Acceleration during neonatal transport and its impact on mechanical ventilation

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► Additional supplemental material is published online only. To view, please visit the journal online (http://dx.doi.org/10.1136/archdischild-2021-323498).

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Received 7 November 2021
Accepted 29 May 2022

ABSTRACT

Objective During interhospital transfer, critically ill neonates frequently require mechanical ventilation and are exposed to physical forces related to movement of the ambulance. In an observational study, we investigated acceleration during emergency transfers and if they result from changes in ambulance speed and direction or from vibration due to road conditions. We also studied how these forces impact on performance of the fabian+nCPAP evolution neonatal ventilator and on patient-ventilator interactions.

Methods We downloaded ventilator parameters at 125 Hz and acceleration data at 100 Hz sampling rates, respectively, during the emergency transfer of 109 infants. Study subjects included term, preterm and extremely preterm infants. We computationally analysed the magnitude, direction and frequency of ambulance acceleration. We also analysed maintenance and variability of ventilator parameters and the shape of pressure-volume loops.

Results While acceleration was <1 m/s^2 most of the time, most babies were occasionally exposed to accelerations>5 m/s^2. Vibration was responsible for most of the acceleration, rather than speed change or vehicle turning. There was no significant difference between periods of high or low vibration in ventilation parameters, their variability and how well targeted parameters were kept close to their target. Speed change or vehicle turning did not affect ventilator parameters or performance. However, during periods of intense vibration, pressure-volume ventilator loops became significantly more irregular.

Conclusions Infants are exposed to significant acceleration and vibration during emergency transport. While these forces do not interfere with overall maintenance of ventilator parameters, they make the pressure-volume loops more irregular.

WHAT IS ALREADY KNOWN ON THIS TOPIC

⇒ Interhospital transport of critically ill infants can cause significant distress to them and may increase the risk of some complications such as intraventricular haemorrhage.
⇒ Infants are exposed to various physical stimuli and forces during the transport, including acceleration and vibration of the vehicle.

WHAT THIS STUDY ADDS

⇒ Vibration, rather than change in speed or direction of the ambulance vehicle, is responsible for most of acceleration forces during transport.
⇒ Even during periods of significant vibration or sustained acceleration, ventilator parameters are maintained close to their set level.
⇒ Significant vibration makes pressure-volume loops more irregular.

HOW THIS STUDY MIGHT AFFECT RESEARCH, PRACTICE AND/OR POLICY

⇒ Advanced ventilation modes such as synchronised and volume targeted ventilation can be safely used during neonatal transport.
⇒ In addition to avoiding quick acceleration and deceleration, ambulances should also try to minimise vibration by road choice and by limiting the speed of the vehicle.

INTRODUCTION

Interhospital neonatal transport is essential for providing high quality neonatal care for a geographical region. In utero transfer of mothers with impending very preterm delivery has been considered good practice for decades,.[1] However, as preterm birth or critical illness of infants is not always predictable[2] and in utero transfer is not always possible,[3] some sick infants are delivered in district hospitals and need to be transferred to level 3 neonatal intensive care units (NICUs) or specialist centres. The increasing centralisation of neonatal services is also dependent on availability high-quality neonatal transport.

Even with dedicated neonatal ambulances and specialist neonatal transport teams, postnatal transport can present significant trauma and risk for vulnerable infants. In population-based studies, survival of extremely preterm infants born in hospitals equipped with level 3 NICUs was better than survival of infants transferred to these centres postnatally.[4 5] Severe intraventricular haemorrhage is also more frequent after ex utero transport,[6] although it is uncertain whether this reflects the impact of postnatal transport or better initial stabilisation in level 3 centres.[7]

Neonatal ground transport is associated with significant vibration and acceleration due to road and traffic conditions.[8–12] It has been suggested that both vibration (acceleration whose magnitude and direction changes periodically with high frequency) and ‘sustained’ acceleration (changes in the ambulance’s speed or its direction due to the vehicle speeding up, slowing down or turning left or right) during transfer may impact on the infant’s condition.[13–15] Animal studies described the adverse

To cite: Lantos L, Széll A, Chong D, *et al*. *Arch Dis Child Fetal Neonatal Ed* Epub ahead of print: [*please include* Day Month Year]. doi:10.1136/archdischild-2021-323498

