Characterization of Whole Body Vibration Exposures in Neonatal Ground Transport

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Abstract

Characterization of Whole Body Vibration Exposures in Neonatal Ground Transport

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Newborn infants delivered in a compromised health state often require transport between secondary and primary care hospitals. The objective of this study was to measure and characterize Whole Body Vibration (WBV) exposures during simulated newborn infant inter-hospital ground transport and determine how vehicle-based vibration is transmitted through the chain of equipment used to support newborn infants and whether there is a need and potential for mitigation of these exposures. These WBV exposures were also compared to two typical daily activities of infants, riding in a car seat and riding in a stroller. A simulated newborn infant was transported over a typical transport route utilizing a standard stretcher system and two potentially mitigating strategies: a modified stretcher system with a stabilizing strut and a new, modified vibration dampening stretcher system. The average-weighted vibrations and the vibration dose values were calculated, and the frequency spectra profiles were examined. Relative to the floor measured vibration (0.36 m/s^2), the standard stretcher system amplified the average weighted vibration through the chain of equipment nearly doubling the vibration at the interface where the simulated neonate rested (0.67 m/s^2). These measures exceeded those found with the car seat and the indoor stroller. The new stretcher system with the built-in suspension reduced the exposure at the interface to 0.48 m/s^2. In contrast, the strut-based stretcher system did not perform as expected, increasing the vibration at the interface (1.2 m/s^2). Results were similar for VDV exposures. The frequency spectra present in the standard stretcher system was primarily between 4-15 Hz, raising concern because of the overlap with natural resonance frequency of the human body (4-12 Hz). The new stretcher with the built-in suspension effectively negated the vibrations in the 4-10 Hz range. The transmissibilities indicated that there is potential for further mitigation at points between the aluminum transfer sled and the interface. This research presents a unique mitigating strategy to reduce elevated neonate whole body vibration exposures and addresses potential further mitigation points. It also contributes information to the field for further development of standards and implementation of whole body vibration exposure limits that are applicable across the lifespan.

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DEDICATION

To Stella and Lincoln

I do this as much for you as for myself. If something is scary or hard, it just may be that much more important to do. You will take the world by storm, I have no doubt.
I am so blessed to be your mommy.

Chapter 1. INTRODUCTION

1.1 BACKGROUND & SIGNIFICANCE

Newborn infants delivered in a compromised health state often require transport between point of delivery and an advanced care pediatric hospital. As described by Messner (2011), "Neonatal Emergency Transport Service" is the transfer of a sick baby during a time that he needs access to neonatal care beyond that which is available at the point of delivery. This transfer to a tertiary care pediatric hospital is undertaken with the intent to improve the health outcomes for this vulnerable population. However, the transport process is not without its own problems. An increase in the morbidity and mortality of infants who are transported between hospitals has long been an issue. In 1988, Bowman, Doyle, Murton, Roy, and Kitchen found that the mortality rate of preterm infants who had been transferred between tertiary perinatal centers was 50%, compared to 24% for those infants who had not been transferred. Additionally, Gleissner, Jorch, and Avenarius (2000) and Mohamed and Aly (2010) found that transport to another hospital was associated with an increased risk of intraventricular hemorrhage among neonates. Macnab, Chen, Gagnon, Bora, and Laszlo (1995) also describe an unexplained deterioration in the condition of some neonates following a long transport.

Concern over the exposure of this vulnerable population to unnecessary external stressors, such as excessive noise, motion, poor lighting, limited space, and mechanical vibrations, during transport has been raised (Messner, 2011). The motion of the infant within the transport vehicle can cause difficulty in clinical assessment and treatment, especially in cases that involve intubation or intravenous treatments. The assessment of breathing and heart rate patterns and blood pressure measurements are also difficult to obtain due to the noise, motion, and vibration that are characteristic of transit in a ground ambulance (Prasad et al., 1994; Sherwood, Donze, & Giebe, 1994). It is understood that humans are vulnerable to mechanical vibrations and that human sensitivity to vibration varies with the frequency of vibration (Campbell, Lightstone, Smith, Kirpalani, & Perlman, 1984). Exposure to whole body vibration (WBV) may impact the infants' near and longer-term health outcomes (Grosek, Mlakar, Vidmar, Ihan, & Primozic, 2009; Macnab et al., 1995). However, it is not clear exactly what the extent of exposure is, what the role of current transport equipment is in these WBV exposures, and whether these exposures are modifiable.

1.2 WBV MEASUREMENT

The primary element in WBV measurement is the vibration exposure. As described by Griffin (1990), the vibration exposure is needed to document vibration conditions, determine which aspects of vibration would benefit from reduction, compare relative severity of different exposures, and compare the vibration experienced with existing standards. Vibrations exposures are complex. Vibration contains many frequencies, occurs in multiple directions, and changes over time (International Standards Organization(ISO), 1997). These measurements are typically gathered utilizing an accelerometer that gathers mechanical energy and converts it into electrical output proportional to acceleration (Griffin, 1990). This measurement is collected at the point where the vibration is considered to enter the body (ISO, 1997) or the interface between the environment and the human body (Griffin, 1990).

According to the International Organization for Standardization (1997), the primary quantity of vibration magnitude is acceleration. Acceleration is used to characterize the displacement of the body along three primary axes. For the seated individual, translational vibration is measured along the axes depicted in the left image of Figure 1.1 and is expressed in meters per second squared (m/s^2) (ISO, 1997). The ISO (1997) standard further states that for recumbent persons vibration will be measured along the X (up and down), Y (side to side), and Z (front to back) axes (right, Figure 1.1). Vibration values are typically mean square (RMS) values weighted according to ISO 2631-1 (1997). The parameters of interest in this thesis are the average weighted vibration exposures (A_w) (Equation 1.1) and Vibration Dose Values (VDV) (Equation 1.2). A_w is representative of the average of the continuous vibration experienced for a given period, whereas VDV is a cumulative measure of the impulsive events that occur during the experience, such as going over railroad tracks or potholes, and is more sensitive to the peak exposures experienced.

Average Weighted Vibration:

$$Aw = \left[\frac{1}{T}\int_0^T acceleration^2(t)dt\right]^{\frac{1}{2}} * \left[\frac{8\ hours*60\ minutes}{minutes\ measured}\right]^{\frac{1}{2}} \tag{1.1}$$

Vibration Dose Value:

$$VDV = \left[\int_0^T \{acceleration^4(t)\}dt\right]^{\frac{1}{4}} \tag{1.2}$$

ISO 2631-1 (1997) states that, for all vibration exposures, magnitude and duration of the exposure will be reported, and information on the frequency content and direction will be included. The frequency range of interest for this purpose is 0.5 Hz to 80 Hz as this is the range associated with human health effects (ISO, 1997). Of specific concern are vibrations in the range of 4-12 Hz as these vibrations are known to be resonance frequencies of the human body, potentially causing amplification of vibration to the internal tissues and organs (ISO, 1997; Macnab et al., 1995; Sallee, Bentley, Walding, & Christofi, 2016).

The United States does have voluntary standards for the assessment and measurement of WBV but does not have regulations pertaining to human exposure to whole body vibration. The European Union (EU) has regulations (Vibration Directives), which were adapted from the International Organization for Standardization (ISO 2631-1) standard. According to the EU Directive (2002), the daily action limits for WBV A_w and VDV are 0.5 m/s^2 and 9.1 $m/s^{1.75}$, respectively. When these levels are exceeded during an 8-hour period the chances for adverse health outcomes are thought to increase. When the same parameters, A_w and VDV, exceed the EU-based daily exposure limits of 1.15 m/s^2 and 21 $m/s^{1.75}$, immediate action and engineering controls should be implemented to reduce the exposure. These standards are applicable for adults in a seated position, but no standards exist for persons in a recumbent position or for children (Browning, Walding, Klasen, & David, 2008; ISO, 1997). For the purposes of this study, as in previous studies in this field, these standards can be used as a metric for comparison (Bailey-Van Kuren & Shukla, 2005; Blaxter et al., 2017)

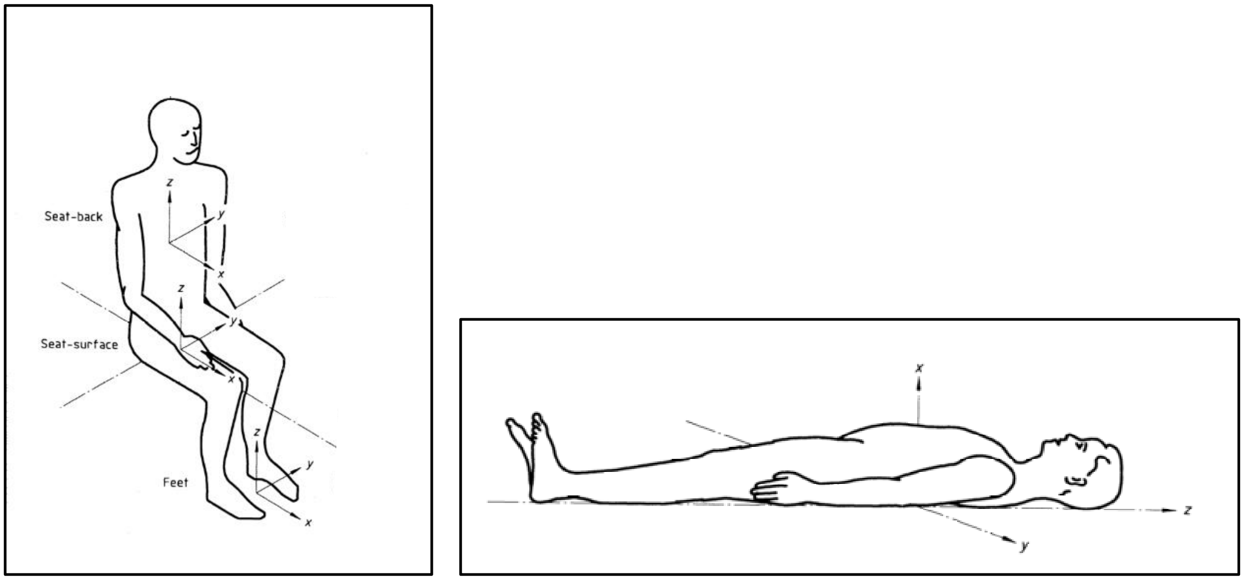

Figure 1.1. Axes of the Human Body; seated (left) and recumbent (right) (Adapted from ISO, 1997)

1.3 VIBRATION EXPOSURE CONCERNS FOR NEONATES IN TRANSPORT

The first documented research measuring the mechanical vibrations present in neonatal transport was published in 1981 by Shenai, Johnson, and Varney. They reported that neonates experience prolonged low-frequency and high-amplitude levels of mechanical vibration and shocks during inter-hospital ground transport. Sherwood et al. (1994) looked at the peak acceleration and vibration levels averaged over a minute at four locations on the transport equipment and on the ambulance floor. Their results indicated an accentuation of vibration from the floor to the isolette – the life support system and housing in which the neonates are transported. In a 1995 study by Macnab et al., the authors reported vibration levels inside an isolette transported by ground ambulance; the maximum exposure levels were greater than 1.5 m/s^2 and average vibration levels reached 0.5-1.0 m/s^2. Campbell et al. (1984) also examined vibration within the isolette during ground transport and reported vibration acceleration of less than 10 Hz, raising concern due to the sensitivity of humans to low frequency vibrations. Similarly, the study by Shenai et al. (1981) measured the vertical accelerations experienced by neonates inside a transport isolette while being transferred by ground ambulance. They found that vibrations were most substantial from 3 to 18 Hz and peak acceleration amplitudes ranged from 2.0 to 6.0 m/sec^2.

