Physical Stressors during Neonatal Transport: Helicopter Compared with Ground Ambulance

Jean-Christophe Bouchut, MD,[1,3] Eric Van Lancker, PhD,[2] Vincent Chritin, PhD,[2] and Pierre-Yves Gueugniaud, MD, PhD[3]

Abstract

Objectives: This study was undertaken to assess concurrent mechanical stresses from shock, vibration, and noise to which a critically ill neonate is exposed during emergency transfer.

Methods: For neonates transported by a French specialized emergency medical service, we measured and analyzed 27 physical parameters recorded during typical transport by ambulance and by helicopter. The noninvasive sensors were placed to allow better representation of the exposure of the newborn to the physical constraints.

Results: Based on 10 hours of transport by ambulance and 2 hours by helicopter, noise, whole body vibration, rate of turn, acceleration, and pitch were extracted as the five most representative dynamic harshness indicators. A helicopter produces a higher-level but more stable (lower relative dispersion) whole body dynamic exposure than an ambulance, with a mean noise level of 86 ± 1 dBA versus 67 ± 3 dBA, mean whole body vibration of 1 ± 0.1 meter per second squared (m/s^2) versus 0.4 6 0.2 m/s^2, and acceleration of 1 6 0.05 m/s^2 versus 0.4 6 0.1 m/s^2. A ground ambulance has many more dynamic effects in terms of braking, shock, and impulsive noise than a helicopter (1 impulsive event per 2 minutes vs. 1 per 11 minutes).

Conclusions: Our results show significant exposure of the sick neonate to both stationary and impulsive dynamic physical stressors during transportation, particularly in a ground ambulance. The study suggests opportunities to reduce physical stressors during neonatal transport.

1. Pediatric Intensive Care Unit, Hôpital Mère-Enfant, Bron, France

2. IAV Engineering, Tannay, Switzerland

3. SAMU, Hôpital Edouard Herriot, Lyon, France

Address for correspondence :
Jean-Christophe Bouchut, MD, PICU and SAMU, Hôpital Edouard Herriot, 69437 Lyon CEDEX 03, France, jean-christophe.bouchut@chu-lyon.fr

This study was presented in part at the 2nd European Academy of Pediatrics meeting 2008, Nice, France.

This study was supported by a grant from the Apicil Foundation. We wish to thank transport teams and pilots for their enthusiasm and support for the conduct of the study.

1067-991X/$36.00

doi:10.1016/j.amj.2010.11.001

Introduction

The goal of neonatal transport by emergency medical service is to improve the clinical status in a critically ill infant who is distant from a hospital that provides the required level of intensive care.[1] Stabilization before transport is of prime importance to avoid deterioration in transit and also to improve the outcome. Although excessive speed is rarely used during transport, the infant is exposed to physical stressors that are potentially hazardous.

Several studies have reported in-vehicle dynamic excitations (noise, vibrations and all kind of kinematics or mechanical effects) at the vehicle floor, incubator, mattress and mannequin, or neonate interface levels.[2-7] Dynamic behaviors were frequently characterized in terms of vertical low-frequency vibrations or noise.[6] However, no data have yet been found in terms of the other whole-body factors to which the transported neonate is potentially exposed, such as acceleration/braking, yaw, pitch and roll, shocks—in other words, all kinds of typical driving or flying kinematic events globally contributing to overall discomfort. The global assessment of such environmental factors encountered by neonates may provide measures to reduce them or reduce the exposure to them. Moreover, such assessment is the first step in studying the probable pathophysiologic effect of transport in newborn infants.[6,8,9]

The aim of the study was thus to record and characterize the dynamic range of physical stressors experienced by neonates during emergency transport by ambulance and helicopter.