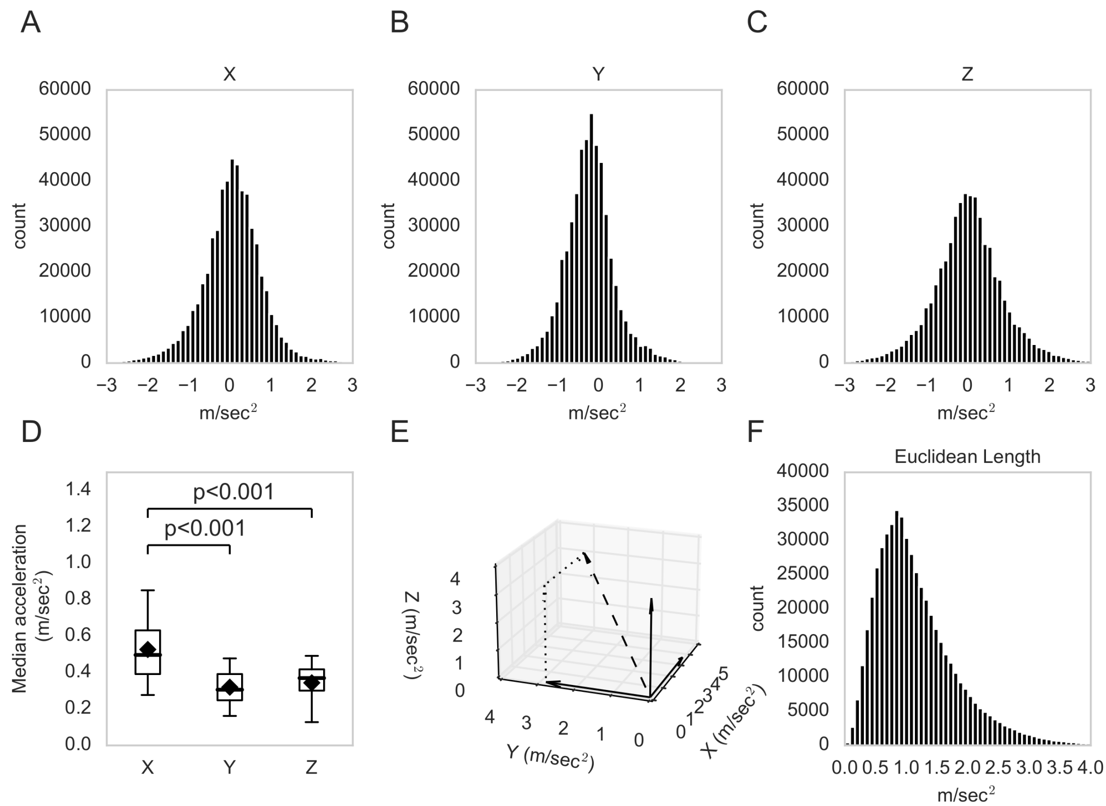

Figure 1 Acceleration of ambulance in the three directions of space. (A–C) Histograms showing the distributions of acceleration measurements during transfer of a preterm infant born at 30 weeks and weighing 950 g. Acceleration vector reading counts are shown separately in the front-back (X), left-right (Y) and up-down Z directions. Sampling rate was 100 Hz. Only acceleration readings up to 3 m/s^2 are shown, although rarely higher values also occurred. Similar graphs for all recordings are shown in online supplemental figure 1. (D) Boxplots showing the distribution of the median absolute acceleration of the recordings in each direction. The largest acceleration occurred in the front-back (X) direction, significantly larger than in the left-right (Y) or up-down (Z) directions. Group medians are marked by horizontal line, means by black diamonds. Boxes represent IQR; error bar corresponds to 95% range. (E) The three components of the acceleration vector: X (front-back), Y (side-to-side), Z (up-down) accelerations. The ambulance is moving in X direction. The graph only shows positive accelerations but acceleration can also be negative when the ambulance is slowing down (X), turn to the right (Y) or during vertical vibration (Z) . Absolute value of an acceleration component is its distance from zero, that is, its value without a sign. The dashed arrow shows the length (Euclidean norm) of the acceleration vector, see main text for more details. (F.) Distribution of the length (Euclidean norm) of the acceleration vector for the same recording as shown in A–C.

health implications of vibration on respiratory and cardiovascular systems.[16]