More recently, Karlsson et al. (2012) found that the WBV exposures in ground ambulance transport were predominantly in the 3-8 Hz frequency range with the peak acceleration exposure at 3.9 m/s^2, further substantiating the vibration findings in previous studies. In an effort to further the field of study and gather representative measurements of whole body kinematics, Bouchut, Van Lancker, Chritin, and Gueugniaud (2011) examined 27 different parameters and compared ground ambulance to helicopter transport. Of note, the authors found that ground ambulance transports had one impulsive event per two minutes compared to helicopter transports that had one impulsive event per every 11 minutes. In most of the studies already mentioned, vibrations experienced by neonates during ground transport reach, and in many cases, surpass the recommended levels for adults (Campbell et al., 1984; Karlsson et al., 2012; Macnab et al., 1995; Shenai et al., 1981).

1.4 HEALTH IMPACTS OF VIBRATION

The effects of WBV in adults and laboratory conditions has long been studied. Vibration is known to cause fatigue, interfere with visual acuity, and decrease response time (Floyd, Broderson, & Goodno, 1973; Griffin, 1990). Clark, Williams, Hood, and Murray (1967) noted cardiovascular effects and respiratory complications in male adults and animal subjects subjected to short-term vibrations, and Floyd et al. (1973) reported decreases in body temperature in rhesus monkeys that were subjected even to relatively benign vibrations (12 Hz) and sharp increases in peripheral-nerve conduction time when they were subjected to severe, low-frequency (6-8 Hz) vibrations. WBV has also been studied in association with increased risk of skeletal and muscle morbidities, specifically low back pain (Bovenzi, 2010).

Neonates, in particular, show a large sensitivity to external stimulation (Browning et al., 2008). There have been several different approaches to determine whether neonates experience increased stress or discomfort due to transport between hospitals. In 2009, Grosek et al. found that neonates experience an increased level of stress during daytime ground transport as evidenced by elevated heart rate levels and elevated leukocyte levels. Another study by Harrison and McKechnie in 2012 looked at heart rate and oxygen saturation combined with behavioral measurements like facial expression to measure the neonates’ response during transport, and they indicated that pain scores, based on facial responses, rise during the transport process. As described by Macnab et al. (1995), researchers have had a difficult time developing a strong case for the specific impact of vibration on neonates due to the numerous variables that can potentially impact the outcome in the transported population.

1.5 PREVIOUS EFFORTS

In an effort to address and overcome the concerns raised by previous researchers, several studies have examined potential mitigating strategies to reduce WBV exposures. Campbell et al. (1984) noted that portions of the isolette were excited and imparted substantial vibrations to the neonate during transit, and they speculated that this may be due to resonances in the isolette itself. They recommended the application of a gasket between surfaces of the isolette to potentially reduce these vibrations. However, Macnab et al. (1995) tested the dampening effects suggested by Campbell and found them ineffective.

Both Gajendragadkar et al. (2000) and Sherwood et al. (1994) looked at using different mattress types to reduce vibration exposures. Gajendragadkar et al. (2000) looked at four different types of mattresses and found no true attenuation for any of the mattresses examined. Sherwood et al. (1994) found that a gel mattress provided some attenuation of vibration, but measurements were only taken over a five-minute route, which may decrease the applicability of these results to longer, or transportation routes that differ in speed or road types . Shah, Rothberger, Caprio, Mally, and Hendricks-Munoz (2008) examined the use of an air-foam mattress as compared to a standard mattress and noted some successful attenuation of vibrations in one dimension. Bailey-Van Kuren and Shukla (2005) looked to reduce the mechanical vibrations during neonatal transport utilizing air-spring systems, both passive and semi-active models. They determined that the passive system they examined provided stable dynamic behavior but did not provide sufficient dampening of the vibration exposures.

In 1995, Macnab et al. compared a new transport isolette to a 15-year-old isolette, and found no significant differences between the two models, indicating that no adjustments had been made to decrease the potential vibration exposures despite past research indicating this need. Prehn et al. (2015) examined 10 different mattress configurations and vibration isolation materials to reduce the vibration exposures experienced by neonates of very low birth weight (VLBW; < 1500 g). They determined that a combination of a gel mattress over an air chambered mattress was effective in reducing vibration exposures for VLBW infants. This study was conducted on an airport runway, limiting the generalization to normal transport routes, but the authors did provide evidence that the effectiveness of vibration reducing mattresses may be influenced by infant weight.

In support of past research and in an effort to contribute to developing appropriate standards, Browning et al. (2008) and Sallee et al. (2016) have worked to determine the baseline vibrations of transport isolettes. Browning et al. (2008) specifically examined the vibration exposures at the level of the tray of a transport isolette and found the maximum average acceleration during intra-hospital transport to be 2.6 m/s^2 and the peak acceleration value during the same route to be 15.9 m/s^2. Sallee et al. (2016) continued this same line of research with forced vibration tests using a large shaker table in a simulated environment. They examined methods for stabilizing the patient tray inside the isolette and found that tethering the patient tray to the rigid frame of the isolette provided significant attenuation of the vibration experienced in the vertical axis during this simulated scenario.

1.6 RESEARCH GAPS AND OPPORTUNITIES

Methods for characterizing the physical trauma incurred by transport-induced forces have not been well documented (Shah et al., 2008), but methods for quantifying the WBV exposures experienced by neonates during ground transport have been increasingly well documented in recent years (Blaxter et al., 2017; Browning et al., 2008; Prehn et al., 2015; Sallee et al., 2016; Shah et al., 2008). However, a gap in the characterization of the overall exposure process and resolution of the problem remains.

Past studies have pointed to important and targeted future research strategies. Based on a study that examined the transport process for 16 neonates, Karlsson et al. (2012) recommended the development of vibration dampening isolettes, and Bouchut et al. (2011) recommended combining their study results with new studies to establish a more comprehensive characterization of the exposures. Macnab et al. (1995) recommended close study of the efficacy of vibration reducing modifications and that efforts be directed at reducing vibration in the low frequency range. Shenai et al. (1981), Campbell et al. (1984), and Macnab et al. (1995) all called for careful evaluation of vibratory stress and the use of attenuation techniques in the design of new transport equipment. The implementation of vibration attenuation techniques into transport isolettes does not appear to have happened, to date, leaving room for updated characterization of exposures and improved modification recommendations.

1.7 RESEARCH OBJECTIVES AND SPECIFIC AIMS

The primary objective of this study was to measure and characterize WBV exposures during inter-hospital ground ambulance transport using a simulated neonate to determine how vibration is transmitted from the floor of the ambulance through the chain of equipment used to support neonates (the stretcher, aluminum transfer sled, and isolette). Additional objectives were to compare transport exposures to common daily activities experienced by infants such as riding in a car seat and riding in a stroller and to compare exposures experienced using standard transport equipment to exposures using potentially mitigating strategies. This study is the first to look at the characterization of the vibration exposures throughout the chain of transport equipment during a normal transport route, both before and after potentially mitigating strategies are implemented, and it will be the first to compare these exposures to reference activities (common activities of daily life) in lieu of standard exposure limits for WBV exposures for infants.

The central hypothesis of this dissertation is that the proposed mitigating strategies will reduce overall WBV exposures experienced by neonates during ground ambulance transport. This hypothesis was formulated, in part, based upon pilot study data that suggests that current WBV exposures experienced by neonates during ground ambulance transport exceed adult exposure limits by up to three times the allowable limit and that the exposure is amplified by the existing equipment used in transport. The rationale for this research is that it has potential to characterize this hazard and identify potential solutions for predicted hazards. These studies are focused on three Specific Aims:

Aim 1. Quantify and characterize the exposure of simulated neonates to whole body vibration during ground ambulance transport using current transport equipment to determine how the equipment may affect WBV exposures.

Hypothesis 1. *WBV exposures experienced by neonates during transport with standard equipment are amplified by the transport equipment used.*

Aim 2. Quantify and characterize the WBV experienced by simulated neonates during stroller and car seat exposures and compare these common activities of daily life to the WBV experienced during ground ambulance transport.

Hypothesis 2. *WBV exposures experienced by neonates during transport are greater than those experienced during common activities of daily life.*

Aim 3. With simulated neonates, characterize the WBV exposures in the chain of transport equipment following implementation of vibration reducing equipment and assess the difference in WBV exposures between current and mitigating strategies to determine if exposures are reduced with use of the new equipment.

Hypothesis 3. *WBV exposures experienced by neonates during transport with mitigating strategies is reduced compared to transport with standard equipment.*

This research is an important contribution to research related to the health outcomes of neonates, an already fragile population. This work examined ground ambulance WBV exposures from their current state through the implementation of mitigating strategies. It contributes to future research in quantifying WBV exposures throughout the chain of transport equipment and informing the development of exposure limits for children, as appropriate. It improves the understanding of current WBV exposures experienced by neonates during ground ambulance transport and identifies potential sources for mitigation. Additionally, it allows for an applicable comparison of the ground transport WBV exposures to standard day-to-day exposures and demonstrates the reduction of WBV exposures through the implementation of mitigating strategies.

