REPORT FROM THE UL SMOKE ALARM STP RESEARCH GROUP ON CHILDHOOD AWAKENING IN RESPONSE TO SMOKE ALARMS

SCOPE OF THE PROBLEM

In the decade between 1991 and 2000 there were 33,227 deaths from residential fires in the United States, of which 7,978 or 24% were in children less than 15 years of age[1]. Children less than age 5 seem to be at particular risk, comprising 34% of children under 15, yet 61% of pediatric deaths. Fatalities from home fires are most common between the hours of 24:00 and 06:00, a time when the inhabitants are likely to be asleep.

Home fire alarms, responding to the presence of heat, smoke, or carbon monoxide, generally produce a pure tone of approximately 85 dB, which is sufficient to trigger an arousal in most sleeping adults[2,3]. However, there are clear developmental variations in auditory arousal thresholds, and evidence that children may not arouse or awaken when presented with a pure tone signal of this amplitude. Recently, a number of anecdotal studies and media reports have increased the awareness that children may not arouse appropriately to smoke alarms. Therefore, Underwriters Laboratories convened a panel with expertise in childhood sleep physiology and smoke alarm technology, to review current research and make recommendations for future areas of study. Thus, the panel members comprised a heterogeneous group of people, including some members with commercial interests in the topic of interest. Panel members reviewed the literature, including a computerized search of the National Library of Medicine's Medline database, supplemented with additional publications thought to be relevant.

This report is directed specifically towards school-aged children and adolescents. In infants producing an arousal will obviously be of no benefit, as they do not have the ability to rescue themselves. In very young children, producing an arousal may actually be counterproductive if it results in an inappropriate response (such as hiding in a closet). In this age group, the primary goal of a smoke alarm is to arouse the child's caregivers, who themselves need to have been educated to have made appropriate rescue plans in this eventuality. However, in older children smoke alarms have the potential to result in the child him/herself arousing and seeking safety.

PHYSIOLOGY OF SLEEP

Sleep is an organized state with developmental changes that occur in a predictable pattern as children grow from newborns to adolescents. In order to understand the dilemma of children not arousing from sleep in response to a smoke alarm or other type of alarm signal, it is necessary to understand several factors about sleep: (i) The physiology of sleep and the developmental changes that occur; (ii) The different threshold of awakening depending on the age of the subject and the stage of sleep; (iii) The meaningfulness of the stimuli to the sleeping individual with respect to arousal.

Developmental Changes In Sleep Physiology

There are 3 states of being: wakefulness, rapid eye movement (REM) sleep and non-REM (NREM) sleep. NREM sleep is further divided into 4 stages; ranging from stage 1 (the lightest stage of sleep) to stage 4, the deepest stage of sleep. Each progressive stage from 1 to 4 is characterized by increasing slowing of the brain. This is demonstrated on the electroencephalogram (EEG) which measures the brainwaves, which become higher in

amplitude and slower as one progresses from stage 1 to 4 of NREM sleep. Sleep stages 3 and 4 are collectively termed slow wave sleep. Humans continuously cycle through these stages of sleep throughout the night.

Significant differences in child and adult sleep relevant to the non-arousal of children to smoke alarms include the following:

1. Changes in total sleep time. Total sleep time is longest in newborns and gradually decreases towards adolescence. The average newborn sleeps 16.5 hours out of 24 hours, whereas the average adolescent sleeps just over 8 hours. Therefore, it is more likely in a 24 hour period that a child will be sleeping when an alarm sounds, because he/she sleeps more than an adult.
2. Children have more slow wave sleep than adults. Slow wave sleep is at its highest percentage of total sleep in young children, and decreases with age. Slow wave sleep comprises approximately 30% of total sleep in infants[4], compared to 10% in the elderly[5]. Thus, children sleep more deeply than adults.
3. Children have higher arousal thresholds than adults.

Arousal Thresholds

Arousal threshold changes with sleep stage. The arousal threshold is highest in slow wave sleep, i.e., it requires a larger stimulus to arouse a child from slow wave sleep than from other stages[6,7]. As children sleep longer at night, and have a higher percentage of slow wave sleep, they spend more time in slow wave sleep than adults. Therefore, children spend more time during sleep in the stage from which it is most difficult to be aroused.

In addition, several studies have shown that children have higher arousal thresholds than adults, even when controlled for sleep stage. A limitation of these studies, in the current context, is that many of the studies evaluated EEG arousals only. There is much less information regarding the stimulus required to arouse a child to the point where he/she would be able to perform a complex, coherent motor task, such as would be required for the child to save him/herself.