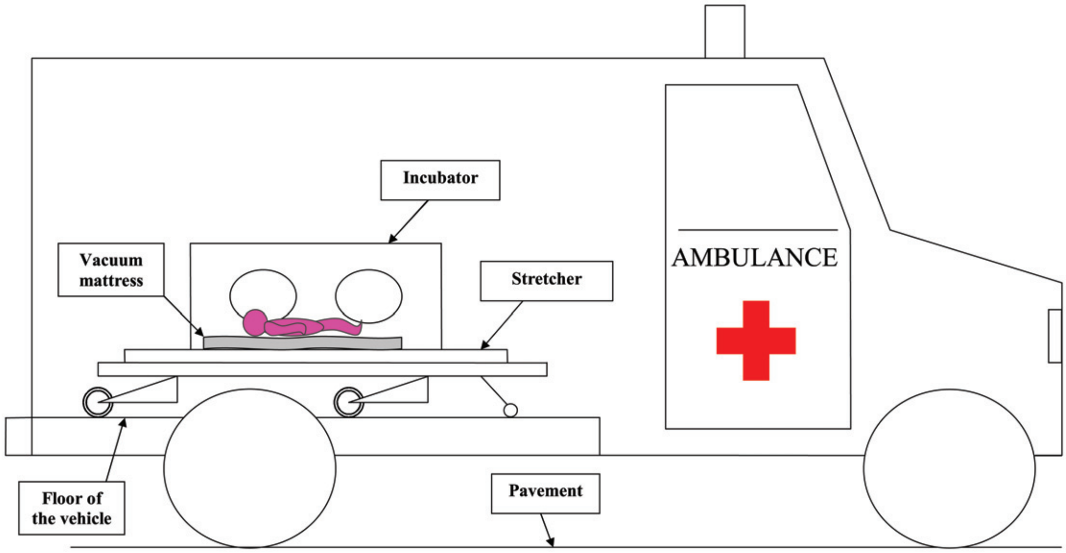
Patients and Methods

Study Design and Population

The study was conducted in a neonatal emergency transport unit of the Service d'Aide Médicale Urgente (SAMU 69) in the Rhône region of France. Fifteen typical urban and periurban postnatal transfers by ambulance and five typical regional transfers by helicopter of neonates requiring a level III neonatal intensive care unit were recorded.

The neonatal transport system consisted of a standard adult stretcher used by emergency medical service with approximately 180 kg (396 lbs) of instrumentation and equipment mounted on the platform, as shown in Figure 1. The neonatal equipment includes a TI 500 incubator (Hill-Rom Air Shields, Hatboro, PA). This existing system does not include a system for shock suppression or vibration isolation. The

Figure 1. Isolette–vehicle–road interface.



ambulance was Renault Master van (2004 Model) with hydropneumatic suspension, and the helicopter was a light twin, four-blade, 2,900 kg (6,400 lbs) gross weight EC135 Eurocopter. The infants were placed in a supine position on a soft, 3-cm (1.2-in) thick "vacuum mattress" with their heads at the rear of the vehicle.

Because patient management was not altered in any way and because information that might identify infants was not collected, neither informed consent nor ethics committee approval for the study was required under French law. Moreover, at no time was the transport team distracted from caring for the infant, because the measurements were carried out exclusively by a dedicated engineer.

Data Collection

Data were all recorded during effective driving or flying phases (ie, the phases of loading and unloading into the vehicles were excluded). Because the evaluation of transfer is highly dependent on the driver and, to a lesser extent on the helicopter pilot, each transport was performed by a different, trained driver or pilot.

The full monitoring setup was designed to capture the best representative measurements of stationary and impulsive or impact noise and whole-body vibrations (in terms of oscillations, shocks, and structure-borne conduction from the structure of the incubator). The objective was to have the best possible representation of what could be perceived in terms of the whole-body kinematics.

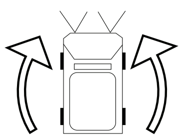
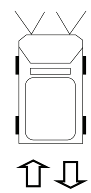
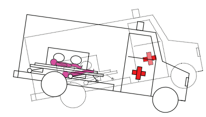
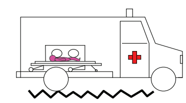
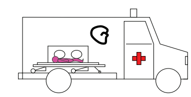
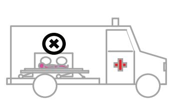
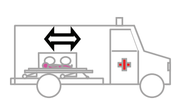
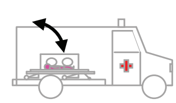
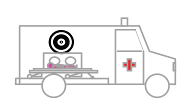
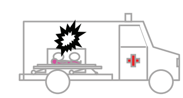
The measurement setup included a triaxial accelerometer glued on a rigid corner of the incubator main frame, a high temporal resolution inclinometer attached to the incubator, a microphone inside the incubator placed approximately 10 cm (4 in) from the infant's ear, and a global positioning system (GPS) antenna placed on the top of the vehicle. All instruments were wired and interfaced to a real-time multichannel digital data acquisition system. This system enabled long-term, non-interpreted, synchronous recording of raw data signals, together with suitable real-time indicator displays and logging, suitable for all in-situ monitoring control needs, (eg, saturation, sample loss, desynchronization), allowing direct in situ data rejection by the authors where necessary.