Chapter 2. CHARACTERIZATION OF NEONATE WBV EXPOSURES IN GROUND AMBULANCE AND COMPARISON ACTIVITIES

2.1 INTRODUCTION

The effects of whole body vibration (WBV) in adults have long been studied. Vibration is known to cause fatigue, interfere with visual acuity, and decrease response time (Floyd et al., 1973; Griffin, 1990). Clark et al. (1967) noted cardiovascular effects and respiratory complications in male adults subjected to short-term vibrations, and WBV has also been associated with increased risk of skeletal and muscle morbidities, specifically low back pain (Bovenzi, 2010). WBV exposures for adults have been measured and classified, and exposure standards and limits have been put in place by the International Standards Organization (ISO) (1997) and by the EU Directive (2002). This same attention has not been given to children. It is not known what health effects WBV exposures have on children, and it is unclear whether there are acceptable levels of vibration exposure or what these levels may be. In adults, prolonged WBV exposure has been linked to multiple physical ailments, but potential health effects for children may be the same as adults, or there may be other unknown impacts.

The health effects on neonates as they are exposed to whole body vibration during transport by ambulance between hospitals are of particular concern. Newborn infants delivered in a compromised health state often require transport between point of delivery and an advanced care pediatric hospital. As described by Messner (2011), “Neonatal Emergency Transport Service” is the transfer of a sick baby during a time that he needs access to neonatal care beyond that which is available at the point of delivery. During a period when they are already at increased vulnerability and risk for increased adverse health outcomes, the introduction of external stressors such as mechanical vibration during transport may cause increased morbidity and even increased mortality (Boenisch et al., 1985; Bowman et al., 1988; Gleissner et al., 2000; Grosek et al., 2009; Shah et al., 2008). Bowman et al. (1988) found that the mortality rate of preterm infants who had been transferred between tertiary perinatal centers was 50%, compared to 24% for those infants who had not been transferred. Additionally, transport to another hospital has been associated with an increased risk of intraventricular hemorrhage (Gleissner et al., 2000; Mohamed & Aly, 2010) and an unexplained deterioration in the condition of some neonates following a long transport (Macnab et al., 1995).

Previous research has begun to look at characterizing these vibration exposures. In 1981, Shenai et al. reported that neonates experience prolonged low-frequency and high-amplitude levels of mechanical vibration and shocks during inter-hospital ground transport. Sherwood et al. (1994) went on to describe an accentuation of vibration from the floor of the ambulance to the isolette—the life support system and housing in which the babies are transported. Raising increased concern, Macnab et al. (1995) reported that the maximum vibration levels inside an isolette transported by ground ambulance were greater than 1.5 m/s^2 and average vibration levels reached 0.5-1.0 m/s^2. Similarly, when examining WBV exposures in ground ambulance transport isolettes, Shenai et al. (1981) found that the vertical peak acceleration amplitudes experienced by neonates ranged from 2 to 6 m/sec^2, and Karlsson et al. (2012) found that the WBV peak acceleration exposure was 3.9 m/s^2. The exposures characterized in these studies all exceed the ISO-2631-1 (1997) and EU Directive (2002) 8-hr daily vibration action values for A_w and VDV exposures for adult occupational exposures, 0.5 m/s^2 and 9.1 $m/s^{1.75}$, respectively. Methods for quantifying the WBV exposures experienced by neonates during ground transport have been improved in recent studies (Blaxter et al., 2017; Browning et al., 2008; Prehn et al., 2015; Sallee et al., 2016; Shah et al., 2008), however, a gap in the characterization of the overall exposure process remains. It is unknown what a safe level of WBV might be for neonates, and, moreover, it is not clear what the current neonate vibration exposure is during ground ambulance transport.

This manuscript aims to characterize WBV exposures during a typical ground ambulance transport route. Additionally, this study looked to quantify and characterize the WBV experienced by simulated neonates during stroller and car seat exposures and compare these common daily activities to the WBV experienced during ground ambulance transport. *It is hypothesized that WBV exposures experienced by neonates during transport with standard equipment are amplified by the transport equipment used, and WBV exposures experienced by neonates during transport are greater than those experienced during common daily activities.* Characterizing these exposures will allow for a more meaningful understanding of the hazards and will assist in identifying potential solutions for identified hazards. It is important to understand whether there is potential to reduce vibration exposures experienced during transport, particularly if this has the potential to improve health outcomes for neonates.

2.2 METHODS

Study Design

Data for this pilot study were collected in coordination with Children's Minnesota, Minneapolis, Minnesota. The study was conducted using a 1.3 kg neonate mannequin transported in a standard isolette (Airborne Voyager Transport Incubator; International Biomedical; Austin, TX) with a mattress underlayer (Pressure diffusing mattress; International Biomedical; Austin, TX) and a fluidized positioner (Z-Flo; Molnlycke; Norcross, GA) on top. The neonate mannequin laid on top of the fluidized positioner inside the isolette. The isolette was transported on a power load cot (Power-PRO IT; Stryker; Kalamazoo, MI) (Figure 2.1) in a 12-year old ground ambulance (International 4300LP; Navistar; Lisle, IL) (Figure 2.2). Continuous vibration was gathered when the ambulance was on a typical transport route between inter-city hospitals (Figure 2.3). This route was 41.8 km, lasted 92 minutes, and was separated into departing and returning legs. These vibration measures were collected on dry road conditions with ambient air temperatures ranging between 9 to 24 Celsius (48 to 75 Fahrenheit).

Figure 2.1. Standard Stretcher System

Figure 2.2. Ground Ambulance

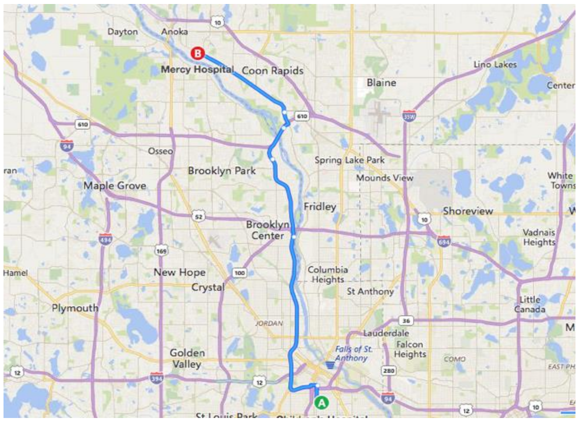

Figure 2.3. Ambulance and car transport route—Route between inter-city hospitals

The same simulated neonate as described above was used for the car and stroller measurements. To identify a commonly used car seat and stroller, five different internet sources (walmart.com, target.com, buybuybaby.com, babiesrus.com, and amazon.com) were searched for their most commonly purchased strollers and car seats. The stroller and car seat chosen for these measures was a popular and frequently purchased model on most of the company websites and was available from Children's Minnesota hospital during the testing timeframe. The car seat and stroller utilized in this study were part of a travel system where the car seat securely snaps into the stroller (B-Agile; Britax Child Safety, Inc.; Fort Mill, SC) (Figure 2.4). The simulated neonate was secured in the car seat as per the manufacturer’s instructions for both car and stroller portions of this study. In order to reduce variability between the modes of neonate transportation evaluated, the same route was used for the ambulance measurements and the car seat measurements. A separate route transporting the stroller outdoors over sidewalks and indoors over smooth surfaces was utilized. The outdoor route was compared to the City Streets from the ambulance and car since the route paralleled the city streets used by the car and ambulance. The indoor route consisted of traversing smooth indoor flooring in a large building.

Figure 2.4. Car seat and stroller (travel system)

Both recumbent (ambulance) and seated (car and stroller) WBV exposures were collected. To accommodate the difference in axis nomenclatures a single-axis system was used where horizontal exposures towards the front and back were referred to as fore-aft, the horizontal side-to-side exposures as lateral, and the translational up-and-down exposures as vertical (Figure 2.5).

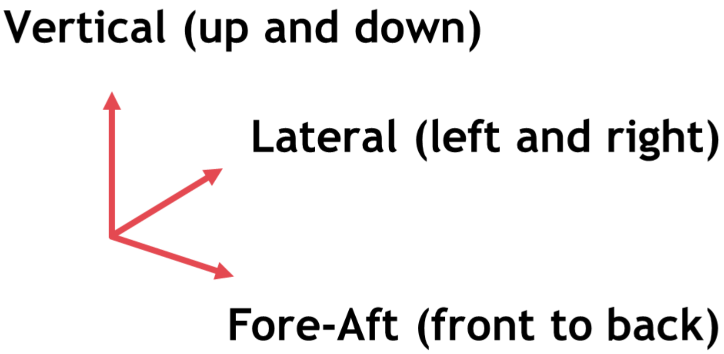

Figure 2.5. Single-axis nomenclature

Instrumentation and Measurement

Ambulance. Measurements were taken at six locations throughout the chain of transport equipment. Accelerometers were placed as depicted in the diagram below (Figure 2.6) (Shah et al., 2008). Continuous vibration was measured using triaxial accelerometers (Model 356B41; PCB Piezotronics; Depew, NY) and single axis accelerometers (Model 352C33; PCB Piezotronics; Depew, NY). Due to equipment limitations, single (vertical) measurements were taken at all locations. Accelerometers were magnetically mounted to the transport equipment at the transfer sled, stretcher top, and stretcher crossmember with duct tape for added security. Accelerometers were firmly secured with tape at all other locations. Data loggers were secured to the top of the transport unit utilizing a combination of adhesive Velcro strips and duct tape. The raw vibration data were collected at 1280 Hz using two eight-channel data loggers (DA-40; Rion Co. LTD; Tokyo, Japan) and concurrent global positioning system (GPS) data were collected at 1 Hz utilizing a portable GPS unit (Model CR-Q1100P; Qstarz Co.; Taipei, Taiwan) (Figure 2.7) (Blood, Rynell, & Johnson, 2011).

