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Heat Stress From Enclosed Vehicles Moderate Ambient Temperatures Cause Significant Temperature Rise in Enclosed Vehicles

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ABSTRACT

Objective. Each year, children die from heat stroke after being left unattended in motor vehicles. In 2003, the total was 42, up from a national average of 29 for the past 5 years. Previous studies found that on days when ambient temperatures exceeded 86°F, the internal temperatures of the vehicle quickly reached 134 to 154°F. We were interested to know whether similarly high temperatures occurred on clear sunny days with more moderate temperatures. The objective of this study was to evaluate the degree of temperature rise and rate of rise in similar and lower ambient temperatures. In addition, we evaluated the effect of having windows "cracked" open.

Methods. In this observational study, temperature rise was measured continuously over a 60-minute period in a dark sedan on 16 different clear sunny days with ambient temperatures ranging from 72 to 96°F. On 2 of these days, additional measurements were made with the windows opened 1.5 inches. Analysis of variance was used to compare how quickly the internal vehicle temperature rose and to compare temperature rise when windows were cracked open 1.5 inches.

Results. Regardless of the outside ambient temperature, the rate of temperature rise inside the vehicle was not significantly different. The average mean increase was 3.2°F per 5-minute interval, with 80% of the temperature rise occurring during the first 30 minutes. The final temperature of the vehicle depended on the starting ambient temperature, but even at the coolest ambient temperature, internal temperatures reached 117°F. On average, there was an ~40°F increase in internal temperature for ambient temperatures spanning 72 to 96°F. Cracking windows open did not decrease the rate of temperature rise in the vehicle (closed: 3.4°F per 5 minutes; opened: 3.1°F per 5 minutes or the final maximum internal temperature.

Conclusions. Even at relatively cool ambient temperatures, the temperature rise in vehicles is significant on clear, sunny days and puts infants at risk for hyperthermia. Vehicles heat up rapidly, with the majority of the temperature rise occurring within the first 15 to 30 minutes. Leaving the windows opened slightly does not significantly slow the heating process or decrease the maximum temperature attained. Increased public awareness and parental education of heat rise in motor vehicles may reduce the incidence of hyperthermia death and improve child passenger safety.

Key Words: child passenger safety • injury prevention and control • hyperthermia

Abbreviations: CI, confidence interval

Every year, children die from heat stroke after being left unattended in a vehicle. From 1998 to 2002, the average number was 29 children per year (Fig 1). In 2003, this number increased to 42 (Fig 2) and was 35 in 2004. In addition to death, it is estimated that annually hundreds of children experience varying degrees of heat illness from being left in cars.¹ This danger exists despite public education efforts and lobbying for laws against leaving children unattended in vehicles. In a survey

performed by Roberts and Roberts,² approximately one quarter of interviewed women who had infants or toddlers admitted to leaving their children unattended in cars.