Critically ill infants frequently require mechanical ventilation during transport. Vibration and sustained acceleration during transfer can potentially influence mechanical ventilation via multiple mechanisms. These physical forces may affect the ventilator's performance, increase variability of the peak inflating pressure (PIP) and the tidal volume (VT) or their deviation from set target values. They might trigger physiological responses in the infant, resulting in changes in respiratory rate, breathing effort and minute ventilation. Finally, they may affect ventilator-patient interactions, resulting in irregular ventilator waveforms and loops. In a recent paper, we reported how closely tidal volumes are maintained to the target volume during volume targeted ventilation in neonatal transport.[17] However, the impact of the ambulance's sustained acceleration and vibration on mechanical ventilation has not been reported yet.

In this study, we analysed the impact of these physical forces on ventilator parameters and ventilator-patient interactions during interhospital neonatal transfers. We wanted to determine the acceleration levels occurring during neonatal transfers and whether they are predominantly due to change in speed or direction of the ambulance or to vibration. We also investigated whether sustained acceleration or vibration impact on the maintenance and variability of ventilator parameters and the occurrence of ventilator-patient interactions.

METHODS

Patients

Clinical, ventilator and ambulance acceleration data were collected from 153 infants transferred by the Neonatal Emergency and Transport Service of the Peter Cerny Foundation (NETS-PCA, Budapest, Hungary) between April 2018 and May 2020. All infants were ventilated during interhospital transport using a fabian+nCPAP evolution neonatal ventilator (Vyaire Medical, Mettawa, Illinois, USA), software V.4.0.1). The transport team included a neonatologist with experience in neonatal transport and a neonatal transport nurse practitioner. Ambulance drivers were professional drivers with several years' experience in driving neonatal ambulances. All transfers were completed using blue lights, siren and ambulance priority.

For this study, we included infants if the net journey time was >10 min after removing periods when baby was ventilated with the transport ventilator before departure or after arrival or when the transport incubator was moved between the neonatal

Table 1 Summary clinical details, ventilator modes used and duration of recordings

Number of cases	109
	Median (range)
Recording duration (min)	44 (11–106)
Clinical details	**Median (range)**
Gestational age (weeks)	36 (22–41)
Postnatal age (hours)	6.0 (1.6–1644)
Postmenstrual age (weeks)	37 (22–45.8)
<29 weeks (n)	15
29–32 weeks (n)	20
33–36 weeks (n)	17
37–40 weeks (n)	15
>40 weeks (n)	12
Birth weight (grams)	2840 (400–4900)
Weight at transfer (grams)	2880 (400–4900)
Primary reason for referral	**Number of cases**
Respiratory failure in preterm infants	37
Respiratory failure in term infants	21
Cardiac	15
Surgical	8
Hypoxic-ischaemic encephalopathy	26
Neurosurgical	2
Ventilator modes	**Recordings**
SIMV	63
SIMV-PS	4
SIPPV	34
More than one mode	8
VG on*	97
VG off*	17

*In some cases, VG was turned on or off during the transfer.
SIMV, synchronised intermittent mandatory ventilation; SIMV-PS, synchronised intermittent mandatory ventilation with pressure support of spontaneous breaths; SIPPV, synchronised intermitted positive pressure ventilation; VG, volume guarantee.

unit and the ambulance or vice versa (n=113). Of them, we excluded four infants whose postmenstrual age was >46 weeks. Respiratory management, including the choice of ventilator mode and settings, was at the discretion of the transport team without an explicit protocol. Babies received sedative medication for the transfer but were not fully sedated or muscle relaxed. Clinical data were collected from electronic healthcare records.

Ambulance equipment, ventilator and accelerometer data

Vehicles were all Mercedes-Benz Sprinter vans with air suspension, equipped and used as dedicated neonatal ambulances. The transport incubator was Dräger TI 5400 (Dräger, Germany), fixed on a bed using a hydraulic antivibration system (HydroSoft, Fahrtec, Germany). The infant was placed on a Vacuum Pillow vacuum mattress (AB Germa, Sweden). Movement periods of the ambulance were retrieved from an iTrack GPS tracking system (iDATA, Hungary, https://www.idatatelematics.com) and were also verified by reviewing patient records.