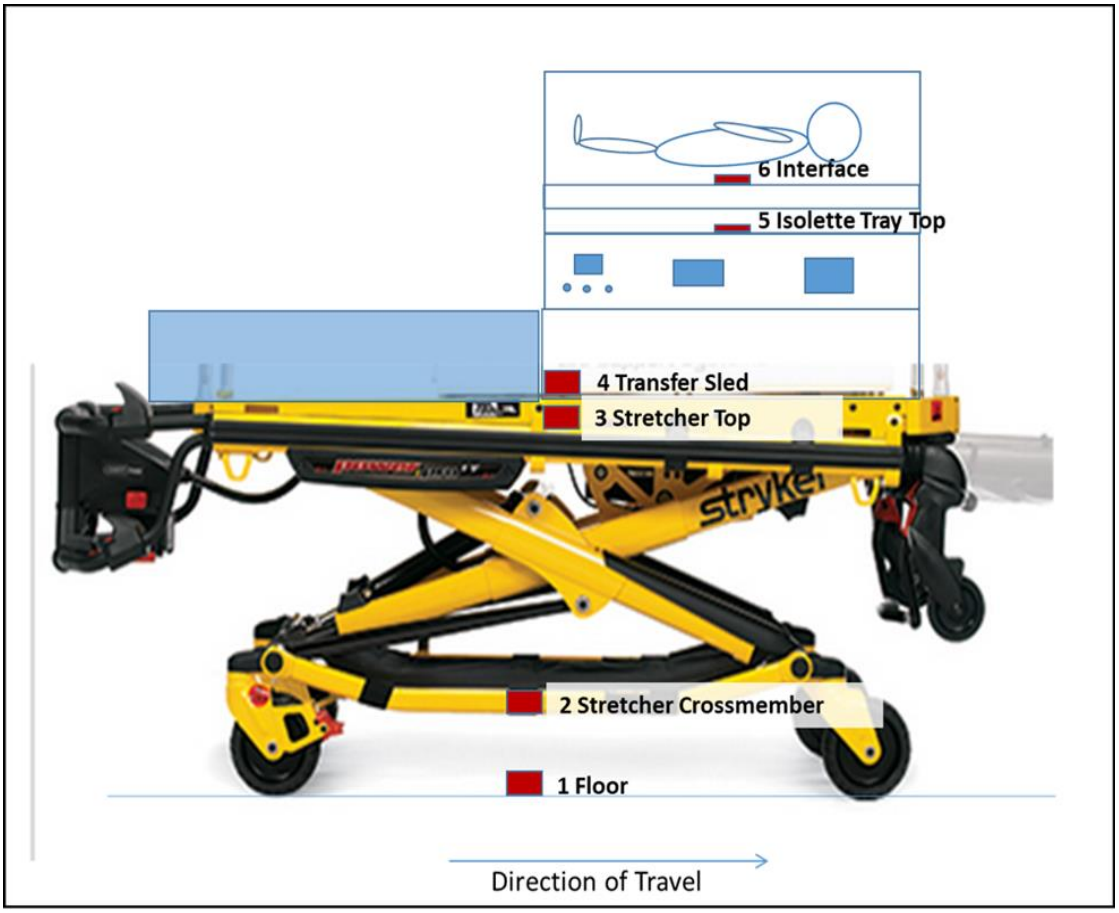

Figure 2.6. Instrumentation Diagram (Red rectangles indicate the position, number, and location of accelerometers on the standard stretcher system)

Figure 2.7. Data Collection System

Car Seat. Vibration data were gathered using the triaxial accelerometer described above with at seatpad and data were logged and stored using the same eight-channel datalogger and GPS as described previously. The seatpad was affixed under the simulated neonate with gaffer's tape to the seat pan of the car seat, a triaxial accelerometer was fixed to the floor of the vehicle using a magnet to secure the accelerometer to a bolt holding the seat to the floor of the vehicle, and the data logger was placed on the floor of the car. The GPS unit was secured with gaffer's tape to the dashboard of the car. The car seat route utilized the same route used for the ambulance route (Figure 2.3) and was measured four times.

Stroller. The same instrumentation utilized for the car seat transportation was also utilized for the stroller measurements. The seatpad was secured with gaffer's tape to the seat of the car seat which was securely snapped onto the frame of the stroller using manufacturer provided clips. A triaxial accelerometer was fixed to a horizontal crossbar at the base of the stroller using gaffer's tape, and the datalogger and GPS unit were stored under the stroller in the storage basket. There were two portions to the stroller route, an indoor route and an outdoor route. The outdoor stroller route consisted of a 25-minute, roughly 1-mile route on typical city sidewalks along the city street portion of the ambulance route surrounding Children's Minnesota (Figure 2.8). This route was measured four times. The indoor route was a 4-minute, 0.15 km route through the halls of the hospital on smooth vinyl flooring. This portion of the route was measured two times.

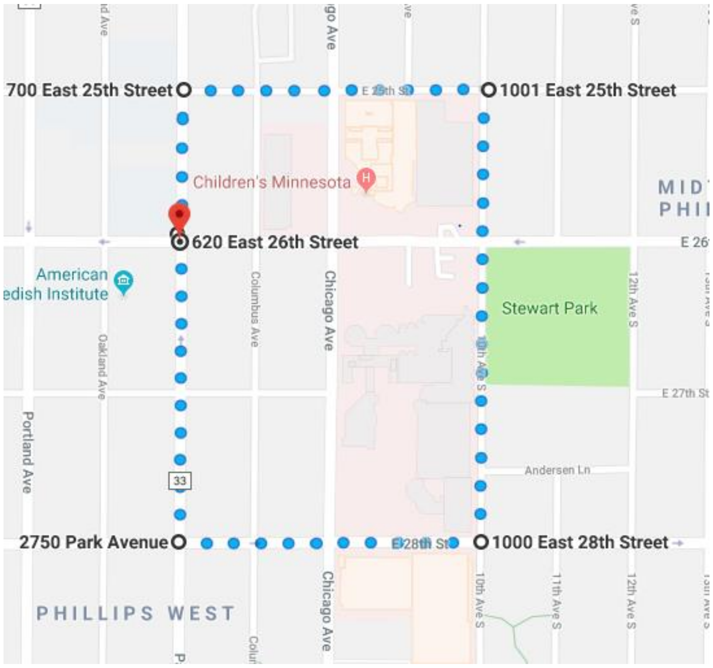

Figure 2.8. Stroller route—outdoor, city streets

Data Processing

Vibration and GPS data were downloaded to a laptop following completion of sampling. Data processing was conducted using a collection of interactive LabVIEW programs (Version 2016; National Instruments; Austin, TX). Data were processed using similar methods as previously described in the literature (Blood et al., 2011). Acceleration data were aligned with GPS data, and these were combined into one file to interpret acceleration data as it related to ambulance speed and type of road. GPS coordinates were used to separate acceleration measurements by road type (highway, freeway, city streets). A LabVIEW program was used to apply weighting as described in ISO 2631-1 (1997) to the raw, unweighted acceleration data, and additional LabVIEW programs were used to calculate the predominant, vertical average weighted vibration exposures (A_w), Vibration Dose Values (VDV).

Data Analysis

Data analysis was conducted using JMP Statistical Discovery Software (Version 9; SAS Institute; Cary, NC). Median, and Min and Max were calculated for A_w and VDV at each of the accelerometer locations. Due to the small sample size and potential for outliers in the vibration data, the Wilcoxon signed-rank test was used to compare vibration measures by location, relative to the floor, and by road type. The medians for A_w and VDV were compared to the EU Directive standards in order to determine if there was a difference between the exposures experienced in our study and the recommended vibration action limits in the standards. In addition, the time to reach these vibration action limits was also calculated and compared between the various locations in the stretcher system and between the two vibration exposure metrics. The formulas below show how the time to action limits were calculated for the two parameters.

A_w Time to Action Limit:

$$T[Aw] = (8\ hours) \times [(0.5\ m/s^2)/\mathrm{Aw}]^2 \qquad (2.1)$$

VDV Time to Action Limit:

$$T[\mathrm{VDV}] = (8\ \mathrm{hours}) \times [(9.1\ \mathrm{m/s^{1.75}})/\mathrm{VDV}]^4 \qquad (2.2)$$

2.3 RESULTS

Routes

The routes over which the WBV exposures were characterized are summarized in Table 2.1. The whole route consisted of all road types between an inter-city and suburban hospital. This route was completed by the ambulance two times and the car four times. As described in the methods, this route was broken down into three different types of road segments (City Street, Freeway, and Highway) for further comparison of vibration exposures. The average speed, distance and duration of travel for the stroller on the outdoor route (n = 4) were 4.9 km/h, 1.9 km and 23 minutes and the average duration for the indoor route (n = 2) was 4.6 min (the GPS could not measure speed and distance indoors).

Table 2.1. The speed, distances, and duration of time over which the WBV exposures were characterized grouped by vehicle type and road segment

	Average Speed (km/h)		**Average Distance (km)**		**Average Time (min)**	
Segment	**Car (n=4)**	**Ambulance (n=2)**	**Car (n=4)**	**Ambulance (n=2)**	**Car (n=4)**	**Ambulance (n=2)**
City Street	25	22	5.4	5.7	13	17
Highway	55	49	8.8	8.8	10	11
Freeway	84	83	21	21	15	15
Whole Route	54	50	36	36	40	44

Determination of Predominant Exposure Axis

The tri-axial exposures measured at the floor, shown in Table 2.2, demonstrate that the vertical axis was the predominant axis of exposure for all modes of transportation except the indoor stroller route. Not shown in Table 2.2 were the exposures measured from the base of the stroller in the indoors (0.44 m/s^2, 0.22 m/s^2, and 0.37 m/s^2 for the fore-aft, lateral and vertical axes, respectively). As a result of the vertical axis predominating in all but one mode of transportation, only the vertical axis exposures will be reported in this and the subsequent chapters.