For each transport, 27 dynamic full-range raw data parameters were recorded (Table 1): longitude, latitude, altitude and speed; yaw, pitch, and roll integrated over a 1-second period (Yaw 1s, Pitch 1s, Roll 1s); gyration around each axis, with a time-constant integration of 1 sec (GyrX 1s, GyrY 1s, GyrZ 1s); and instantaneous (impulse) gyrations round each axis (GyrX Imp, GyrY Imp, GyrZ Imp); acceleration of the incubator as a measure of acceleration of the vehicle itself, both integrated (1 s) and impulse (AccX 1s, AccY 1s, AccZ 1s, AccX Imp, AccY Imp, AccZ Imp); acceleration as the oscillating vibrations of the incubator frame, both integrated and impulse (Ax 1s, Ay 1s, Az 1s, Ax Imp, Ay Imp, Az Imp); and the equivalent noise level in decibels, both integrated and impulse (Leq 1s, Leq Imp).

Impulsive events are defined as sudden events, typically less than 1 second in duration and with a high emergence level. High emergence level means that the impulsive events are not visible in long-term distributions and were isolated separately. Detection criteria for these impulsive events were emergences of up to more than 10 dBA and beyond 85 dB in terms of impact noise, and accelerations with values of up to 2 m/s^2 in terms of vibrations (pavement shocks) and horizontal deceleration (hard braking).[10] No relevant impulse phenomenon was tracked for yaw and pitch because of the mode of transport.

The system enabled the capture and postprocessing of 27 high-resolution, full-dynamic-range parameters, with the final objective being to produce the most representative

Table 1. Description of the Five Parameters Studied

	Events			Background & Events	
	Rate of Turn	**Acceleration / Braking**	**Up/Downhill**	**Vibrations**	**Noise**
Transport situations					
	(GyrY 1s)	(AccX 1s)	(Pitch 1s)	(Ax Ay Az 1s)	(Leq 1s)
	Deg (/second)	$m.s^{-2}$	Deg	$m.s^{-2}$	dBA
	1 sec.	1 sec.	1 sec.	1 sec.	1 sec.
	Quasi-static (0..10 Hz)	Quasi-static (0..10 Hz)	Quasi-static (0..10 Hz)	Dynamic 1 – 100 Hz	Dynamic 20 Hz – 20 kHz
Expected effects on transported neonates	Centrifugal inertial force strain 	Head-to-feet + and - inertial force strain 	Body inclination 	Mixed whole-body and vibrational absorbed power 	Hearing stress 

behavioral indicators of the observed phenomenon. The distributions (over their full range of amplitude) of the following five independent dynamic harshness parameters were found to be the most pertinent representation:

- Distribution of instantaneous acceleration in the horizontal axis in meter per second squared (integrated from continuous 0 Hz acceleration up to10 Hz range, ie, the range of all dominant accelerations in the concerned observations)
- Distribution of instantaneous rate of turn or yaw, degrees per second gyration over the same representative 0–10-Hz range
- Distribution of instantaneous vibrations or shock as the root-mean-square of whole-body vibration in the x, y, and z axis in meters per second squared, over the 1-Hz to 20-kHz range (range of all perceivable vibrations and shocks in the concerned observations)
- Noise level distribution inside the incubator expressed in dB SPL over the 20 Hz to 20 kHz A-weighted range (ie, according to noise monitoring standards)
- Distribution of pitch (vertical angle) in degrees over the 0–10-Hz range (far over the full range of interest)