Busby and Pivik[8] studied 12 children aged 8-12 years in a sleep laboratory over 3 nights. Sounds of up to 123 dB failed to produce sustained arousal in any of the children during the first sleep cycle on either night, though short lived, partial arousals were triggered in 50% of the children during stage 2 sleep, and 25% during stage 4 sleep. Another study by the same group of investigators[7] studied arousal to a 120 dB acoustic stimulus in young children (5-7 years of age), preadolescents (8-12 years of age), adolescents (13-16 years) and adults. Children aroused on 43%, preadolescents on 54%, adolescents on 72% and adults on 100% of trials. In all non-adult groups, subjects were less likely to arouse in the first third of the night, when they were in a deeper stage of sleep. Furthermore, all non-adult groups had some partial arousals as compared to complete awakenings. In stage 4 sleep, approximately three-quarters of all pediatric subjects did not awaken to the stimulus.

Only one investigator has evaluated arousal responses to actual smoke alarms in children. Bruck[9] compared 20 children, aged 6-17 years old, to their parents, aged 30-59 years, using actigraphy to document arousal in response to 3 minute 60 dB alarms. All adults awoke, but only 31% of children awoke at least once, and only 15 % woke up consistently in response to the

alarms. Since EEG was not recorded, the authors were unable to comment on the effect of sleep stage. In a second study, only 29% of children aged 6-10 years awoke consistently to the alarm, as did 71% of adolescents aged 11-15 years[10].

Arousals Are Dependant On The Meaningfulness Of Stimuli

There is a discriminative response to different stimuli during sleep. For example, young adults awaken more rapidly in response to a tape recording of their own name then in response to a recording of gibberish[11]. This is important in the context of children and smoke alarms. Although children may have practice with smoke alarm drills when awake, the stimulus during sleep may not be as meaningful as to adults who appreciate the dire consequences of not arousing, and therefore the same stimulus may be less likely to arouse a child.

Habituation occurs in response to stimuli during sleep. Therefore, a person may arouse when first perceiving a stimulus. However, if the stimulus continues to be repeated with the same timing and level of intensity, the arousal threshold increases and the person is less likely to respond[12].

Confusional Arousals

Stimuli during sleep may result in a *partial arousal* or *confusional arousal* rather than a full awakening. In this state, children appear awake but behave irrationally, appear disorientated and have poor recall for the event. Sleep walking is a parasomnia that is similar to confusional arousals, and may also be elicited by a disturbance from sleep. Confusional arousals may last from several minutes to several hours[13]. Confusional arousals are common during early to mid childhood, especially when children are aroused from slow wave sleep. Confusional arousals may result in bizarre behavior and may account for some of the incidents where, for example, children were found to be hiding in a closet rather than escaping a fire, despite having received training in fire drills. Thus, a child may arouse to a smoke alarm but not respond appropriately, and in fact may have inappropriate behavior such as hiding that would make it more difficult for rescue personnel to save the child.

RECOMMENDED FURTHER RESEARCH

In summary, there is a preponderance of evidence that acoustic stimuli at the level currently used in smoke alarms will not reliably awaken children. Future studies should be directed at evaluating alternative stimuli. The following are suggestions by the committee for the design of further research.

Potential Stimuli

Studies should initially be performed with the stimulus at the level of the pillow. Current smoke alarm technology (installed per current NFPA 72 –11, National Fire Alarm Code chapter 11) consists of an 85 dB alarm at 500 – 4,000 Hz with a 3-pulse temporal pattern. Below are listed alternative potential stimuli that could be tested. Currently, none of these stimuli has been shown to be effective at causing reproducible awakenings in sleeping subjects.

Other Acoustic Stimuli
It is doubtful that a similar but louder stimulus would be effective as children have been shown not to arouse to a stimulus as high as 120 dB[7,8]. Furthermore, this degree of loudness can cause significant hearing damage[14].

Humans are more likely to arouse to a stimulus that is personally meaningful, as well as to a stimulus of a varying rather than monotonic nature. Potential acoustic stimuli worthy of study include arousal to a tape recording of a human voice, particularly a personalized message such as a caregiver calling the child's name; and auditory alarms that vary in frequency and intensity.

Optical Stimulation
Optical stimuli, such as strobe lights, have been used to alert hearing-impaired subjects to dangerous situations. However, one scientific study in adults demonstrated that strobe lights were unable to reliably cause arousal from the deeper stages of sleep[15]. Furthermore, strobe lights can be impaired by smoky conditions, and can cause temporary blindness or disorientation of subjects. The flash rate is limited by UL 1971 Signaling Devices for the Hearing Impaired in order to reduce the risk of inducing epileptic seizures. Nevertheless, further research of this modality, both alone and in combination, may be warranted.