Table 2.2. Median floor tri-axial A_w and VDV fore-aft, lateral and vertical WBV exposures by mode of transportation and road type. As outlined in the ISO 2631-1 standards, the fore-aft and lateral WBV exposures were multiplied by 1.4 to account for health effects. Ambulance (n = 2) Stroller (n = 2) Car (n = 4)

	Transport Type	**Axis**	**Whole Route**	**City Streets**	**Highway**	**Freeway**
A_w m/s^2	**Ambulance**	fore-aft	0.07	0.08	0.07	0.04
		lateral	0.12	0.12	0.12	0.09
		vertical	0.36	0.32	0.44	0.34
	Car	fore-aft	0.12	0.13	0.08	0.05
		lateral	0.11	0.13	0.08	0.07
		vertical	0.33	0.40	0.34	0.26
	Stroller	fore-aft	-	0.65	-	-
		lateral	-	0.44	-	-
		vertical	-	0.68	-	-
VDV $m/s^{1.75}$	**Ambulance**	fore-aft	1.1	0.88	0.64	0.52
		lateral	1.2	1.3	1.3	0.85
		vertical	5.4	4.5	3.9	3.7
	Car	fore-aft	2.1	1.5	1.0	0.64
		lateral	1.5	1.2	0.73	0.70
		vertical	4.7	4.3	2.8	3.0
	Stroller	fore-aft	-	6.5	-	-
		lateral	-	5.8	-	-
		vertical	-	8.4	-	-

- means no measurements obtained on these road types

WBV Exposures During Ambulance Transport

As can be seen in Table 2.3, amplification for both the A_w and VDV exposures occurred throughout the chain of transport equipment from the floor to the interface location where the simulated neonate rested. The A_w and VDV exposures at the floor for all road conditions were below the corresponding adult, occupation-based Daily Vibration Action Limits (DVAL). However, as measured over the whole route, both the A_w and VDV measures increased to exceed the corresponding DVAL at the level of the transfer sled (0.6 m/s^2 and 9.2 m/s$^{1.75}$, respectively). Both measures continued to increase through the equipment chain on all route segments, with the A_w exposures universally exceeding the corresponding DVAL at the interface level. The interface VDV exposures exceeded the VDV DVAL on the city streets and over the whole route.

Table 2.3. Ambulance median A_w and VDV single axis (vertical) WBV exposures (n = 2). Shaded cells indicate where exposures were above Daily Vibration Action Limits (DVAL): A_w > 0.5 m/s2 and VDV > 9.1 m/s1.75.

	Location	**Whole Route**	**City Streets**	**Highway**	**Freeway**
A_w m/s^2	**Interface**	0.66	0.66	0.76	0.59
	Isotray Top	0.65	0.67	0.74	0.56
	Transfer Sled	0.60	0.55	0.64	0.63
	Stretcher Top	0.46	0.43	0.51	0.47
	Floor	0.36	0.32	0.44	0.34
VDV m/s$^{1.75}$	**Interface**	10.9	9.9	6.7	6.6
	Isotray Top	10.5	9.6	6.5	6.2
	Transfer Sled	9.2	8.1	5.8	6.1
	Stretcher Top	6.8	5.9	4.4	4.6
	Floor	5.4	4.5	3.9	3.7

The vibration exposures at the interface level were then compared relative to the floor input exposures to determine how the stretcher system was accentuating or attenuating vibrations through the equipment chain (Table 2.4). Numbers less than one signify attenuation and numbers greater than one signify accentuation. The stretcher system consistently accentuated the vibrations delivered from the floor of the ambulance to the stretcher. The transmissibility of the continuous A_w exposures measured at the interface over the whole route was 1.82 and the cumulative, impulsive VDV transmissibility was 1.99, signifying a near doubling of the exposures from the floor to the interface. The A_w and VDV interface measures taken over the city streets showed a 2.05 and 2.21 transmissibility, respectively, whereas the interface measures over the highway and freeway segments ranged from 1.71-1.75. These measures all indicate that vibration energy is being transmitted through and accentuated by the individual components in the transport equipment chain.

Table 2.4. Ambulance median A_w and VDV single axis (vertical) WBV transmissibilities relative to the ambulance floor (n = 2).

	Location	Whole Route	City Streets	Highway	Freeway
A_w m/s^2	**Interface**	1.82	2.05	1.74	1.73
	Isotray Top	1.79	2.08	1.70	1.63
	Transfer Sled	1.65	1.71	1.47	1.84
	Stretcher Top	1.27	1.33	1.16	1.37
	Floor	1.00	1.00	1.00	1.00
VDV m/s$^{1.75}$	**Interface**	1.99	2.21	1.75	1.71
	Isotray Top	1.91	2.14	1.66	1.64
	Transfer Sled	1.68	1.81	1.64	1.46
	Stretcher Top	1.25	1.33	1.22	1.13
	Floor	1.00	1.00	1.00	1.00

WBV Exposures During Comparison Activities

Measurements taken at the floor and interface in the car seat and stroller were compared to the same locations in the ambulance stretcher system (floor and interface). Due to the varied route length for each mode of travel, to enable equivalent comparisons, the average, vertical WBV exposures measured at the floor and interface of the ambulance, car and stroller were normalized to 1 hour of transportation time. The normalized A_w floor exposures for the ambulance and car were similar. However, when measured at the interface in the stretcher system, the transmissibility was 1.82 compared to 1.41 with the car seat, indicating there was vibration amplification in both modes of transport but greater vibration amplification in the ambulance.

As shown in the top portion of Table 2.5, the vibration measured at the base of the stroller during transportation indoors was comparable to the floor measured vibration in the ambulance and car. When the stroller was transported outside on the sidewalks, the vibration exposures measured at the base of the stroller nearly doubled and were roughly twice as high as the ambulance and car floor-measured exposures. The stroller also amplified the vibration, the transmissibility from the stroller base to the interface was 1.20 when operated indoors on smooth surfaces and 1.48 when operated outdoors on the sidewalks.

Both the ambulance and outdoor stroller WBV exposures exceeded the ISO adult occupational daily vibration action limits of 0.5 m/s^2. In addition, the transportation time in hours to reach adult occupational ISO Daily Vibration Action Limits (DVAL) was calculated. Using the normalized A_w measures, a simulated neonate would reach the DVAL in 2.0 hours during stroller transportation outdoors compared to 12.4 hours during indoor transportation. For the ambulance and car transportation, the DVAL would be reached in 4.6 and 9.2 hours, respectively.

Table 2.5. Median A_w and VDV exposures at the floor and interface, normalized to 1 hour of transportation time; the transmissibility of the vibration between the floor and interface; and the transportation time (in hours) to reach Daily Vibration Action Limits (DVAL).

		Floor	**Interface**	**Transmissibility**	**DVAL (hrs)**
A_w m/s^2	**Stroller - Outdoors**	0.68	1.00	1.48	2.0
	Stroller - Indoors	0.37	0.43	1.20	12.4
	Car Seat - Whole Route	0.33	0.47	1.41	9.2
	Ambulance - Whole Route	0.36	0.66	1.82	4.6
VDV m/s$^{1.75}$	**Stroller - Outdoors**	10.6	15.0	1.40	0.1
	Stroller - Indoors	5.8	6.3	1.16	6.0
	Car Seat - Whole Route	5.3	7.6	1.43	2.1
	Ambulance - Whole Route	5.9	11.8	1.99	0.4

Similar to the A_w exposures, as shown in the bottom half of Table 2.5, the median VDV exposures at the floor and interface for the car and stroller (both outdoor and indoor) were calculated and compared to the corresponding measurements from the ambulance. Again, the vibration measured at the floor of the ambulance was similar to both the car and stroller being transported indoors, and the measurements at the interface indicated that the VDV exposures were also amplified by the various transportation modalities.

The transmissibility of the floor transmitted VDV exposures to the interface were also calculated. The ambulance stretcher system doubled the exposures measured at the interface compared to those at the floor (transmissibility 1.99), whereas the car and indoor and outdoor stroller transportation had transmissibilities of 1.43, 1.16 and 1.40 respectively.

The time to DVAL for the normalized VDV exposures was considerably more limiting than A_w exposures. The allowable time to travel in an ambulance before reaching the action limit was just 24 minutes, less than the time to complete half of the route used for this study. An infant traveling in a car over the same route may travel just over two hours before reaching the same limit. Indoor stroller use would take 6 hours to reach these action limits, and with stroller use outdoors, the action limit would be reached in just 6 minutes. It is important to note that these times to action limits are based on adult occupational vibration exposures anticipated to be encountered over several years of work. Comparing and interpreting these relative transportation times is challenging, so cautious interpretation is merited.

2.4 DISCUSSION

The objective of this study was to characterize the WBV exposures experienced by a simulated neonate using existing standard ground ambulance transport equipment. Additionally, this study compared these exposures to the WBV measurements gathered from a car seat and stroller using the same simulated neonate. Current WBV standards only address seated, adult, occupational-based exposures. ISO 2631-1 (1997) provides guidance for evaluation of vibration exposures to recumbent individuals but only as it relates to comfort and perception, not as it relates to health impacts. The WBV exposures that a neonate experiences are difficult to compare to the occupational adult seated exposures due to the smaller mass of the neonate, recumbent position, shorter duration of exposure, and likely compromised state of health. In order to allow a more applicable comparison, car seat and stroller activities were chosen to characterize and compare the ambulance exposures to activities that an infant may experience during their normal daily activities. This is the first time such work has been presented in the literature. As hypothesized, the ambulance exposures do appear to be amplified by the transport equipment, and the WBV exposures experienced by neonates during ambulance transport are greater than those experienced during a comparable car seat ride.

The measurements gathered at the interface of the ambulance where the neonate rested demonstrated that the average weighted vibration exposures under all road conditions exceeded the current adult, occupational-based daily vibration action limit (DVAL) of 0.50 m/s^2 for A_w. The cumulative, impulsive measurements exceeded their corresponding action limit (9.1 $m/s^{1.75}$) over the whole route and over the city streets. These results are consistent with those found by Sherwood et al. (1994), Macnab et al. (1995), and Browning et al. (2008) who also found exposures exceeded the recommended vibration action limits. All the floor measurements were below vibration action limits, indicating that vibration energy was being amplified by the transport equipment.

WBV exposures were higher in the ambulance compared to the car for both the average weighted vibration and the cumulative impulsive vibrations. The car seat exposures were measured over the same route of travel as the ambulance. The floor input vibrations for the car and ambulance were similar for both the average weighted and cumulative impulsive exposures. The car exposures did not exceed the current DVAL. As previously noted, WBV exposures were amplified up the chain of transport equipment in the ambulance.

The ambulance exposures were compared to exposures experienced by the same simulated neonate on two different stroller routes, indoor and outdoor. The exposures measured at the base of the stroller on the indoor route and the interface where the simulated neonate was supported by the car seat were similar to those experienced in the car for both the A_w and VDV exposures. The indoor stroller measurements remained below the adult occupational DVAL and below those exposures measured in the ambulance. In contrast, the measurements taken at the base and interface of the stroller on the outdoor route exceeded the other modes of travel. This increase in vibration exposures in the stroller is likely due to the difference in tire stiffness/hardness and the lack of a suspension when compared to the car or ambulance. The stroller tires were hard, and the lack of any suspension did not protect the simulated neonate from the terrain induced vibrations encountered over the outdoor route.

