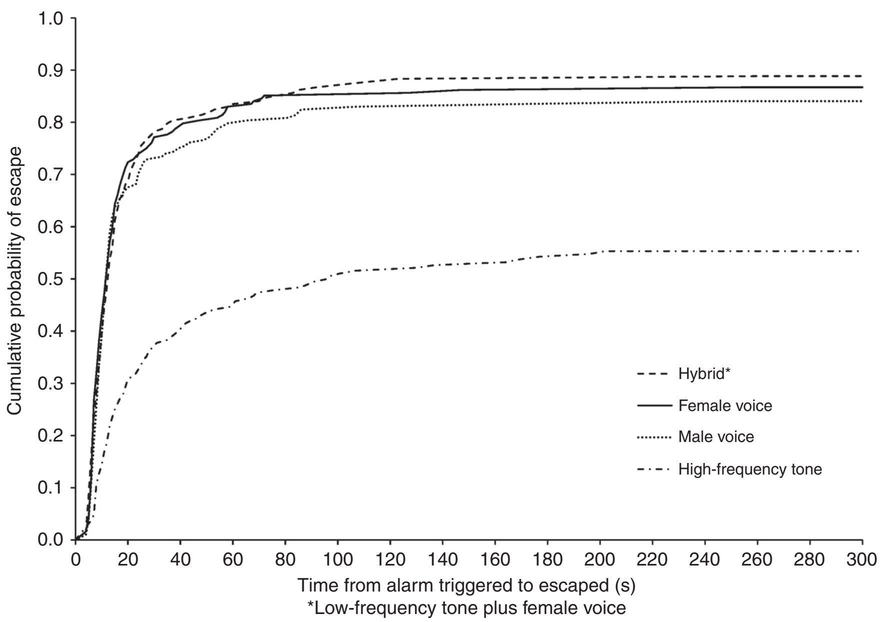

Fig. 2 Cumulative probability of escape by type of alarm. The hybrid alarm consists of a low-frequency tone plus a female voice.

voice alarm each performed better than the comparator alarms.[9] Although the differences were not statistically significant, the low-frequency tone was slightly better at awakening children but had a somewhat longer time-to-escape than the female stranger's voice alarm, which led to us to combine these signals into a hybrid voice-tone alarm for this study.[9] Use of a male voice smoke alarm during sleep has not been extensively evaluated, although a pilot evaluation among six young adults suggested a better response to a male voice than a female voice, and in another study among 45 older adults, a male voice alarm was outperformed by a mixed-frequency T-3 tone alarm.[10] To our knowledge, our study is the first to evaluate a male voice alarm among sleeping children.

The content of the voice alarm may provide valuable instructions regarding life-saving escape behaviors to a child in the event of a fire emergency.[12] This may be especially helpful during the period of confusion associated with sleep inertia upon awakening. We observed this phenomenon in an earlier study when the alarm signal was inadvertently paused after a child got out of bed; the child stood in the middle of the bedroom looking disoriented until the alarm message restarted, at which time, he walked to the door and exited as instructed by the message. Based on our study's findings, voice alarms that employ a male or female voice, as well as the hybrid alarm that combines a low-frequency tone with a female voice, perform equally well. Because these alarms do not have to be personalized with a child's name or a mother's voice, they can be manufactured at a lower cost using a generic recording and can be installed without the effort of personalization by the consumer. The decreased cost and increased ease of installation would increase the likelihood that the alarm would be used and installed correctly.[26]

The proportion of children who awakened and escaped increased with increasing age for each of the alarm types,

Table 3. Comparisons of time-to-awaken and time-to-escape between types of alarms.