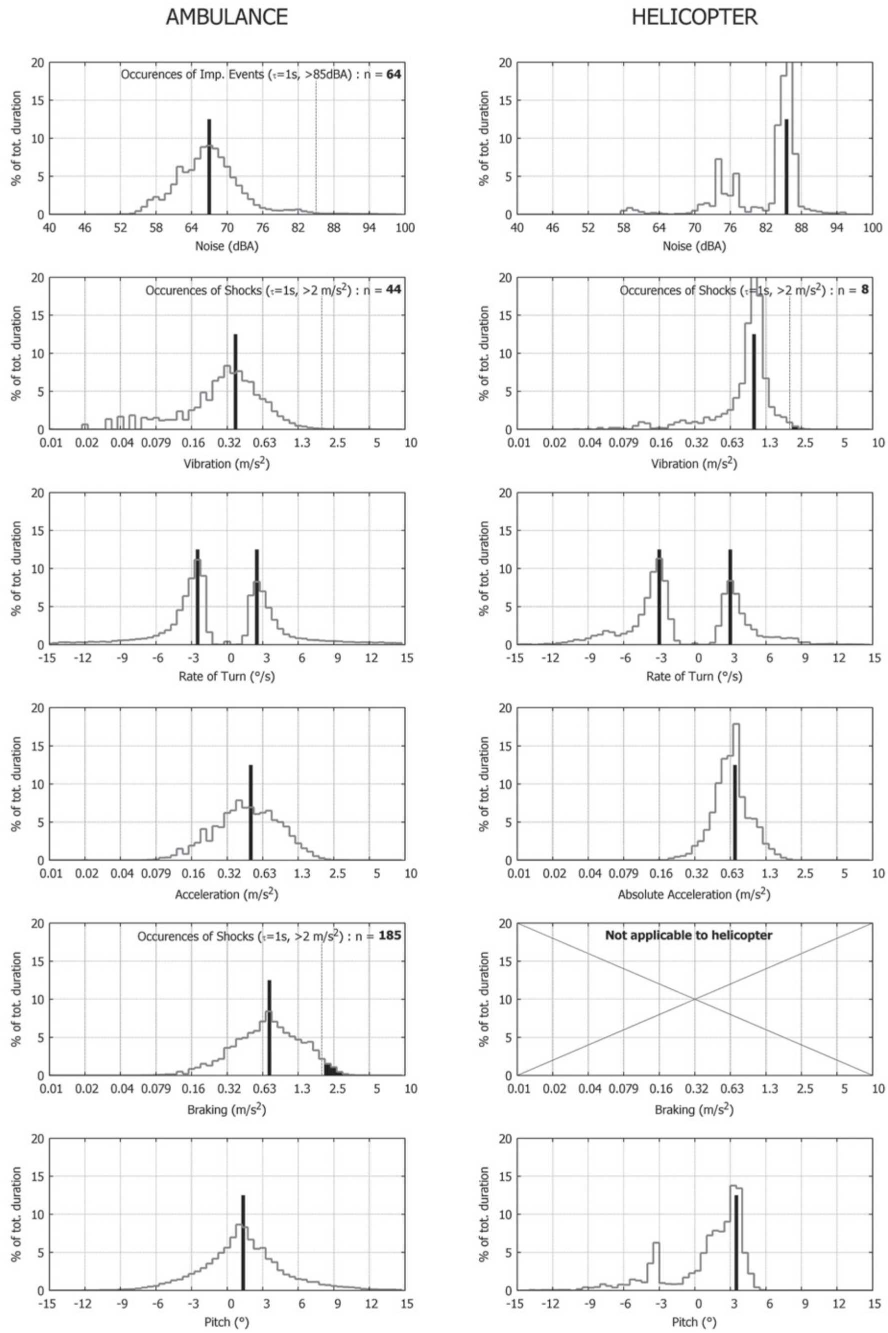
Results are presented as the mean with standard deviation expressed as percentages "+" and "–" rather than as absolute values to point out asymmetry and differences in the distribution.

Results

Figure 2 shows the distribution of the five most representative dynamic indicators based on 10 hours 26 minutes of transport by ambulance and 1 hour 50 minutes by helicopter. Both were considered sufficiently representative volumes of data as demonstrated by the convergence profile of the distributions obtained as a function of the duration of recordings (new measurements would only add minimal information to the results).