As part of the comprehensive characterization of these exposures, the transmissibility between the floor/base and the interface in each of these modes of travel was compared. The ambulance far exceeded the other modes of transport for floor input vibration that was transmitted to the interface where the simulated neonate rested. The ambulance transport equipment increased the A_w and VDV exposures at the interface by 82% and 99%, respectively, nearly doubling the cumulative impulsive exposures compared to the floor level. The car and outdoor stroller route increased the A_w and VDV exposures at the interface by ~40% and the indoor stroller route increased the A_w and VDV exposures at the interface by 20% and 16%, respectively. It is apparent that the chain of transport equipment utilized in the ground ambulance is interacting and amplifying the exposures as the vibrations are transmitted up the equipment chain to the neonate, which is consistent with existing literature (Sherwood et al., 1994; Gajendragadkar et al., 2000; Sallee et al., 2016; Browning et al., 2008).

The amount of time an infant could travel in these various modes of transportation before reaching the adult, occupational DVAL was calculated. The cumulative, impulsive exposures were more limiting, allowing the infant to travel just 0.4 hours in the ambulance before reaching the adult, occupational VDV DVAL, whereas the infant traveling in the car and stroller on the indoor route would be allowed to travel 2.1 and 6.0 hours, respectively, before reaching the same limit. The infant traveling in the ambulance would be allowed to travel 4.6 hours, compared to 9.2 hours in the car and 12.4 hours in the stroller on the indoor route, before reaching the A_w DVAL. The stroller traversing the outdoor route again was the most limiting with respect to travel time, allowing 2.0 hours of travel time before reaching the A_w DVAL and just 0.1 hours before reaching the VDV DVAL.

The current study had several strengths compared to similar studies. The use of the same driver, vehicle, and route for all ambulance trials was helpful in reducing variability associated with different driving styles, road types, and equipment configurations. The use of a typical transport route and typical transport equipment, car seat, and stroller helped to improve the generalizability of our study results. A limitation of the study was the small sample size.

However, it does appear that with the use of a standardized route and the limited variability, our samples are representative of typical transport exposures, limiting the error normally associated with a small sample size. Another potential limitation was the use of a simulated neonate in lieu of live infants. The resonant frequency may differ between the two, and the simulated neonate does not have the muscle response or spontaneous movement that a live infant would have (Shah et al., 2008). Additionally, the simulated neonate was 1.3 kg. The mass of live infants in transport varies, and infants with different masses may interact differently with the supporting structures in the isolette (Prehn et al., 2015). Future studies should look to further classify the vibration exposures in the frequency domain and should look to implement mitigating strategies that decrease the overall amplitude of vibrations experienced by the neonate during ground transport.

These study results could be used by others to further characterize current exposures and aid in the development of proper mitigating strategies and appropriate standards for limiting and determining acceptable neonate exposures. These results should be cautiously interpreted, though. The standards they are being compared to are designed to limit exposures that usually occur over an 8-hour period, daily, typically for five years or longer. Infants will not be experiencing the same duration of exposure, but as these are the only standards in place they can be used as a metric for relative comparison (Bailey-Van Kuren & Shukla, 2005; Blaxter et al., 2017). The relatively short duration to exposures that neonates encounter during transport is particularly concerning because health-related effects can occur during transports that are typically an hour or less (Bailey-Van Kuren & Shukla, 2005). The findings presented here represent an important first step in the development and validation of applicable standards for human vibration exposure, across the lifespan.

2.5 CONCLUSION

The current study demonstrated that vibration exposures measured at the interface of the ambulance exceed those measured at the floor, supporting the hypothesis that the transport equipment is exacerbating the vibrations experienced at the level of the interface. Additionally, exposures measured at the interface of a simulated neonate transported by ground ambulance exceed those standards put in place for adults. Car seat and stroller vibration exposures provide context for interpreting the vibration exposures experienced in the ambulance, although infants who use car seats and strollers are typically healthier and less vulnerable to adverse effects of WBV. The results demonstrated that the ambulance exposures at the interface are greater than car transport and indoor stroller transport. These higher exposures at the interface level of the ambulance during neonate transport indicated that there is an opportunity and a need for further classification of vibration exposures and development of appropriate WBV limits and exposure mitigating strategies for neonates.

Chapter 3. THE CHARACTERIZATION AND EVALUATION OF TWO INTERVENTIONS TO REDUCE NEONATE WHOLE BODY VIBRATION EXPOSURES DURING AMBULANCE TRANSPORT

3.1 INTRODUCTION

Prolonged whole-body vibration (WBV) exposure has been linked to multiple adverse health outcomes in adults. WBV is known to cause fatigue, interfere with visual acuity, and decrease response time (Floydet al., 1973; Griffin, 1990). It has also been associated with cardiovascular effects, respiratory complications (Clark et al., 1967), and an increased risk of skeletal and muscular morbidities (Bovenzi, 2010).

Potential health effects for children may be similar, or there may be other unknown and/or additional impacts due to their more fragile developmental state. Newborn infants delivered in a compromised health state often require transport between point of delivery and a tertiary care hospital. During a period when they are already at increased vulnerability and risk for adverse health outcomes, WBV exposures, when high, may impact the infants' near and longer-term health outcomes (Grosek et al., 2009). Macnab et al., (1995) describe an unexplained deterioration in the condition of some neonates following a long transport, and transport to another hospital was further associated with an increased risk of intraventricular hemorrhage among neonates (Gleissner et al., 2000; Mohamed & Aly, 2010). Additionally, the introduction of external stressors such as mechanical vibration during transport may cause increased morbidity and even increased mortality (Shah et al., 2008). In 1988, Bowman et al. found that the mortality rate of preterm infants transferred between tertiary perinatal centers was 50%, compared to 24% for a comparable group of infants who had not been transferred.

The current occupational WBV standard for adults (ISO, 1997) suggests two methods for evaluating WBV exposures: 1) the weighted root mean square (r.m.s.) acceleration (A_w) in m/s^2; and 2) the vibration dose value (VDV) in m/s$^{1.75}$ when vehicle vibrations are expected to contain impulsive jarring and mechanical shocks. The A_w is averaged over time and was designed to measure the vehicle occupant's exposure to continuous, typically lower amplitude, cyclical vibration exposures. In contrast, the VDV is a cumulative measure and was designed to measure the cumulative impact on the vehicle occupant's body from the larger amplitude mechanical shocks and jolts. The ISO-2631-1 (1997) and EU Directive (2002) 8-hr daily vibration action values for A_w and VDV exposures for adult occupational exposures are 0.5 m/s^2 and 9.1 m/s$^{1.75}$, respectively.

Previous research has repeatedly found the WBV exposures experienced by neonates during ground transport to be in excess of these standards. In 1981, Shenai et al. first documented the mechanical vibrations present in neonatal transport. They reported that neonates experience prolonged low-frequency and high-amplitude levels of mechanical vibration and shocks during inter-hospital ground transport. They found that peak acceleration amplitudes ranged from 2.0 to 6.0 m/sec^2. Sherwood et al. (1994) looked at the peak acceleration and vibration levels at four locations on the transport equipment and on the ambulance floor. Their results indicated an accentuation of vibration from the floor to the isolette – the life support system and housing in which the babies are transported. More recently, Karlsson et al. (2012) found that the WBV peak acceleration exposure in ground ambulance transport was 3.9 m/s^2, further substantiating the vibration findings in previous studies. In their study, Macnab et al. (1995) compared a new transport isolette to a 15-year-old isolette, and found no significant differences between the two models, indicating that no adjustments had been made to decrease the potential vibration exposures despite past research indicating this need. The authors reported average vibration levels inside the isolette transported by ground ambulance reached between 0.5-1.0 m/s^2. They recommended close study of the efficacy of vibration reducing modifications and that efforts be directed at reducing vibration in the low frequency range.

It is clear that there is continued cause for concern, but it is not clear what the extent of the current exposure is or how the transport equipment affects these WBV exposures. In an effort to contribute to developing appropriate standards, Browning et al. (2008) and Sallee et al. (2016) have worked to determine the baseline vibrations of transport incubators. Browning et al. (2008) specifically examined the vibration exposures at the level of the tray of a transport isolette and found the maximum average acceleration during intra-hospital transport to be 2.6 m/s^2 and the peak acceleration value during the same route to be 15.9 m/s^2. Sallee et al. (2016) examined methods for stabilizing the patient tray inside the isolette in a simulated environment and found that tethering the patient tray to the rigid frame of the isolette provided significant attenuation of the vibration experienced in the vertical axis during this simulated scenario.

The primary objective of this study was to measure and characterize WBV exposures during simulated newborn infant inter-hospital ground transport and determine how the vehicle-based vibrations are transmitted through the stretcher and the chain of equipment used to support and protect the newborn infants. This study also characterized and compared WBV exposures between a standard stretcher system and two potentially mitigating strategies: a modified stabilized stretcher system and a new, modified stretcher with a built-in suspension system designed to absorb and reduce vehicle-induced vibrations. Simulated neonate WBV exposures were measured and characterized using the standard, modified, and new stretcher systems to characterize vibration exposure levels, determine whether the equipment in the stretcher systems altered vibration exposures and whether there were differences in vibration exposures between the stretcher systems. *It is hypothesized that the proposed mitigating strategies will reduce overall WBV exposures experienced by neonates during ground ambulance transport.* This manuscript will examine WBV exposures from their current state through the implementation of mitigating strategies and will contribute to quantifying WBV exposures throughout the chain of transport equipment.

3.2 METHODS

Study Design

Data for this study were collected in coordination with Children's Minnesota, Minneapolis, Minnesota. This study used a 1.3 kg neonate mannequin (simulated neonate) to evaluate and compare simulated neonate vibration exposures with three different stretcher systems. Data were gathered on a typical transport route between inter-city hospitals (Figure 3.1). This route was 36 km and was separated into departing and returning legs. The data were collected on dry road conditions with ambient air temperatures ranging between 9 to 24 Celsius (48 to 75 Fahrenheit).

