Original Article

Mechanical Vibration in Neonatal Transport: A Randomized Study of Different Mattresses

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OBJECTIVE:
To test the hypothesis that a gel mattress is most effective in attenuating mechanical vibration in neonatal transport, we performed a randomized block study of four mattress combinations (none, foam, gel, gel on foam) using mannequins and an ambulance traveling on fixed routes (city, highway).

STUDY DESIGN:
Mechanical vibration was assessed by measuring vertical accelerations at two locations: the forehead of a 2000-gm mannequin and the transport incubator base. From time histories of these accelerations, root mean square (RMS) values and power spectral density functions were calculated. The effect of the mattress on the transmission of vibration was determined from ratios of the RMS values at the two locations. An RMS ratio of <1.0 indicates attenuation, whereas a ratio of >1.0 indicates accentuation of vibration. From the power spectral density functions, the natural frequency of the system was determined for each mattress combination in relation to the natural frequencies of the ambulance. To determine the effect of the weight of the mannequin on vibration, additional measurements were performed using a 300-gm mannequin.

RESULTS:
All the observed RMS ratios were >1. The highest ratios were observed on the city route in the absence of the gel mattress. The gel mattress, used alone or with the foam mattress, in contrast to foam or no mattress, shifted the natural frequency of the system away from the natural frequencies of the ambulance, avoiding a large amplification of vibration. A decrease in the weight of the mannequin caused the gel mattress to be less effective in attenuating vibration.

CONCLUSION:
A gel mattress, used alone or with a foam mattress, results in the least accentuation of vibration, but vibration in ambulance transport is *not* attenuated by any of the mattress combinations. The hazard of vibration may be particularly relevant when transporting extremely low birth weight neonates. These findings indicate a need for study and design of more effective devices that can reduce the vibratory stress.
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In the perinatal health care system, sick newborn infants often are transported from community hospitals to specialized care facilities. It is also common to transport convalescing newborn infants back to community hospitals before home discharge. During these transports, infants are exposed to prolonged, low-frequency, high-amplitude mechanical vibration.[1–3] In adult humans and experimental animals, this vibration has adverse effects on cardiorespiratory function,[4–8] the peripheral and central nervous system,[8–10] electroencephalographic activity,[11] body temperature,[12] metabolic and endocrinologic function,[8] and the gastrointestinal system.[8] In addition, vibration may contribute to general discomfort, motion sickness, vomiting, and increased intracranial pressure[8,13] and may also compromise clinical observation.[14] Vibration has deleterious effects on pregnant women and fetuses. Vibration is associated with the risk of premature delivery in transported pregnant women.[15] Even brief exposure to vibration in the gravid mouse is associated with abnormalities of growth and development of the embryos.[16]

The pathophysiological effects of vibration have not been studied systematically in human newborn infants. It is likely, however, that the adverse effects of vibration occur in transported newborn infants, and may be pronounced in sick or extremely low birth weight neonates. At the very least, the stability and observation of the infant in transport may be compromised.

Different types of mattresses, including air, foam, and gel mattresses, are used inside the transport incubator and are believed to attenuate the vibration.[17] We hypothesized that the gel mattress, used alone or in combination with the foam mattress, would be most effective in attenuating vibration in ambulance transport. To test this hypothesis, we assessed vibration in an ambulance under various transport conditions using mannequins and a randomized sequence of mattresses.

METHODS

Transport Procedures

Four mattress combinations (no mattress, foam mattress alone, gel mattress alone, and gel mattress on top of foam mattress) were tested during 24 sample runs in a licensed neonatal intensive care ambulance (Ford F350XLT Lariat ambulance, 1990 model) equipped with a standard transport incubator (Air-Shields TI5000; Air-Shields, Hatboro, PA). The foam mattress was prepared from standard foam material, ~3.0 cm thick, and covered with an insulating cotton blanket. The gel mattress was a moldable gel-filled mattress (Squishon 91017; Bimeco, Largo, FL), ~3.0 cm thick, and covered with an insulating cotton blanket. Using a randomized block study design, each mattress combination was tested in triplicate over two routes, a city route and a highway route, traveled at ~30 mph and ~60 mph, respectively. The triplicate testing was performed in three separate 30-second time windows. The same routes were used for all the sample runs. The driver was blinded to the mattress combination tested on each run.

Vibration Measurements and Analysis

To assess mechanical vibration, vertical accelerations were measured using two accelerometers (Kistler 8303A10M08; Kistler Instrument Corp., Amherst, NY). Each accelerometer weighed ~8 gm and could detect vibration in the frequency range of 0 Hz to 150 Hz. The accelerometers were secured with an adhesive tape at two different locations inside the ambulance. One accelerometer was attached to the forehead of a 2000-gm mannequin placed supine inside the transport incubator. The second accelerometer was attached to a fixed point at the base of the transport incubator. Time histories of vertical accelerations were recorded using a data acquisition card (Keithley KPCMCIA-12A1; Keithley, Cleveland, OH) and a laptop computer. For each acceleration time history, a root mean square (RMS) value was calculated. At a rate of 100 observations per second and using a 30-second time window, 3000 measurements of vertical acceleration were incorporated into the calculation of each RMS value. The RMS value represents an average intensity of vibration experienced in transport.[1] To determine the effect of the mattress on the transmission of vibration, the vertical accelerations obtained at the two locations, mannequin forehead and incubator base, were analyzed using ratios of corresponding RMS values. One RMS ratio was calculated for each replication of the eight experimental conditions: four mattress combinations times two ambulance routes. An RMS ratio of <1.0 indicates attenuation of vibration, whereas a ratio of >1.0 indicates accentuation of vibration.