Other Stimuli
Other potential arousal stimuli include tactile stimuli such as buzzers/vibrators and cold air jets, or olfactory stimuli. Vibration may induce arousal in adults[16]. In general, arousal to olfactory stimuli in adults is poor[17]. No data are available regarding arousal to these stimuli in children older than infancy. Finally, a combination of stimuli (e.g., an acoustic stimulus coupled with a strobe light and vibratory stimulus) may potentially be more effective than a single stimulus.

Study Design
Subjects should be stratified for age, as the arousal threshold of a preschool child will be different from that of an adolescent. The initial stratification could consist of preschool children, school-aged children and adolescents.

There are many variables that could potentially influence whether a child awakens to a smoke alarm besides age, including body position, sleep stage, time of day/night, environmental temperature and previous sleep deprivation. These variables need to be considered in designing future studies. The position of a sleeping child may influence his arousal threshold, as infants have been shown to have a higher arousal thresholds when in the prone position[18]. The arousal threshold has also been shown to vary with sleep stage, so that arousals are less likely to occur from slow wave sleep. Thus, it would be important to measure sleep state during the study to ensure that the stimulus was delivered during this high-risk state. Circadian factors (i.e., the time of day or night) may also play a role . Moreover, there could be significant inter-individual differences in arousal threshold, even when one controls for these variables. Thus, a sample size large enough to ensure sufficient power would be important.

Type of Response
As mentioned above, the committee members thought it important to measure sleep stage so that it could be ensured that at least some of the studies were conducted during slow wave sleep.

Sleep stage is measured using a variety of surface electrodes to measure brain waves (electroencephalography), muscle tone (electromyography) and eye movements (electrooculogram). These are standard measurements that are routinely performed in children in sleep laboratories. These measurements can now be performed with portable technology, thus allowing studies to be performed in the subject's home environment.

A given alarm stimulus may result in a spectrum of arousal responses. The lowest level of response is a subcortical (deep brain) or autonomic arousal, marked by increases in heart rate and blood pressure. A stronger stimulus may result in a cortical (EEG) arousal; if sustained, this could lead to a behavioral awakening. A simple awakening, however, may not be the desired endpoint. Rather, a behavioral awakening with appropriate, goal-directed activity (i.e., sustained wakefulness with the ability to flee from the hazardous setting) is the most important parameter to assess in determining real-life benefit. On the other hand, complex but inappropriate behavior after awakening may indicate a partial (confusional) arousal, an end-point that should also be scrutinized in determining an alarm's effectiveness.

In summary, there are many important and complex issues that need to be resolved in order to answer the question of what alarm design is best for awakening the sleeping child. The best approach to this research may be a coordinated, multi-centered effort with consistent methods and complementary study designs.

SUMMARY

- During sleep, most children less than ten years of age are developmentally incapable of arousing from a pure tone auditory stimulus of 85 dB to a level of wakefulness that can result in rapid performance of procedural tasks required to escape from fire/smoke hazards. Although adolescents are more likely to awaken to smoke alarms than younger children, evidence suggests that adolescents up to age 16 do not awaken consistently.
- Pure tone auditory stimuli during sleep that do not cause full awakening may result in no response, confusional arousals or brief unsustained awakening.
- Objective, scientific data regarding arousal and/or awakening of children to other types of alerting stimuli are not available.
- During sleep, an appropriate procedural response to a stimulus during a fire/smoke emergency requires sustained awakening with performance appropriate to extricate oneself from the hazard. Current data on the arousal threshold in children strongly support a lack of children's ability to wake to this level of alertness secondary to an auditory stimulus produced by commercially available smoke alarms. Furthermore, panic during emergency conditions may also adversely influence a child's behavior and performance.

CONCLUSIONS AND RECOMMENDATIONS

1. The majority of children between the ages of birth and five years are developmentally incapable of responding appropriately during fire/smoke emergencies. Caretaker rescue is the only reliable method to decrease morbidity and mortality in this age group.
2. Children aged 5-16 years of age are unlikely to awaken fully to auditory stimuli currently produced by commercially available smoke alarms.

3. There are no standardized scientific data exist regarding arousal and/or awakening to other types of non-biological stimuli in this age group.
4. *Therefore, pending further research, rescue is the only currently known reliable method to decrease morbidity and mortality in sleeping children when faced with a fire/smoke emergency.*

Suggested Areas of Research

1. Categorization and standardization of definitions of arousal and awakening responses to external stimuli, including evaluation of appropriate behavioral performance.
2. Comparison of validated arousal responses to different external stimuli as well as combinations of stimuli.
3. Comparison of stimuli and arousal responses in the laboratory versus the home environment.
4. Affect of age on the arousal response.

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