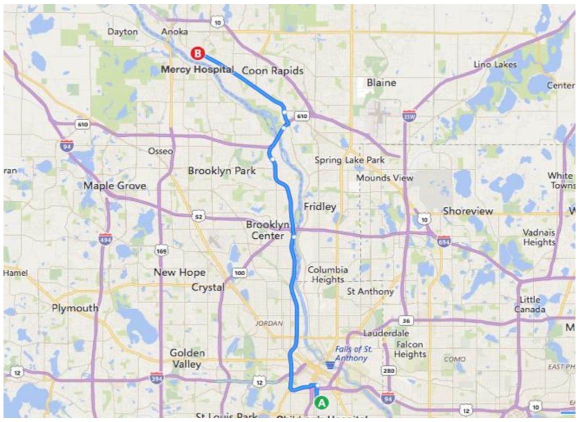

Figure 3.1. Transport Route—Route between inter-city hospitals

Vibration Mitigation Approaches

Three stretcher system configurations were evaluated for the ground ambulance transport of neonates: 1) a standard neonate ground transport stretcher system, 2) a standard neonate ground transport stretcher system where the base of the stretcher was modified with a strut to make the stretcher system more rigid, and 3) a custom-made stretcher system with a built-in suspension. All stretcher systems were evaluated in the same 12-year old ground ambulance (International 4300LP; Navistar; Lisle, IL) (Figure 3.2).

Figure 3.2. Ground Ambulance

The standard stretcher system consisted of an isolette (Airborne Voyager Transport Incubator; International Biomedical; Austin, TX) with a mattress underlayer (Pressure diffusing mattress; International Biomedical; Austin, TX) and a fluidized positioner (Z-Flo; Molnlycke; Norcross, GA) on top. The neonate mannequin laid on top of the fluidized positioner inside the isolette. The isolette was transported on a power load cot (Power-PRO IT; Stryker; Kalamazoo, MI) (Figure 3.3). The modified stretcher system was similar in set-up to the standard system with the exception that base of the power load cot was more rigidly secured to the ambulance floor. Here, a metal strut, a non-compliant connection, was fabricated to join the front of the stretcher to the metal loops rigidly secured to the floor of the ambulance. The strut was designed to go into compression and tension with the movement of the ambulance floor instead of bending.

Figure 3.3. Standard Stretcher System

Finally, the stretcher with the built-in suspension consisted of the same stretcher base, except it was modified to have three suspension systems designed to attenuate the vertical, fore and aft, and the side-to side/lateral exposures. The stretcher with the built-in suspension was fabricated by Bose Corporation, Framingham, MA. The prototype triaxial suspension system was placed between the power load cot and the detachable aluminum transfer sled which holds the medical equipment and the isolette. As shown in the photos of Figure 3.4, the prototype was designed to use compressed air and a scissor mechanism to attenuate vibrations in the up and down (vertical) direction and linear ball bearings to attenuate movement in the fore/aft and lateral, side-to-side directions.

Figure 3.4. New stretcher system with the built-in suspension (left) and with the transfer sled and isolette (right)

Instrumentation and Measurement

Continuous vibration data were measured using triaxial accelerometers (Model 356B41; PCB Piezotronics; Depew, NY), and single axis (vertical) accelerometers (Model 352C33; PCB Piezotronics; Depew, NY). The vibration data were recorded using two eight-channel dataloggers (DA-40; Rion Co. LTD; Tokyo, Japan) (Figure 3.5). Vibration data were gathered at a sample rate of 1280 Hz and concurrent global positioning system (GPS) data were collected at 1 Hz utilizing a portable GPS unit (Model CR-Q1100P; Qstarz Co.; Taipei, Taiwan) (Figure 3.5). (Blood et al., 2011).

Figure 3.5. Data Collection System

The instrumentation procedures for this study replicate the procedures previously used during phase one of this study (Chapter 2) to ensure comparability of existing, modified and new stretcher system measurements. Measurements were taken at six locations throughout the chain of transport equipment. Accelerometers were placed as depicted in the diagram below (Figure 3.6) (Shah et al., 2008). Single (vertical) measurements were taken at all locations. Accelerometers were magnetically mounted at the stretcher crossmember, stretcher top, and transfer sled with duct tape for added security. Accelerometers were firmly secured with tape at all other equipment locations. Data loggers were secured to the top of the transport unit utilizing a combination of adhesive Velcro strips and duct tape.

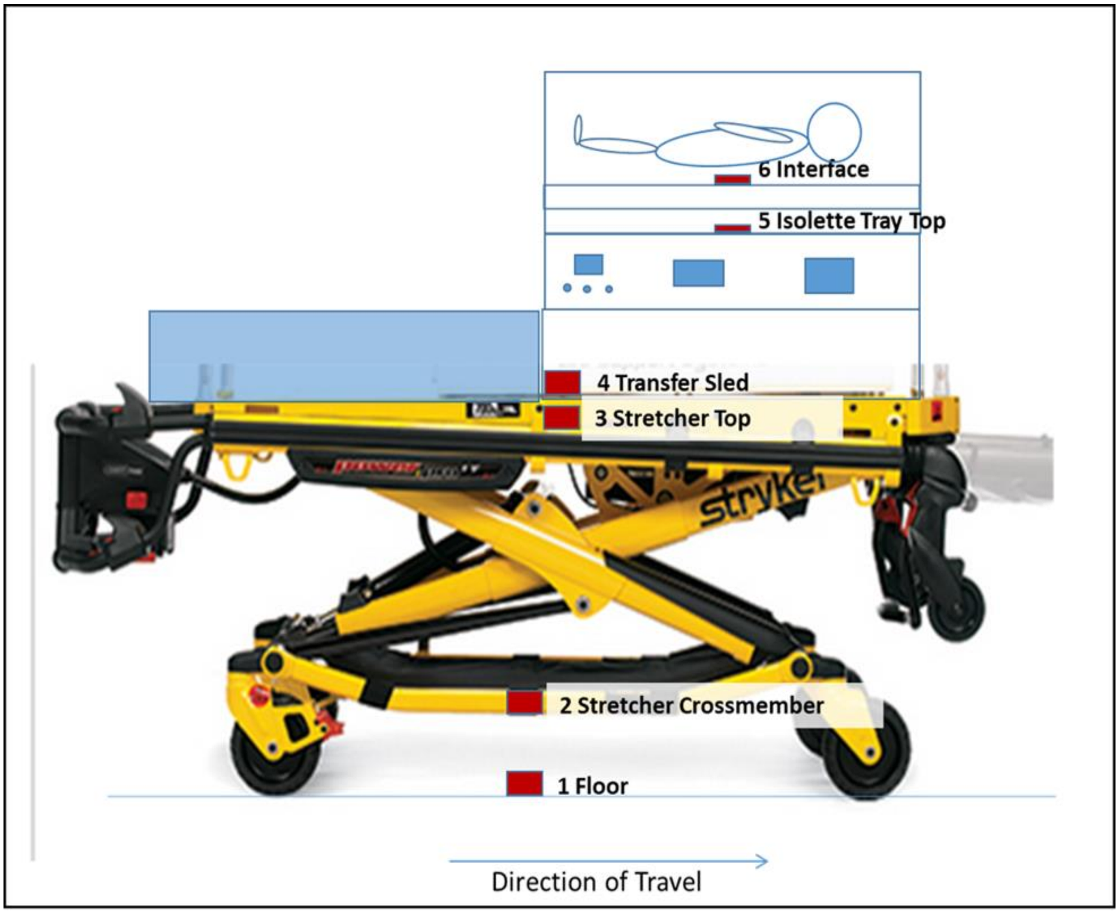

Figure 3.6. Instrumentation Diagram (Red rectangles indicate the position, number, and location of accelerometers on the three stretcher systems evaluated)

Data Processing

Vibration and GPS data were downloaded to a laptop following completion of sampling. Data processing was conducted using a collection of interactive LabVIEW programs (Version 2016; National Instruments; Austin, TX). Data were processed using similar methods as previously described in the literature (Blood et al., 2011). Acceleration data were aligned with GPS data, and these were combined into one file to interpret acceleration data as it related to ambulance speed and location. A LabVIEW program was used to apply weighting as described in ISO 2631-1 (1997) to the raw, unweighted acceleration data, and additional LabVIEW programs were used to calculate the predominant, vertical average weighted vibration exposures (A_w) and Vibration Dose Values (VDV).

Data Analysis

Data analysis was conducted using JMP Statistical Discovery Software (Version 9; SAS Institute; Cary, NC). Due to the small sample size and potential for outliers in the vibration measurements, Median and min and max values were calculated for both VDV and A_w for each stretcher systems and at each of the accelerometer locations. Wilcoxon signed-rank and Friedman tests were used to compare vibration measures within the equipment chain of each stretcher system and between equipment systems. The medians for VDV and A_w were compared under all test conditions relative to the action and exposure limits in the EU Directive (2002) in order to determine whether the exposures experienced by the simulated neonate varied between test conditions and to determine whether exposures were above action and exposure limits. The amount of time taken to reach the action limits for both VDV and A_w was also compared across all test scenarios. In order to better compare the stretcher systems, the vibration exposures of each stretcher system were normalized at the floor and compared up the chain of the transport equipment and between the stretcher configurations. In addition, the relative time to reach vibration action limits was normalized to one hour and calculated relative to the vibration exposures at the floor of the ambulance.

3.3 RESULTS

Standard Stretcher System and Standard Stretcher System with Strut Exposure Levels

As seen in Figure 3.7, the effects of the stabilizing strut and the impact on the vibration exposures in standard stretcher system were different than anticipated. As shown in the left portion of Figure 3.7, the median, vertical, WBV exposures (A_w) measured from the ambulance floor using both the standard stretcher system (0.36 m/s^2) and the standard system with the strut (0.38 m/s^2), were below the adult, occupational-based, daily vibration action limits (0.50 m/s^2). The standard stretcher system with the strut (gray lines, Figure 3.7) monotonically amplified the floor level vibrations (0.38 m/s^2) throughout the chain of equipment to 1.24 m/s^2 at the interface where the simulated neonate rested. As shown in the right portion of Figure 3.7, the trends for the impulsive, vertical, WBV exposures (VDV) within and between the standard stretcher system and the stretcher system with the strut were similar to the results of the average weighted vibrations (A_w). When comparing exposures at the interface level between the stretcher systems, the A_w exposures were 0.67 m/s^2 and 1.24 m/s^2 and the and VDV exposures were 10.9 m/s$^{1.75}$ and 15.4 m/s$^{1.75}$ for the standard system and the stretcher system with the strut, respectively.