In addition, a power spectral density (PSD) function was calculated for each acceleration time history using Matlab software (The MathWorks, Inc., Natick, MA). The PSD function separates the vibration into its individual elemental frequencies and provides a measure of the relative contribution of each frequency to the overall vibration.[18] Using the PSD functions of the incubator base accelerations, the natural frequencies of the ambulance were determined. Using these PSD functions and those of the mannequin forehead accelerations, the natural frequency of the system was estimated for each mattress combination. The system is the medium between the incubator base and the mannequin forehead, and consists of the incubator tray, any mattress combination tested, and the mannequin itself. The natural frequency of the system is the frequency at which the system, when excited by that frequency, resonates and amplifies its vibration.[18] Weight influences the natural frequency of the system. Decreasing the weight increases the natural frequency, whereas increasing the weight decreases the natural frequency. To determine the effect of the weight of the mannequin on the vibration, six additional ambulance runs were performed using a mannequin of a lower weight (300 gm) on a gel mattress.

Statistical Methods

The observed RMS ratios (relative vertical accelerations between mannequin forehead and incubator base) were examined graphically (S-PLUS; Data Analysis Products Division, MathSoft, Inc., Seattle, WA). The ratios were then modeled as a function of mattress type, ambulance route, and randomization block (replicate number) using multiple linear regression with least squares estimation (Stata Statistical Software; Stata Corp., College Station, TX). Simpler models with fewer explanatory variables were fitted using a backward-elimination approach and significance level $\alpha = 0.05$ for inclusion of variables in the final model. Based on this model, estimates of the expected ratios were calculated for each mattress and route combination. Regression coefficients are presented ± SE along with their associated p values. A p value of <0.05 was considered statistically significant. The coefficient of determination (R^2) was calculated to indicate the proportion of variation in the RMS ratios explained by the final model.

RESULTS

Vertical accelerations were measured satisfactorily in 23 of the 24 ambulance runs. Observed RMS values and model-based estimates are shown in Figure 1. Each of the 23 RMS ratios was >1, indicating a consistent accentuation of vibration regardless of mattress combination and ambulance route (city versus highway). A marked increase in accentuation of vibration was observed on the city route in the absence of the gel mattress (regression coefficient ± SE = 1.08 ± 0.15; $p < 0.001$), with the greatest accentuation noted when the foam mattress was used alone. This effect of using the foam mattress alone was observed on both city and highway routes (regression coefficient ± SE = 0.42 ± 0.16; $p = 0.017$). There was no statistically significant difference between the gel mattress and gel on foam mattress ($p > 0.05$). The multiple coefficient of determination for the final model was $R^2 = 0.815$.

The PSD function for an acceleration time history measured on the

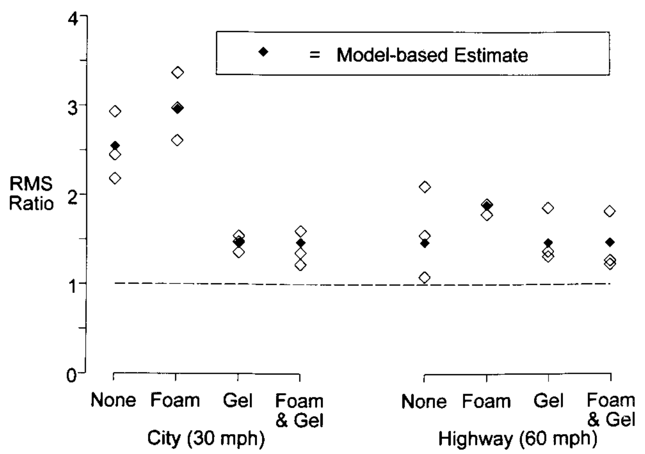

Figure 1. RMS ratios in ambulance transport of a 2000-gm mannequin under eight different experimental conditions: four mattress combinations times two ambulance routes. Replicates are displayed as separate points. The RMS ratio measures relative magnitudes of RMS values of vertical acceleration obtained at mannequin forehead and incubator base. A ratio of <1.0 indicates attenuation of vibration, whereas a ratio of >1.0 indicates accentuation of vibration. The model-based estimates are calculated using the final model from the multiple linear regression procedure described in *Statistical Methods*.