Ventilator data were recorded by a data logger developed by Vyaire for research purposes. The software downloaded airway pressure, flow and volume data at 125 Hz frequency. It also downloaded ventilator parameters (eg, PIP, tidal volume, ventilator rate, minute ventilation, fraction of inspired oxygen and so on) with 0.5 Hz sampling rate. Ventilator settings and their changes were also recorded. The 0.5 Hz PIP and tidal volume data correspond to the last inflation that occurred before the time stamp. Minute ventilation is calculated as rolling mean over 30 s, and it includes both ventilator inflations and spontaneous breaths, if present. Data were retrieved with millisecond time stamps and exported as text files.

Ambulance acceleration data were collected using a freely available software (Accelerometer Analyzer, V.16.11.27, https://chipapk.com/app/39720) installed on a mobile phone, which was fixed on the top of the transport incubator, correctly aligned with the direction of travel. The internal clocks of the accelerometer and the ventilator were synchronised to the minute before each transfer. The accelerometer's sensor collects acceleration data with 100 Hz sampling rate along three dimensions: front-back (X), left-right (Y) and up-down (Z). The sensor's resolution is 0.009 m/s^2, its maximum range is 39 m/s^2 and its minimum delay is 10 milliseconds. Acceleration data were exported as text files.

Data analysis

Data were analysed using Python (V.3.7.4, https://www.python.org) and its data science packages (for details, see online supplementary methods 1). Notebooks containing and explaining all steps of data processing and analysis can be viewed on GitHub code repository at https://github.com/belteki/ambulance_acceleration.

For accelerometer data, we subtracted the gravitational acceleration (9.81 m/s^2) from the vertical (Z) acceleration measurements. To separate high-frequency vibration and low-frequency 'sustained' acceleration (due to the ambulance accelerating, decelerating or turning left or right), we used third order Butterworth high-pass and low-pass filters, respectively.[18] Cut-off frequency was 0.5 Hz in both cases. For each minute and along each axis (X, Y and Z), we calculated the median of the absolute value (the quantity without the sign) of the vibration and of the sustained acceleration vectors during the minute. To determine the overall acceleration or vibration (irrespective of direction), we calculated the Euclidean length (also known as L2 norm) of the vectors as square root of ($X^2+Y^2+Z^2$) (see figure 1E).[19]

For ventilator parameters showing normal distribution, arithmetic mean and SD, for parameters with non-parametric distribution, median and IQR were calculated for each minute. For each recording, the 1 min periods with the highest and lowest vibration or sustained acceleration were compared. Paired T-tests were used for significance testing.

To investigate how irregular pressure-volume (PV) loops become at different vibration levels, all inflations and breaths over 1 min periods were plotted on the same chart. Irregularity of these composite loops was quantitated as the number of PV data pairs occurring over the 1 min period. The 1 min periods with the lowest and the highest median vibration for each recording were then compared.

RESULTS

We analysed accelerometer and ventilator data from 109 infants receiving mechanical ventilation during interhospital emergency transfer. Basic clinical data of the infants are shown in table 1. The total duration of recordings was 82.4 hours.

Vibration is responsible for most of ambulance acceleration

Acceleration was less than 1 m/s^2 in each direction most of the time (figure 1A–C, see online supplemental figure 1 for similar graphs for all recordings). However, periods of high acceleration occurred (online supplemental figure 2), with of >5 m/s^2