The helicopter produces higher-level but more stable (lower relative dispersion) whole-body dynamic exposure than the ambulance, with a mean noise level of 86 ± 1 dBA versus 67 ± 3 dBA, mean whole-body vibration of $0.9^{+12\%}_{-10\%}$ m/s^2 versus $0.35^{+40\%}_{-28\%}$ m/s^2, and acceleration of $0.7^{+26\%}_{-20\%}$ m/s^2 versus $0.45^{+100\%}_{-50\%}$ m/s^2. The ground ambulance has more dynamic effects in terms of braking, shock, and impact noise than the helicopter (1 impulsive event per 2 minutes vs. 1 per 11 minutes). No difference was seen in the rate of turn and pitch

Figure 2. Distribution of five representative indicators based on 10 hours 26 minutes of transport by ambulance and 1 hour 50 minutes by helicopter. N values as impulsive events are expressed when present or relevant. Vertical black lines represent an indication of the median of the distribution.



amplitudes between the two transport modes. The helicopter has a constant flying angle, compared with a more distributed pitch along country and urban roads for ambulance.

Discussion

Our study provides new data on characterization of whole-body dynamic stresses to which neonates are exposed during transport. Ground ambulance transfers are characterized by numerous dynamic events, whereas air transfers are generally more stable. In air transfers, global whole-body vibrations and noise are of higher levels but usually of gradual and predictable onset, with a stationary profile type (low variability and no impulses).

No studies recording simultaneously all physical parameters during actual transports have been previously performed in neonatal transport. The current study is not intended to supply a specific characterization of whole-body vibration during neonatal transport, supplementary noise survey, or other such targeted single descriptor; rather, the study investigates a maximally representative measurement of the global effective dynamic exposure during emergency transport as encountered by neonates in a typical French specialized service. Because environmental vibration levels or intensities vary with type of transportation, mechanical mounting structure, and with flight or driving conditions, our results should be considered as an initial standard reference basis that, when supplemented with new studies, may help to establish a more comprehensive characterization of the physical stressors encountered by neonates.

The whole-body vibration in a ground ambulance as measured is in the range of 0.3 to 0.6 m/s^2, which is commonly described by the guide to International Standard ISO 2631 as being "a little uncomfortable."[10] With a mean level of 1 m/s^2, the helicopter may be described as "uncomfortable." However, this approach may be insufficient to establish the level of discomfort, because experimental and theoretical evidence shows that short-duration, high-acceleration events have a greater influence on human health and subjective discomfort than the long-term averaged indicators.[11]

During the course of the study, we recorded five times more impulsive shocks in ambulances than in helicopters. With continuous interactions with roads and traffic, a driver may potentially have greater influence on the transport dynamic than the pilot does. When transporting by road, rapid positive and negative (eg, with hard braking) changes in horizontal acceleration, and also rate of turn, produce acute negative gravity forces (Gz) and centrifugal perturbations that are particularly dangerous for the brain patient.[12] Dynamically, the most common situation of a neonate transported in an ambulance forms a mechanical subsystem and associated behaviors as follows:

- At the first level, of main interest, the neonate itself, supine position, head at the rear of the vehicle
- A viscoelastic, or in other words a more or less rigid and dissipative, interface between the neonate and the incubator (the mattress)
- An incubator with a mostly rigid supporting structure frame, with possible integrated dampers, viscoelastic suspension or low-pressure inflated tires
- A suspended vehicle floor (interface between the incubator wheels and the vehicle chassis), and more generally all cabin structures
- Unsprung masses of the vehicle (axles, wheels)

This multi–degree-of-freedom system interacts continuously with road interfaces (eg, road surface, pavements), road trajectory (straight lines, turns), and topography (ascent, descent).

Because of the interaction of these elements, the emphasis should be to optimize driving by avoiding erratic driving and hard braking, in particular in the initial and final phases of braking. Assuming that the noise from the siren perceived inside the incubator seems far less critical than the kinematic and dynamic effects of movements and acceleration, the infants should be transferred using "blue lights and siren," not for increased speed with the risk of crash,[13] but to continuously open and clear traffic for fluid operation and avoid all deleterious effects of potentially adverse movements. Noise and vibration reduction efforts at the different mechanical levels could always be made, particularly by improving the yaw compensation and by the design of the vibration isolation or shock suppression system.[14] However, the authors strongly believe that an improvement in short-term outcomes lies in driver and pilot education, either through introduction of periodic training and certification or through complementary real-time feedback technology.[15]