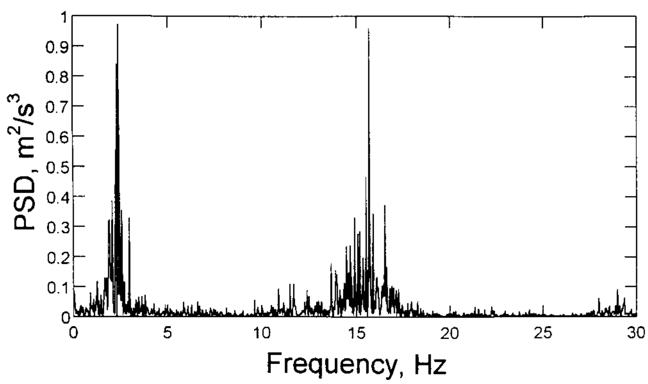

Figure 2. PSD function for an acceleration time history measured at the incubator base. The energy is concentrated at frequencies close to 2.5 Hz and 15 Hz. These frequencies represent the natural frequencies of the ambulance.

city route at the incubator base is shown in Figure 2. The energy in this acceleration time history was concentrated at frequencies close to 2.5 Hz and 15 Hz. These two frequencies were estimated to be the natural frequencies of the ambulance. The natural frequency of the system without any mattress or with the foam mattress was ~12 Hz to ~16 Hz. Thus, under both conditions (no mattress and foam mattress), the natural frequency of the system overlapped the natural frequency of the ambulance, resulting in accentuation of vibration and consequent high RMS ratios. However, the natural frequency of the system when the gel mattress was used, either alone or in combination with the foam mattress, shifted to the range of ~8 Hz to ~10 Hz. Thus, under both of these conditions (gel mattress and gel on foam mattress), the natural frequency of the system did not overlap the natural frequency of the ambulance. The accentuation of vibration was therefore relatively less, and the consequent RMS ratios were lower.

Vertical accelerations were measured satisfactorily in the six ambulance runs using the 300-gm mannequin on a gel mattress. The natural frequency of the system was influenced by the weight of the mannequin. Tests using the 2000-gm mannequin and the gel mattress indicated that the natural frequency ranged from 8 Hz to 10 Hz, which did not overlap the natural frequency of the ambulance. In contrast, tests using the 300-gm mannequin and the gel mattress indicated a shift of the natural frequency toward 15 Hz, which overlapped the natural frequency of the ambulance. This shift of the natural frequency was consistent with the accentuation of vibration that was observed for the lower weight mannequin relative to the higher weight mannequin.

DISCUSSION

In this study, mechanical vibration in ambulance transport was not attenuated by any of the mattress combinations. Vibration was most pronounced at low speed on the city route in the absence of the gel mattress. The gel mattress, used alone or in combination with the foam mattress, produced the least accentuation of vibration. This finding that the gel mattress was superior to the foam mattress with respect to transmission of vibration is in agreement with a previous observation by Sherwood et al.[17] The PSD functions provide an explanation for this superior performance of the gel mattress. In our study, the gel mattress, used alone or in combination with the foam mattress, shifted the natural frequency of the system away from the natural frequency of the ambulance and consequently avoided a large amplification of the vibration. In contrast, the natural frequency of the system when a foam mattress or no mattress was used added resonance to the system by overlapping the natural frequency of the ambulance and consequently further amplified the vibration. Notwithstanding the superior performance of the gel mattress, no mattress combination in our study actually attenuated the vibration under any transport conditions. This finding is in contrast to the previous observation by Sherwood et al.[17] Differences in the methods of assessment of vibration might account for this discrepancy. Nonetheless, the lack of a substantial attenuation of vibration by any of the mattress combinations observed in our study indicates a need for the design of more effective devices that can reduce the hazard of vibration in ambulance transport.

In our study, varying the weight of the mannequin altered the performance of the gel mattress. Specifically, a decrease in weight caused the gel mattress to be less effective in attenuating vibration. Using a 300-gm mannequin, the effect of decreasing weight on vibration might have been exaggerated in our study. Nonetheless, this observation is important, because the hazard of vibration may be most significant in extremely low birth weight infants, and the need to attenuate vibration may be most critical in such transports. To confirm this hazard of vibration, further studies are needed that explore the pathophysiological effects of vibration in human neonates during transport.

Mechanical vibration in transport includes linear motion as well as rotational motion.[18] The linear motion occurs in vertical (heave), horizontal (surge), and lateral (sway) directions, and is pronounced in ground transport.[19] The rotational motion includes pitch, yaw, and roll, and is pronounced in air transport.[19] Although measurements of vertical acceleration, as performed in our study, provide an accurate measure of the amplitude and frequency of vibration,[18] additional measurements of acceleration in both horizontal and lateral directions as well as measurements of rotational motion yield a more detailed representation of the vibration. By limiting our observations to vertical acceleration, we may have underestimated the hazard of vibration in ambulance transport. Newer designs of transport equipment may benefit from the study of these additional aspects of vibration.

In summary, we assessed mechanical vibration in ambulance transport and determined the effect of different mattresses inside the transport incubator on vibration. We conclude that although the gel mattress, used alone or in combination with the foam mattress, results in the least accentuation of vibration, none of the mattresses is effective in attenuating the vibration. The hazard of vibration may be particularly relevant when transporting extremely low birth weight neonates. These findings indicate a need for the study and design of more effective devices that can reduce the vibratory stress.

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