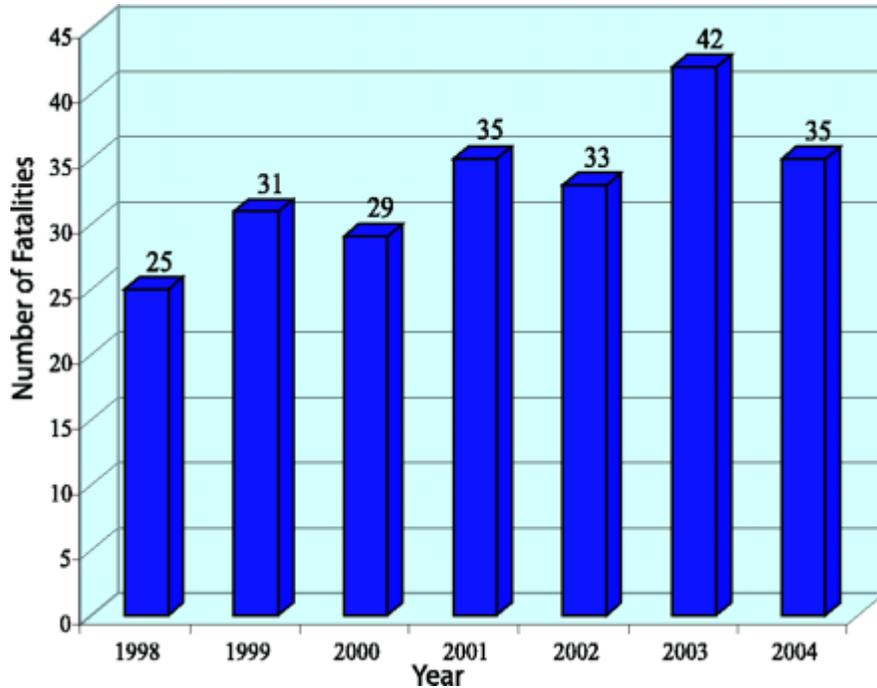


Fig 1. Annual vehicle-related hyperthermia fatalities in children.

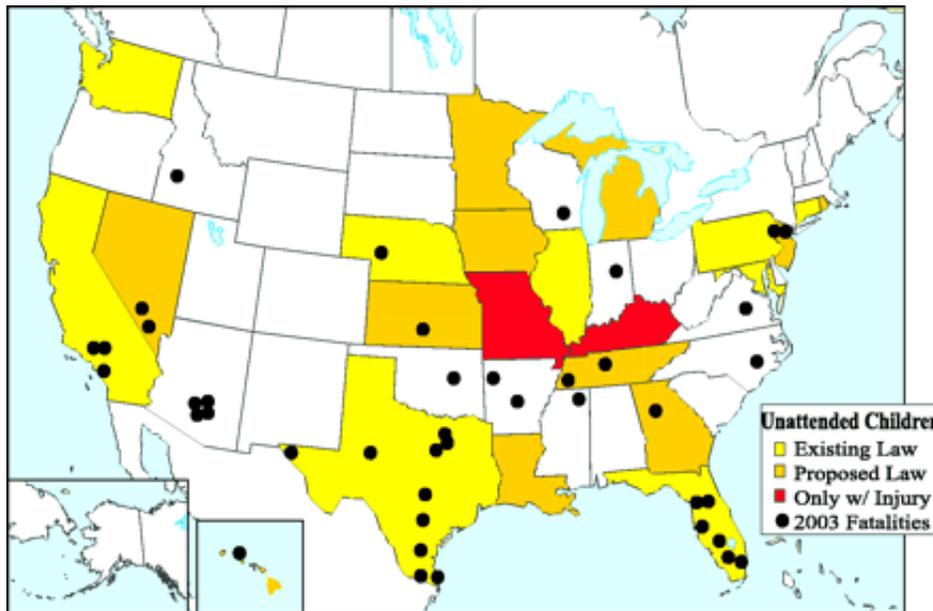


Fig 2. Location of 42 vehicle-related hyperthermia deaths of children in 2003. States are color-coded by status of legislation for leaving a child unattended in a vehicle.

Previous studies have examined the internal environment of motor vehicles. King et al³ found that in an ambient temperature of 36.8°C (98.2°F), 75% of the maximum temperature rise occurred within 5 minutes of closing the doors and maximized within 15 minutes to 51 to 67°C (124–153°F). Opening the windows 20 cm (~8 inches) had minimal effect on the temperature rise and maximum temperature attained. Roberts and Roberts² had similar findings. Most studies examined temperature rise on days with ambient temperatures >90°F, except for the study of Robert and Roberts, in which the ambient temperature was 83°F. These studies show that, not surprising, significant heat rise occurs on hot days.

We hypothesized, however, that even on cooler days, the risk for heat illness is significant inside a vehicle. This study was designed to quantify the amount and the rate of heating inside vehicles

over a broader range of ambient temperatures. We also sought to determine whether "cracked" windows made any difference on the heating of vehicles, because in a survey, fewer than one third of mothers would leave the windows half open because of theft concerns.

METHODS

Study Design

This was an observational study in which we measured the interior vehicle temperature on 16 different cloud-free days between May 16 and August 8, 2002, in Fremont, California. Ambient temperatures ranged from 72 to 96°F. The vehicle was parked in full sun, oriented 45 degrees to the sun's rays to minimize direct sunlight through the windshield. Internal vehicle temperature was measured continuously from time 0 to 1 hour. Temperature was recorded at time 0 and every 5 minutes for 1 hour. The vehicle was a dark-blue 2000 Honda Accord with medium-gray interior and without tinted windows. Recordings were made with closed windows on 16 different days. On 2 of these days, recordings were made first with the windows closed. Then the doors were opened to return the vehicle to ambient temperature, and a second hour of measurements was made with the windows cracked 1.5 inches. It was ensured that no significant change in ambient temperature occurred during these 2 hours.