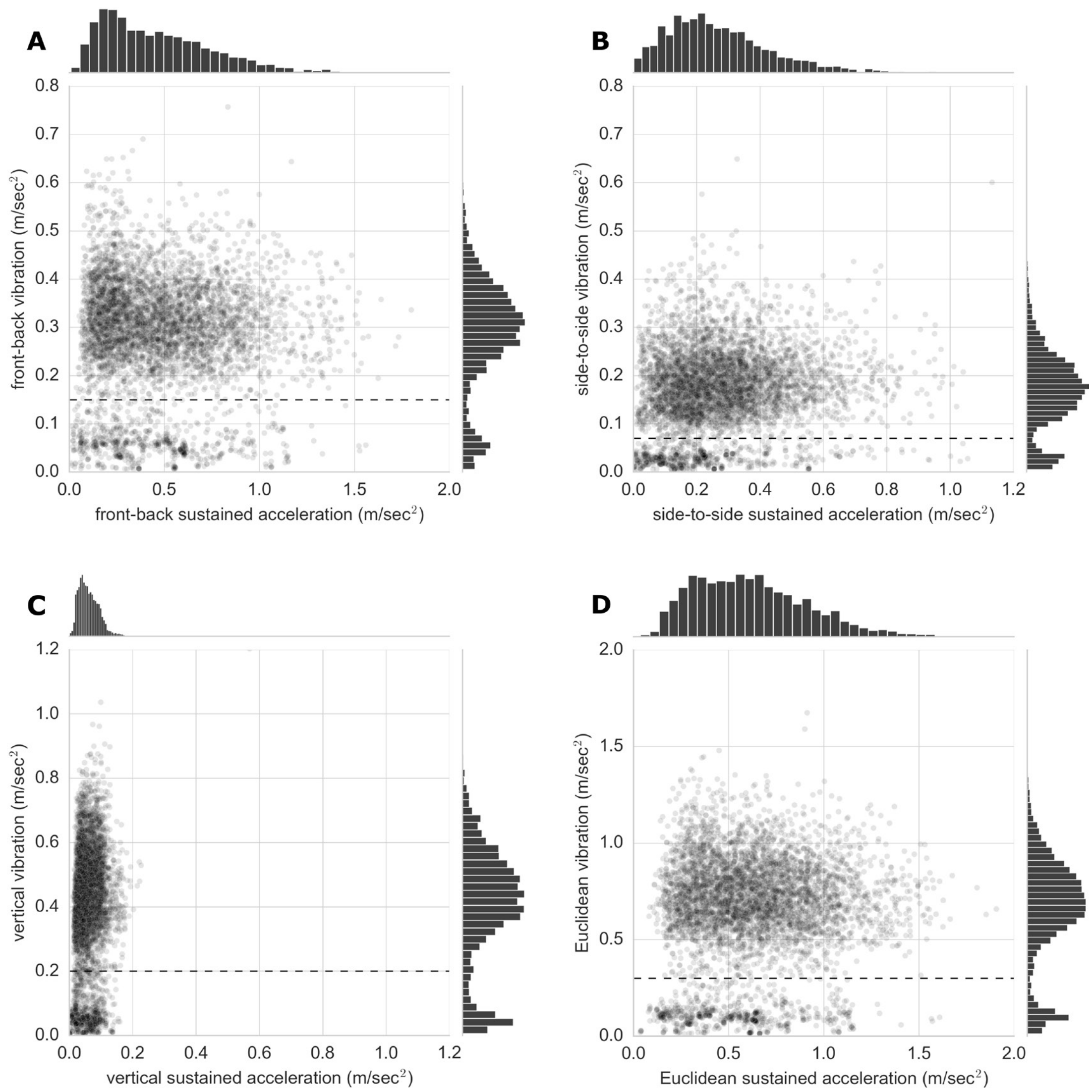

Figure 2 Scatterplots showing the median vibration during each 1 min period plotted against the median sustained acceleration over the same period. Histograms for each variable are shown along the axes. (A–C) Acceleration and vibration along the front-back (X), left-right (Y) and up-down (Z) axes, respectively. In vertical direction (Z) only vibration was possible. (D.) Euclidean length of the acceleration and vibration vector for each minute. Minutes when vibration was >0.3 m/s^2 (area above the dashed lines on D) were considered as periods of vibration (with or without sustained acceleration). Minutes when the sustained acceleration was high but there was no vibration likely correspond to periods when the ambulance changed its speed or direction frequently while travelling on a smooth road surface.

acceleration readings occurring in most recordings. Overall, the acceleration component in the direction of ambulance movement (X) was the largest, ranging between 0.16 and 1.37 m/s^2 (group median 0.51 m/s^2), significantly ($p<0.001$) larger than the side-to-side (Y, 0.11–0.64 m/s^2, group median 0.32 m/s^2) or up-down (Z, 0.03–0.55 m/s^2, group median 0.38 m/s^2) accelerations (figure 1D).

We plotted the median sustained acceleration against the median vibration for each minute in each direction (figure 2A–C). This showed that during most minutes, there was significant vibration in all directions. However, in the X (front-back) and Y (side-to-side) directions, there were also minutes characterised by significant sustained acceleration but with little vibration; they likely represent periods when the ambulance was increasing or decreasing its speed on a relatively smooth surface (direction X, see figure 2A), or turned left or right (direction Y, see figure 2B). As expected, in vertical direction (Z) there was only vibration (figure 2C and).