The sound levels measured in the incubator in a helicopter are higher than in an ambulance, however, with very few impulsive noise events. The typically 85-dB stationary high-level noise suggests that ear plugs for infants could therefore be considered. A model that would bring a typical 7-dB overall noise reduction would theoretically reduce the in-ear noise dose by typically a factor of 4 (-3dB = half power). Conversely, the duration of flight rarely exceeds 1 hour, and the mean noise level is lower than the level measured in the mouth of neonates under long-time nasal continuous positive airway pressure.[16]

As associated ergonomic and practical recommendations, the design of the transportation unit for the helicopter should take into account the higher cabin ambient noise level as greatly limiting the audibility of alarms (monitor, infusion pumps, and ventilator). Second, infant supplies and equipment should be placed to allow good visual access from the primary side of observation.

At landing, rapid deceleration has been suspected as the cause of a sudden rise in venous cerebral perfusion and a potential risk of cerebral bleeding.[17] Indeed, the most severe vibration levels occur during landing, twice as much as during normal cruise.[18] However, no study demonstrates the relation between helicopter transport and intraventricular hemorrhage in newborn infants. Epidemiologic data support the fact that transport is associated with a high risk of cerebral bleeding in very-low-birth-weight infants but with no consideration of mode of transport.[19,20] Moreover, a recent population-based study reports an air transport–related mortality rate similar to a study in which neonates were transported by ground.[21] In our study, high impulsive shocks while flying are far less frequent than in an ambulance, but occur during the shutdown of the rotor. As a predictable and repeatable event, this event could be quite conveniently controlled partially by a person raising the baby and the mattress by hand in the isolette. Other countermeasures should be studied.

The frequency range of interest for all kinematics aspects (yaw, pitch, roll, horizontal acceleration/deceleration) has been determined to be those frequencies situated from the quasi-static domain to the few Hz range in ambulances, and helicopters. For noise and vibrations, the frequency range of interest strictly extends wideband up to 20 kHz, but with vibrational energetic components typically below 30 Hz in helicopters (low-frequency dynamics governed by the rotating pass-by frequency of the rotor, 26 Hz for the EC135 model), and below 100 Hz in ambulance (6.7 and 16 Hz for the vehicle used). The only energetic components in the medium- and high-frequency range thus remaining are the siren noise in the case of the ambulance and the turbine noise in the case of the helicopter.

If little is known about the effects of horizontal frequencies on the neonate's body, it could be of high clinical importance in the risk of mobilizing prostheses (lines and tubes) and hence the need to secure them.

The asymmetrical result, showing more ascents than descents, is simply related to the fact that more transports were done to the level III neonatal intensive care unit that is situated on the top of a hill.

Loading and unloading phases, which are probably the most critical phases of transportation, were not studied.[22] However, these phases are very similar in our unit between helicopter and ground ambulance and probably do not make a difference when comparing the two types of transportation. In cases in which the landing zones are far from the hospital, the number of loading and unloading events can be up to six events, which is probably in disfavor of helicopter transport.

Because fixed-wing aircraft transportation is very rare in our practice, this type of transportation was excluded from our study.

The research presented in this article offers new insights into dynamic hazards experienced by neonates, which are a prerequisite for a better understanding of the pathophysiologic stress response during transport. The effects and interactions of physical stressors in critically ill infants during transportation are unknown. The thresholds of tolerance or the scale of comfort described from adult, military, or animal studies cannot be applied to neonates. Grosek et al[9] found an association between daytime ground transportation and increased heart rate and peripheral blood leukocyte counts. Because of many compounding factors, including population studied, reason for transfer, treatment given, or the kind of transport, the pathophysiologic effect of transport is difficult to study. Our results emphasize the importance of stabilizing sick neonates before transport to minimize the impact of physical strain and a preference for antenatal transfer whenever possible.

Conclusion

This study provides new information on dynamic physical parameters encountered by sick neonates during transport. Ground ambulance transfers are characterized by successive numerous dynamic events, whereas helicopter transfers have global whole-body vibrations and higher noise, typically with a gradual and predictable onset. The study raises major concerns about the degree of exposure of the sick neonate to stationary and impulsive physical stressors during transportation, despite specialized teams and modern means of transportation. An assessment of stress during transport is highly desirable but requires a better understanding of the pathophysiologic effects of transport in newborn infants. Efforts should be made continuously to reduce physical stressors to enhance the safety of neonatal transport.