Data Collection

Ambient temperature was recorded continuously with a Davis Instruments Vantage Pro Sensor Suite. Wireless temperature sensors were placed in the test vehicles in the rear passenger section ~15 inches above the seat, in the shade and not in direct contact with any part of the car. The temperature sensors had a resolution of 1°F and accuracy of $\pm 1^\circ\text{F}$. All recorded data were transmitted to the Vantage Pro base station.

Statistical Analysis

Data were recorded on an excel spreadsheet (Microsoft Corp, Seattle, WA) and imported into SPSS 11.0 (Chicago, IL) for statistical analysis. Analysis of variance evaluated for differences in the rate of temperature rise and final enclosed temperatures for the varying ambient temperatures. Analysis of variance was also used to compare the rate of temperature rise and maximum temperature attained with windows cracked open or closed. The recordings on the 2 separate days for these measures were averaged at each 5-minute interval, before analysis.

RESULTS

Rate of Temperature Rise Versus Ambient Temperature

Regardless of the ambient temperature, the rate of internal vehicle temperature rise was similar ($P = 1.0$). Figure 3 shows how the slope of the temperature over time was virtually the same for the different ambient temperatures. Eighty percent of the temperature rise occurred during the first 30 minutes ($P < .0001$).

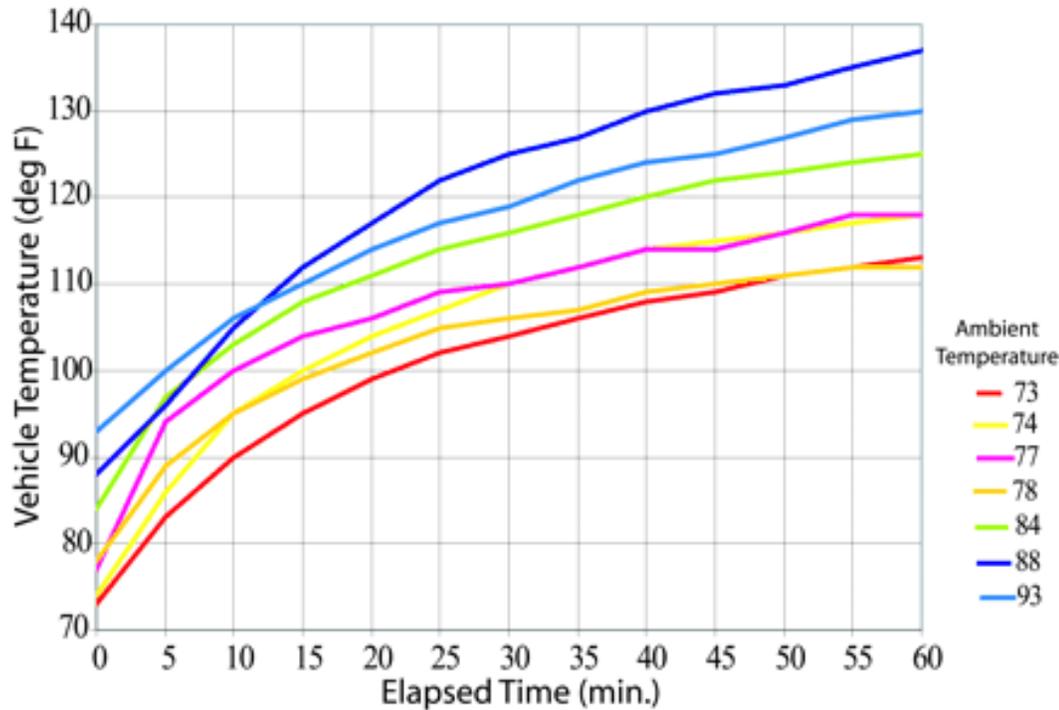


Fig 3.
Representative vehicle temperature rise over time.

The effect of air conditioning the vehicle before start of measurements was negligible. In preliminary measurements, the vehicle consistently reached ambient temperatures within 5 minutes of the air conditioning's being turning off and then would heat up at a similar rate to non-air-conditioned cases.