Neither vibration nor sustained acceleration significantly affect ventilator parameters

There was no alignment between periods of high or variable acceleration and variability of tidal or minute volume, respiratory rate, PIP and fraction of inspired oxygen (online supplemental figure 2).

As they represent different physical forces and potentially impact differently on the ventilator and the baby, we studied the impact of vibration and sustained acceleration separately. We considered minutes as periods of vehicle vibration when the median vibration was >0.3 m/s^2 (figure 2D). Minutes when vibration was <0.3 m/s^2 were considered as periods of no vibration, although significant sustained acceleration occurred during some of them.

We compared ventilator parameters during the minute with the highest and the lowest vibration in each recording (table 2). There was no difference in the average expired tidal volume, PIP,

Table 2 Comparison of ventilator parameters during periods of low and high vibration

	Minute with lowest vibration	Minute with largest vibration	
All transfers (n=109)			
	Group mean (SD)	**Group mean (SD)**	**P value***
Vibration (m/s^2) †	0.40 (0.07)	1.09 (0.19)	<0.0001
VTemand (mL/kg)	5.23 (1.79)	5.28 (1.86)	0.55
MV (mL/kg/min)	0.28 (0.11)	0.29 (0.11)	0.07
PIP (cmH$_2$O)	18.2 (6.7)	18.0 (6.7)	0.49
FiO$_2$ (%)	37.3 (22.6)	37.0 (21.6)	0.64
Volume guarantee ventilation (n=97)‡			
	Group mean (SD)	**Group mean (SD)**	**P value***
Vibration (m/s^2) †	0.41 (0.08)	1.09 (0.19)	<0.0001
VTemand (mL/kg)	5.19 (1.54)	5.29 (1.73)	0.27
PIP (cm H$_2$O)	18.0 (7.1)	17.8 (7.0)	0.57
	Group median (range)	**Group median (range)**	**P value§**
VTdiff (mL/kg)	0.54 (0.03–6.76)	0.51 (0.03–5.05)	0.63
Pdiff (cm H$_2$O)	12.5 (0.2–32.9)	11.8 (0.1–30.8)	0.60
Pressure limited ventilation (n=17)‡			
	Group mean (SD)	**Group mean (SD)**	**P value***
Vibration (m/s^2) †	0.44 (0.12)	1.04 (0.21)	<0.0001
VTemand (mL/kg)	5.54 (2.74)	5.33 (2.36)	0.45
PIP (cm H$_2$O)	18.6 (3.6)	18.7 (3.3)	0.75
	Group median (range)	**Group median (range)**	**P value§**
Pdiff (cm H$_2$O)	0.3 (0.2–1.7)	0.5 (0.2–0.6)	0.58
SIPPV mode (n=34)			
	Group mean (SD)	**Group mean (SD)**	**P value***
Vibration (m/s^2) †	0.4 (0.07)	1.14 (0.22)	<0.0001
RR (1 /min)	58.6 (16.2)	60.3 (14.0)	0.21
	Group median (range)	**Group median (range)**	**P value§**
RRdiff (1 /min)	13.3 (0–56.5)	16.5 (0–50)	0.29
SIMV mode (n=63)			
	Group mean (SD)	**Group mean (SD)**	**P value***
Vibration (m/sec^2) †	0.40 (0.07)	1.06 (0.16)	<0.0001
VTemand (mL/kg)	5.53 (2.14)	5.57 (2.21)	0.69
VTespon (mL/kg)	2.43 (2.47)	2.54 (2.68)	0.53

For each minute of recording, the median acceleration and the mean of the ventilator parameters were calculated. For each recording, the 1 min periods with lowest and highest vibration were chosen. Group statistics of these data are shown in table.
*Two-tailed paired Student T-test.
†Euclidean length of acceleration vector (see Methods section).
‡During some transfers volume guarantee was turned on only for part of the transfer.
§Wilcoxon signed rank test
FiO$_2$, fraction of inspired oxygen; MV, minute ventilation; Pdiff, absolute difference between the set and actual PIP (during pressure limited ventilation) or the maximum allowed inflating pressure and actual PIP (during volume guarantee ventilation); PIP, peak inflating pressure; RR, ventilator rate; RRdiff, the difference between the ventilator rate and the set minimum backup rate during SIPPV mode; SD, standard deviation; SIMV, synchronised intermittent mandatory ventilation; SIPPV, synchronised intermittent positive pressure ventilation; VTdiff, absolute difference between the target and actual expired tidal volume during volume guarantee ventilation; VTemand, expired tidal volume of ventilator inflations; VTespon, the tidal volume of spontaneous breaths during SIMV mode.