References

1. Cornette L. Transporting the sick neonate. Current Paediatr 2004;14:20-5.
2. Campbell AN, Lightstone AD, Smith JM, Kirpalani H, Perlman M. Mechanical vibration and sound levels experienced in neonatal transport. Am J Dis Child 1984;138:967-70.
3. Robertson A, Cooper-Peel C, Vos P. Sound transmission into incubators in the neonatal intensive care unit. J Perinatol 1999;19:494-7.
4. Giacomin J, Gallo S. In-vehicle vibration study of child safety seats. Ergonomics 2003;46:1500-12.
5. Shenai JP, Johnson GE, Varney RV. Mechanical vibration in neonatal transport. Pediatrics 1981;68:55-7.
6. Macnab A, Chen Y, Gagnon F, Bora B, Laszlo C. Vibration and noise in pediatric emergency transport vehicles: a potential cause of morbidity? Aviat Space Environ Med 1995;66:212-9.
7. Buckland L, Austin N, Jackson A, Inder T. Excessive exposure of sick neonates to sound during transport. Arch Dis Child Fetal Neonatal Ed 2003;88:F513-6.
8. Hohlagschwandtner M, Husslein P, Klebermass K, Weninger M, Nardi A, Langer M. Perinatal mortality and morbidity: comparison between maternal transport, neonatal transport and inpatient antenatal treatment. Arch Gynecol Obstet 2001;265:113-8.
9. Grosek S, Mlakar G, Vidmar I, Ihan A, Primozic J. Heart rate and leukocytes after air and ground transportation in artificially ventilated neonates: a prospective observational study. Intensive Care Med 2009;35:161-5.
10. International Organization for Standardization (1997) Mechanical vibration and shock: evaluation of human exposure to whole-body vibration, Part 1: General requirements. ISO 2631-1:1997.
11. Sandover J. High acceleration events: an introduction and review of expert opinion. Journal of Sound and Vibration 1998;215:927-45.
12. Handy JM. The physiological effects of transferring critically ill patients. Clin Intensive Care 2005;16:65-9.
13. Hunt RC, Brown LH, Cabinum ES, Whitley TW, Prasad NH, Owens CF Jr, et al. Is ambulance transport time with lights and siren faster than that without? Ann Emerg Med 1995;25:507-11.
14. Bailey-Van Kuren M, Shukla A. System design for isolation of a neonatal transport unit using passive and semi-active control strategies. Journal of Sound and Vibration 2005;286:382-94.
15. Levick NR, Swanson J. An Optimal Solution for Enhancing Ambulance Safety: Implementing a Driver Performance Feedback and Monitoring Device in Ground Ambulances. Proceedings, 49th Annual Conference of the Association for the Advancement of Automotive Medicine, September 2005.
16. Karam O, Donatiello C, Van Lancker E, Chritin V, Pfister RE, Rimensberger PC. Noise levels during nCPAP are flow-dependent but not device-dependent. Arch Dis Child Fetal Neonatal Ed 2008;93:F132-4.
17. Skeoch CH, Jackson L, Wilson AM, Booth P. Fit to fly: practical challenges in neonatal transfers by air. Arch Dis Child Fetal Neonatal Ed 2005;90:F456-60.
18. Wu J, Zhang RR, Wu Q, Stevens KK. Environmental vibration assessment and its applications in accelerated tests for medical devices. Journal of Sound and Vibration 2003;267:371-81.
19. Towers CV, Bonebrake R, Padilla G, Rumney P. The effect of transport on the rate of severe intraventricular hemorrhage in very low birth weight infants. Obstet Gynecol 2000;95:291-5.
20. Bowman E, Doyle LW, Murton LJ, Roy RN, Kitchen WH. Increased mortality of preterm infants transferred between tertiary perinatal centres. BMJ 1998;29:1098-100.
21. Lang A, Brun H, Kaaresen PI, Klingenberg C. A population based 10-year study of neonatal air transport in North Norway. Acta Paediatr 2007;96:995-9.
22. Alberti E, Chiappa D, Moschioni G, Saggin B, Tarabini M. Whole body vibration in mountain-rescue operations. Journal of Sound and Vibration 2006;298:580-93.