Alarm signal comparisons	Time-to-awaken		Time-to-escape	
	Wilcoxon's *P* value	Hazard ratio (95% CI)[b]	Wilcoxon's *P* value	Hazard ratio (95% CI)[b]
Overall				
Equality of alarm signals	<0.001		<0.001	
Pairwise comparisons				
Hybrid[a] vs high-frequency tone	<0.001	2.63 (2.06–3.37)	<0.001	2.77 (2.16–3.54)
Female voice vs high-frequency tone	<0.001	2.67 (2.09–3.42)	<0.001	2.75 (2.14–3.52)
Male vs high-frequency tone	<0.001	2.45 (1.91–3.14)	<0.001	2.50 (1.95–3.21)
Hybrid[a] vs female voice	0.568		0.809	
Hybrid[a] vs male voice	0.630		0.541	
Female voice vs male voice	0.292		0.393	

[a]The hybrid alarm consists of a low-frequency tone plus a female voice.
[b]Hazard ratio and 95% confidence interval was calculated only for each pair of alarm signals where there was a statistically significant difference using the generalized Wilcoxon test.

which agrees with previous research.[5,6] There was no association observed between the child's sex and awakening or escaping in this study. This is consistent with two previous studies;[6] however, there was a trend toward a greater proportion of girls awakening and escaping than boys in one prior study, although the statistical significance of the observed differences was not consistent for all alarm types.[5]

Study limitations
This study had some limitations. The study did not include an adaptation night, which is often employed to avoid a "first night effect." However, such an effect was minimized by the repeated-measures study design and by waking children from S4S, which is the sleep stage least influenced by potential confounders because of decreased cortical arousability.[13] Children rehearsed the escape procedure immediately before falling asleep in this study, which may have affected results regarding escape, although some families practice a fire escape plan with their children. Future research should evaluate how a child's escape response upon awakening is influenced by the message content of a voice alarm using a study protocol that does not prime the children before going to sleep about what to do when the alarm sounds.

CONCLUSIONS

The male voice, female voice, and hybrid alarms were each significantly more effective than a high-frequency tone alarm in awakening children aged 5–12 years from slow wave sleep and prompting their performance of an escape procedure under conditions mimicking a residential setting. There were no significant differences in the effectiveness of the male voice, female voice, and hybrid alarms when compared with each other. Use of these alarms in children's sleep areas may reduce residential fire-related injuries and deaths among children old enough to perform self-rescue. Now that optimized smoke alarm signals for children have been identified, future research should test them among older age groups. The goal is to develop a residential smoke alarm that is effective among persons of all ages.

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AUTHOR CONTRIBUTIONS

Each author has met the *Pediatric Research* authorship requirements. G.A. Smith contributed substantially to the conception and design of the study, acquisition of data, and analysis and interpretation of data; he drafted the article, approved the final version to be published, and agrees to be accountable for all aspects of the work. T. Chounthirath conducted data analyses and contributed substantially to interpretation of data; he revised the article critically for important intellectual content, approved the final version to be published, and agrees to be accountable for all aspects of the work. M. Splaingard contributed substantially to the conception and design of the study, acquisition of data, and interpretation of data; he revised the article critically for important intellectual content, approved the final version to be published, and agrees to be accountable for all aspects of the work.

ADDITIONAL INFORMATION

Competing interests: The authors declare no competing interests.

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REFERENCES

1. Bruck, D. & Horasan, M. Non-arousal and non-action of normal sleepers in response to a smoke detector alarm. *Fire Saf. J.* **25**, 125–139 (1996).
2. Nober, E. H., Pierce, H. & Well, A. Waking effectiveness of household smoke and fire detection devices. *Fire J.* **75**, 86–130 (1981).
3. Busby, K. A., Mercier, L. & Pivik, R. T. Ontogenetic variations in auditory arousal threshold during sleep. *Psychophysiology* **31**, 182–188 (1994).
4. Underwriters Laboratories & Smoke Alarm STP Research Group. *Report from the UL Smoke Alarm STP Research Group on Childhood Awakening in Response to Smoke Alarms* (Underwriters Laboratories, Northbrook, IL, 2003).
5. Smith, G. A., Chounthirath, T. & Splaingard, M. Effectiveness of a voice smoke alarm using the child's name for sleeping children: a randomized trial. *J. Pediatr.* **205**, 250–256.e1 (2019).
6. Smith, G. A., Splaingard, M., Hayes, J. R. & Xiang, H. Comparison of a personalized parent voice smoke alarm with a conventional residential tone smoke alarm for awakening children. *Pediatrics* **118**, 1623–1632 (2006).
7. Bruck, D. & Ball, M. Optimizing emergency awakening to audible smoke alarms: an update. *Hum. Factors* **49**, 585–601 (2007).
8. Runyan, C. W., Bangdiwala, S. I., Linzer, M. A., Sacks, J. J. & Butts, J. Risk factors for fatal residential fires. *N. Engl. J. Med.* **327**, 859–863 (1992).
9. Smith, G. A., Chounthirath, T. & Splaingard, M. Do sleeping children respond better to a smoke alarm that uses their mother's voice? *Acad. Pediatr.* https://doi.org/10.1016/j.acap.2019.06.016 (2019).
10. Bruck, D. & Thomas, I. Comparison of the effectiveness of different fire notification signals in sleeping older adults. *Fire Technol.* **44**, 15–38 (2008).