Final Internal Vehicle Temperature Versus Ambient Temperature

The maximum internal temperature was attained at ~60 minutes of exposure in our study. We also found that the final vehicle temperature was dependent on the initial ambient temperature. In addition, an average 41°F (range: 28–49°F) increase from starting ambient temperature occurred for the ambient temperature range of 72 to 96°F.

Comparison of Closed Versus Cracked Open Windows

Figure 4 illustrates a nonsignificant trend to faster heating in the first 20 minutes with the windows closed 6.25°F per 5 minutes (95% confidence interval [CI]: 1.0–11.5) versus 5.5°F per 5 minutes (95% CI: 1.2–9.8) with the windows cracked open. However, overall, the rate of temperature rise for windows that were cracked open was 3.4°F per 5 minutes (95% CI: 2.4–4.4°F) compared with the rate for closed windows of 3.1°F per 5 minutes (95% CI: 1.4–4.8°F), with the final temperature for both circumstances being identical.

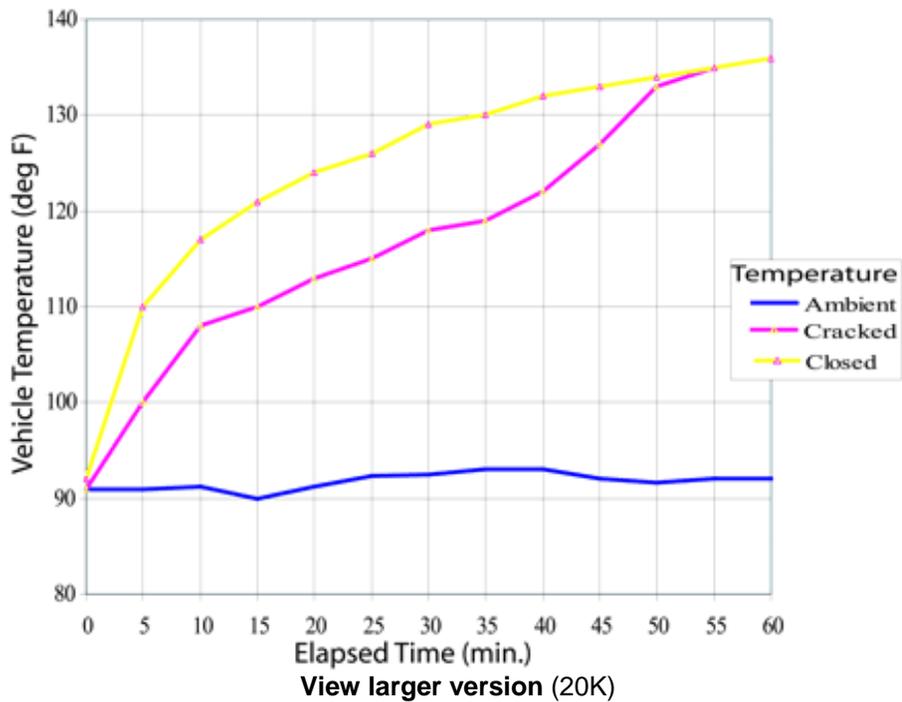


Fig 4. Interior vehicle temperature over time: closed versus cracked windows.

DISCUSSION

We demonstrated that on sunny days, even when the ambient temperature is mild or relatively cool, there is rapid and significant heating of the interior of vehicles. On days when the ambient temperature was 72°F, we showed that the internal vehicle temperature can reach 117°F within 60 minutes, with 80% of the temperature rise occurring in the first 30 minutes. In general, after 60 minutes, one can expect an ~40°F increase in internal temperatures for ambient temperatures spanning 72 to 96°F, putting children and pets at significant risk. We also determined that cracking open windows is not effective in decreasing either the rate of heat rise or the maximum temperature attained.