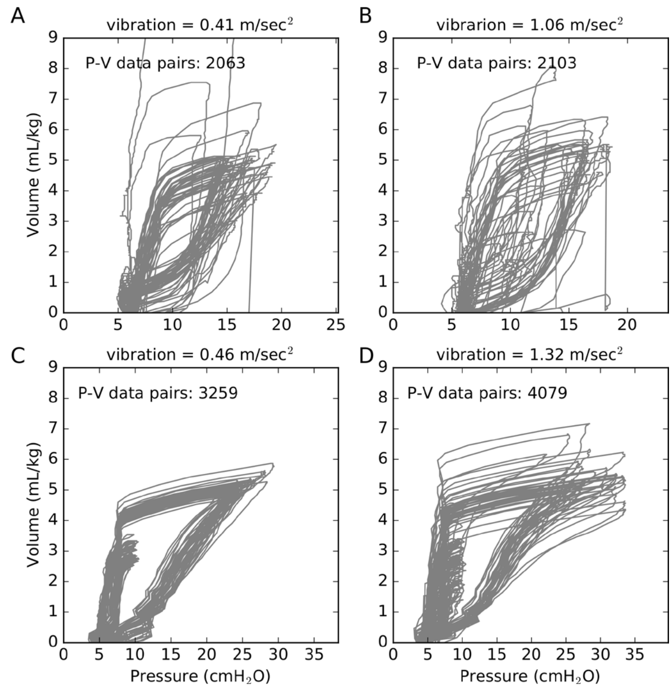

Figure 3 Composite pressure-volume loops over 1 min periods with low and high vibration. The graphs show the loops of all respiratory cycles (mandatory or spontaneous) occurring during the minute. Median vibration is shown above the graphs. The number of pressure-volume (P-V) data pairs occurring during the period are shown in the chart area. Higher number of P-V data pairs correspond to more irregular loops. (A,B) P-V loops of an infant born at 26 weeks of gestation who was 32 days old and weighed 1325 g at the time of the transfer. (C,D) P-V loops from a baby born at 36 weeks of gestation and transferred on the first day of life. During the period of intense vibration, PV loops became more irregular in both cases, with the number of P-V data pairs increasing.

minute ventilation and fraction of inspired oxygen between these periods. The variability of these parameters was also not affected by vibration (data not shown). No differences were seen even in extremely preterm infants (online supplemental table 1). During volume guaranteed ventilation, the tidal volume was maintained equally well during periods of high vibration compared with periods of low vibration; during pressure limited ventilation the PIP was delivered as set by the user. In synchronised intermittent positive pressure ventilation (also known as assist-control), infants did not trigger more inflations during the vibration periods.

We also compared ventilator parameters during the minutes with the highest and lowest sustained (front-back or side-to-side) acceleration but without significant vibration, and found no differences in these parameters or in their variability either (online supplemental table 2).

Impact of vibration on pressure-volume loops

Vibration frequently made the PV loops more irregular (figure 3). Overall, the complexity (expressed as the number of PV data pairs during a period) of the PV loops was higher during the 1 min period with the highest vibration than during the minute with lowest vibration (online supplemental table 3). The median (IQR) number of PV data pairs were 2522 (1928–3148) and 2740 (2029–3418), respectively ($p<0.0001$, Wilcoxon signed rank test).

DISCUSSION

In this study, we found that during most minutes, there was significant vibration, with or without significant change the speed of vehicle or its direction. We also found that even significant vibration or sustained acceleration did not affect ventilator parameters or ventilator performance. As vibration is largely influenced by road surface and vehicle speed, our findings highlight the importance of preferring roads with even surface and limiting the speed of the ambulance, rather than simply avoiding quick acceleration, deceleration or turning.

A strength of our study is that we studied a large number (n=109) of babies requiring emergency transport for reasons which are representative of the activities of most neonatal transport services. Ventilation and acceleration data were collected prospectively and computationally, eliminating the biases and limitations associated with manual data collection.