11. Hellier, E., Edworthy, J., Weedon, B., Walters, K. & Adams, A. The perceived urgency of speech warnings: semantics versus acoustics. *Hum. Factors* **44**, 1–17 (2002).
12. Smith, J. J. & Wogalter, M. S. Perceived effectiveness of warning messages for use as vocal warnings in residential fire alarms. *Proc. Human Factors Ergonom. Soc. Annu. Meeting* **51**, 1398–1402 (2007).
13. Bonnet, M. H., Johnson, L. C. & Webb, W. B. The reliability of arousal threshold during sleep. *Psychophysiology* **15**, 412–416 (1978).
14. Bruck, D. The who, what, where and why of waking to fire alarms: a review. *Fire Saf. J.* **36**, 623–639 (2001).
15. Zepelin, H., McDonald, C. S. & Zammit, G. K. Effects of age on auditory awakening thresholds. *J. Gerontol.* **39**, 294–300 (1984).
16. International Organization for Standardization. ISO 8201, alarm systems – audible emergency evacuation signal – requirements. https://www.iso.org/standard/67046.html (2017). Accessed 27 Dec 2018.
17. National Fire Protection Association. *NFPA 72: National Fire Alarm and Signaling Code* (National Fire Protection Association, Quincy, MA, 2016).
18. Proulx, G. & Laroche, C. Recollection, identification and perceived urgency of the temporal-three evacuation signal. *J. Fire Prot. Eng.* **13**, 67–82 (2003).
19. Bruck, D. Technical Report FCRC-TR 98-04: arousal from sleep with a smoke detector alarm in children and adults. http://www.abcb.gov.au/-/media/Files/Resources/Research/FCRC-TR-98-04-Arousal-from-sleep-smoke-detector-in-children-and-adults.pdf (1998). Accessed 27 Dec 2018.
20. Rechtschaffen, A. & Kales, A. *A Manual of Standardized Terminology, Techniques and Scoring Systems for Sleep Stages of Human Subjects* (US Government Printing Office, Washington, DC, 1968).
21. Ahrens, M. Characteristics of home fire victims. https://www.nfpa.org/-/media/Files/News-and-Research/Fire-statistics-and-reports/Building-and-life-safety/oshomevictims.ashx?la=en (2014). Accessed 27 Dec 2018.
22. Bruck, D. Non-awakening in children in response to a smoke detector alarm. *Fire Saf. J.* **32**, 369–376 (1999).
23. Bruck, D. & Bliss, R. A. Sleeping children and smoke alarms. In *Proceedings of the 4th Asia-Oceania Symposium on Fire Science and Technology* 603–611 (Japan Association for Fire Science and Engineering, Tokyo, 2000).
24. Bruck, D., Reid, S., Kouzma, J. & Ball, M. The effectiveness of different alarms in waking sleeping children. In *Proceedings from the 3rd International Symposium on Human Behaviour in Fire*. 279–290 (Interscience Communications Ltd., Belfast, 2004).
25. Bruck, D. & Thomas, I. R. Community-based research on the effectiveness of the home smoke alarm in waking up children. *Fire Mater.* **36**, 339–348 (2012).
26. Baker, S. P. Childhood injuries: the community approach to prevention. *J. Public Health Policy* **2**, 235–246 (1981).