The exact affect of such temperatures on infants is unknown, but from case reports, we know that they can be devastating. We do know that heat illness is a continuum that is divided into 3 phases. The mildest form is heat stress, the physical discomfort and physiologic strain as a result of a hot environment. Next is heat exhaustion, a mild to moderate illness associated with dehydration and a core temperature ranging from 37°C to 40°C. Symptoms of heat exhaustion include intense thirst, weakness, discomfort, anxiety, dizziness, fainting, and headache. Finally, heat stroke is a life-threatening illness characterized by an elevated core body temperature >40°C with central nervous system dysfunction resulting in delirium, convulsions, coma, and death.⁴

Young children and infants are more susceptible to heat illness than adults for several reasons. Physiologically, toddlers and infants, despite their increased body surface area to mass ratio, seem to have less effective thermoregulation in comparison with adults as proposed by Tsuzuki-Hayakawa and Tochiara.⁵ In their study, they demonstrated that children (aged between 9 months and 4.5 years) who were placed for 30 minutes in rooms that were 35°C (95°F) had a rectal temperature that increased more rapidly and was significantly higher than their mothers'. This was despite that children and infant perspire more by body mass in comparison with their mothers. This finding was speculated to occur because smaller masses warm more quickly and that young children have an immature thermoregulatory system. In addition to the potential physical and physiologic differences, adults have the ability to modify behavior on the basis of the environment. They can undergo cooling measures: take off excess clothing, obtain cold drinks, and seek cooler environments (eg, get out of a hot car).

Although these results are significant numerically and perhaps would be sufficient to influence

parental behavior and perhaps lawmakers, the question still remains as to what is an unsafe temperature for an infant and how long until the infant experiences adverse effects from a particular heat. Intuitively, it would seem unconscionable to subject a child to an 117°F environment, and that is probably why the literature is sparse in quantifying the effect of heat on infants and children. As mentioned earlier, Tsuzuki-Hayakawa and Tochiwara⁵ found that infants and young children developed significantly higher core and surface body temperatures compared with their mothers despite increased perspiration. Studies by Levine and Ginandes⁶⁻⁸ proposed that a 12-month-old infant loses 1 to 2 mL/kg per hour through perspiration at an ambient temperature of 86°F. In studies of adults in extreme heat exposure, the maximum loss measured has been 10 to 20 mL/kg per hour.⁹ It is thought that similar fluid loss is possible in children and probably greater according to the work of Tsuzuki-Hayakawa. This would conservatively amount to a loss of 400 to 800 mL over a 4-hour period, or ~4% to 8% dehydration of a 10-kg infant. Future study to evaluate heat stress in infants and children would be difficult to do for obvious ethical reasons, so although we may never know the rate of dehydration and body temperature rise for infants and children in enclosed vehicles, the risk is clear.

Our results were consistent with previous research for similar temperature ranges except in 1 respect.^{2,3,10,11} King et al³ noted 75% of the maximum stabilized temperature within 5 minutes of closing the doors as opposed to our finding of 30 minutes required for attaining 80% of the maximum temperature. We believe that this difference occurred because their sensor was placed in direct sun, whereas our sensor was in the shade. This suggests that if a child were positioned in full sun, then the heat stress would be greater and more rapid in onset than stated here.

In addition to heat illness, leaving children unattended in vehicles puts them at risk for other harm, such as thermal burns from buckles, abduction, and injury from the child's putting the car in motion or operating power control features. The *Morbidity and Mortality Weekly Report* found that 78 children died from July 2000 to June 2001 from being left unattended in or around motor vehicles. In addition, there were 9160 nonfatal injuries reported. Of those who died, ~35% were attributable to heat illness and 82% were between the ages of 0 and 3 years.¹²

Prevention of heat illness in children and potentially other injuries is straightforward. Do not leave them in the car. Parental attitudes and behavior may be related to erroneous beliefs regarding the internal heat rise of vehicles on milder and even cool sunny days as well as the effects of cracking the windows. Laws regarding kids in cars currently exist in 9 states and are proposed in an additional 9.¹³ Although the problem of nonexertional hyperthermia in children pales in comparison with that of the top 3 causes of unintentional death (motor vehicle accidents, drowning, and burns) heat illness is conceivably easier to prevent if their caregivers are aware of the danger. It is worth considering incorporating this message along with a discussion of the importance of car seats as part of child passenger safety education for caregivers. Legislation efforts may help to raise awareness, but as these events are mostly unintentional, additional public education efforts ultimately are necessary to decrease the incidence of this fatal yet preventable behavior.

FOOTNOTES

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No conflict of interest declared.

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