Our study has some limitations. It was observational rather than a randomised controlled trial; however, exposing babies to higher acceleration and vibration than absolutely necessary would be unethical. We did not record and analyse physiological parameters such as oxygen saturation, heart rate or blood pressure which could have provided more information about clinical instability or distress in these infants. As we used the ventilator's sensors for measuring ventilator performance, our experimental setup did not detect potential sensor errors. Finally, as the clocks of the ventilator and the accelerometer were manually synchronised, our data were not suitable to detect instantaneous and specific responses to acceleration shorter than 1 min.

Acceleration and vibration levels inside emergency vehicles are affected by road conditions, traffic, driving style, vehicle make, model and suspension. Moreover, the acceleration transferred to the transport incubator and to the infant also depends on how the incubator is fixed within the ambulance and how the infant's position is stabilised within the incubator. In our ambulances, the incubator was mounted on a pneumatic anti-vibration system, while in some ambulances, a solid mechanical fixation is used, potentially resulting in more vibration transferred to the incubator and to the baby. Despite all these variables, the acceleration values obtained in our study are similar to those obtained by others.[11 20] Finally, we fixed the accelerometer to the top wall of the transport incubator, while in some studies, it was attached directly to the infant;[12] however, babies probably faced similar acceleration and vibration levels as measured because they were stabilised by a vacuum mattress inside the incubator.

We used the fabian+nCPAP evolution neonatal ventilator. Our findings may not necessarily generalise to all neonatal ventilators. The ventilator is not registered for interhospital neonatal transfer by its manufacturer; however, it is used by several neonatal transport services after integration into transport trolleys by third party services, as in our case (Andreas Waldmann, Vyaire, personal communication). Nonetheless, our work provides evidence that modern ventilation modes such as synchronised ventilation and volume targeting can be used safely during neonatal transport without significant interference from the physical forces arising during the journey.

Despite stability of ventilator parameters, we found that intense vibration made the PV loops more irregular and complex, although the extent of this was variable. This phenomenon may be due to the direct physical effect of vibration on the ventilator-patient unit or it may reflect physiological responses of the baby. The latter can be influenced by gestation and weight, postnatal age, critical illness and sedation. The large number of potential covariates may be responsible for the variable impact of vibration in different recordings. Nonetheless, our paper provides the first evidence that vibration during transport may affect ventilator-patient interactions in some critically ill infants.

In summary, we have found that sustained acceleration and vibration of the neonatal ambulance does not affect significantly ventilator parameters and performance of the fabian+nCPAP evolution neonatal ventilator, even when using advanced ventilation modes. Similar studies with other ventilator models will further establish the safety of modern ventilators during neonatal transport.

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Acknowledgements We thank to Rainer Kühner (Vyaire) for help with exporting data from the fabian +nCPAP evolution ventilator. We thank to Professor Colin Morley and Dr Amanda Ogilvy-Stuart for their advice and comments on the manuscript.

Contributors GB designed the study, wrote the computer programs to analyse ventilator data and performed the data analysis. LL, AS and ZS performed the transfers and collected clinical data. DC wrote some of the computer programs required for data analysis. GB is reponsible for the overall content of the paper as the guarantor. All authors revised and approved the final manuscript.

Funding The authors have not declared a specific grant for this research from any funding agency in the public, commercial or not-for-profit sectors.

Competing interests GB is a consultant to Vyaire Medical (Mettawa, IL, USA) and Dräger Medical (Lübeck, Germany). Vyaire Medical did not participate in this research and did not provide any payment for it.

Patient consent for publication Not applicable.

Ethics approval The study was approved by the Scientific and Medical Research Council Ethics Committee of Hungary (reference: 40158-2/2018/EKU). As this was an observational study, the Research Ethics Committee has waived the need for individual parental consent. All procedures were performed in accordance with the ethical standards of the Research Ethics Committee and the amended Helsinki Declaration (1983).

Provenance and peer review Not commissioned; externally peer reviewed.

Data availability statement Data are available on reasonable request. The Jupyter notebooks containing and explaining all the computer (python) code used for data processing and analysis can be viewed on GitHub code repository at https://github.com/belteki/ambulance_acceleration. Raw ventilator and accelerometer data are available on request.

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