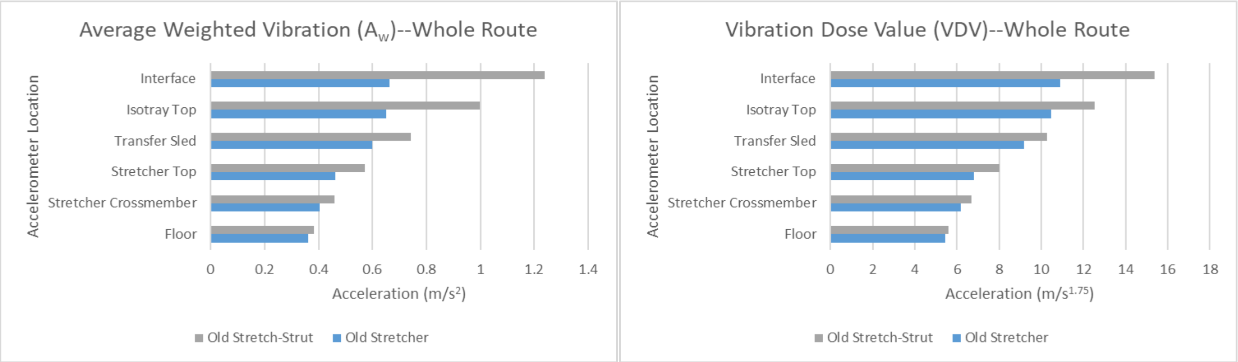

Figure 3.7. Median values for average weighted vibration exposures (A_w, left) and cumulative impulsive vibration exposures (VDV, right) for the standard (n = 2) and standard with strut (n = 2) stretcher systems. Measurements were averaged over the inter-hospital routes which were ~46 minutes long.

Standard Stretcher System and Standard Stretcher System with Strut Transmissibilities

When the transmissibilities of WBV exposures for both the standard stretcher system and standard stretcher system with the strut were compared, both systems amplified and transmitted vibrations up the equipment chain (Figure 3.8). When comparing the input vibrations measured at the floor to those measured at the interface, the standard stretcher system amplified the average continuous A_w exposures and the cumulative impulsive VDV exposures by 1.8- and 2-fold respectively (blue lines in left and right portions of Figure 3.8). In contrast, with the standard stretcher system with strut (gray lines in Figure 3.8), the A_w and VDV exposures at the interface were amplified 3.5-fold and 2.75-fold respectively, relative to the floor.

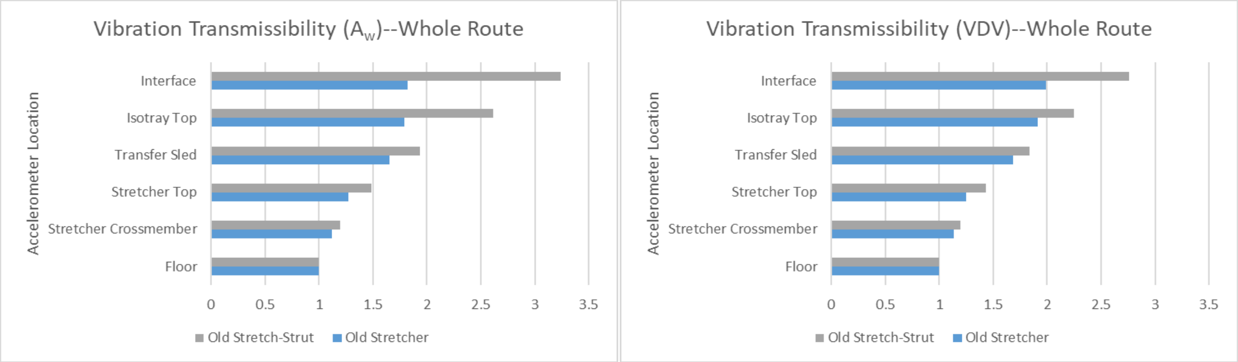

Figure 3.8. Median vibration transmissibilities relative to the floor for the standard (n = 2) and standard stretcher system with strut (n = 2) showing the average continuous exposures (A_w, left) and cumulative, impulsive exposures (VDV, right). Measurements were averaged over the inter-hospital routes which were ~46 minutes long.

Standard Stretcher System and New Stretcher System Exposure Levels

As shown in the left portion of Figure 3.9, the median, vertical, WBV exposures (A_w) measured from the ambulance floor using both the standard (0.36 m/s^2) and the new stretcher systems (0.44 m/s^2), were below the adult, occupational-based, daily vibration action limits (0.50 m/s^2). However, the new stretcher system did not amplify the vibration exposures up the equipment chain between the floor and the interface where the simulated neonate was supported (orange lines, Figure 3.9). Utilizing the standard stretcher system, the WBV exposures at the floor were 0.36 m/s^2, increased to 0.60 m/s^2 at the transfer sled, and further increased to 0.67 m/s^2 at the interface; with the interface exposures nearly double the exposures measured at the floor. With the new stretcher system, which contained the built-in suspension, the floor measured vibration was 0.44 m/s^2, then decreased to 0.25 m/s^2 at the aluminum transfer sled (the point immediately above the built-in suspension), and then increased to a maximum of 0.48 m/s^2 at the interface. As shown in the right portion of Figure 3.9, the trends within and between stretcher systems with the impulsive, vertical, WBV exposures (VDV) for the most part mirrored the results of the average weighted vibrations (A_w). When comparing exposures at the interface level between the stretcher systems, the A_w exposures were 0.67 m/s^2 and 0.48 m/s^2 and the VDV exposures were 10.9 m/s$^{1.75}$ and 6.6 m/s$^{1.75}$ for the standard and new stretcher systems, respectively.

When the WBV exposures between the transfer sled and the interface were compared in the standard system, the A_w exposures increased from 0.60 m/s^2 at the transfer sled, to 0.65 m/s^2 and 0.66 m/s^2 at the isotray top and the interface, respectively. The VDV exposures showed a similar trend, with 9.2 m/s$^{1.75}$ measured at the transfer sled and then increasing to 10.5 m/s$^{1.75}$ and 10.9 m/s$^{1.75}$ at the isotray top and interface, respectively. When the same three locations were compared in the new stretcher system, slightly different results were observed where there was more of a monotonical increase in the vibration exposures. A_w exposures increased from 0.25 m/s^2 at the transfer sled, to 0.38 m/s^2 and 0.45 m/s^2 at the isotray top and the interface, respectively. The VDV exposures increased from 4.2 m/s$^{1.75}$ at the transfer sled to 5.7 m/s$^{1.75}$ and 6.6 m/s$^{1.75}$ at the isotray top and interface, respectively.

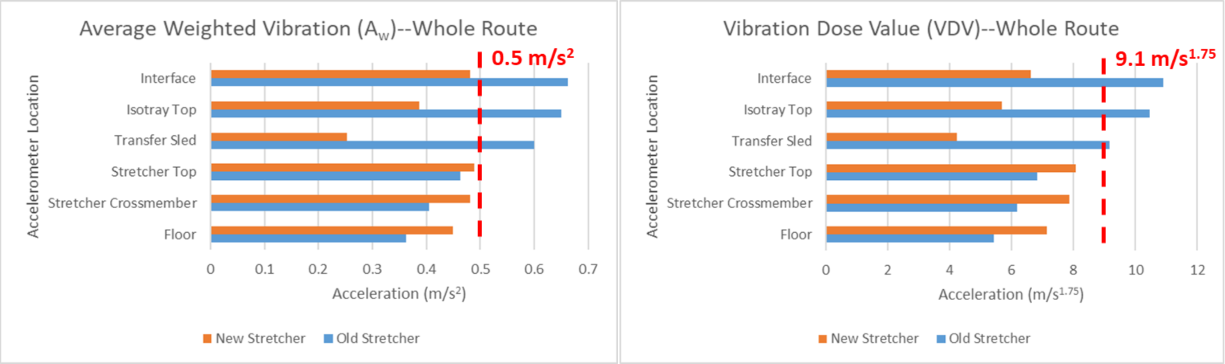

Figure 3.9. Median values for average weighted vibration exposures (A_w, left) and cumulative impulsive vibration exposures (VDV, right) for the standard (n = 2) and new (n = 4) stretcher systems. Measurements averaged over the inter-hospital routes which were ~46 minutes long. The red dashed lines indicate the adult occupational daily (8-hr) vibration action limits from the ISO 2631-1 standard.

Standard Stretcher System and new Stretcher Systems Transmissibilities

The WBV exposures for both the standard and new stretcher systems were then compared to characterize whether the stretcher systems were amplifying or attenuating vibrations relative to the input vibrations measured at the floor. As can be seen in Figure 3.10, both systems transmitted vibrations up the equipment chain. When comparing the input vibrations measured at the floor to those measured at the interface, the standard stretcher system amplified the average continuous A_w exposures and the cumulative impulsive VDV exposures by 1.8- and 2-fold respectively (blue lines in left and right portions of Figure 3.10). In contrast, with the new stretcher system (orange lines in Figure 3.10), 107% and 93% of the floor-measured A_w and VDV exposures were transmitted to the interface (A_w increased by 7% and VDV exposures were reduced 7%) respectively.

The floor to interface transmissibilities were then broken down further to determine and compare the vibration behaviors between stretcher systems above and below the transfer sled. From the floor to the transfer sled in the standard system, the A_w and VDV exposures increased by 65% and 68% respectively. In contrast, the A_w and VDV exposures in the new system were reduced by 42% and 41%, respectively. As described in the prior section which characterized A_w and VDV exposure levels, the structures above the transfer sled amplified exposures. Between the transfer sled and the isotray top, in the standard system, the A_w and VDV exposures increased an additional 14% and 23% respectively, and then increased an additional 3% and 8% between the isotray top and the interface, respectively. In contrast to the attenuation between the floor and transfer sled with the new system, above the transfer sled the vibration exposures were amplified, and to a greater degree than those encountered with the standard system. With the new system, the A_w and VDV exposures increased 29% and 21% between the transfer sled and the isotray top respectively, and then increased an additional 20% and 13% respectively between the isotray top and the interface.

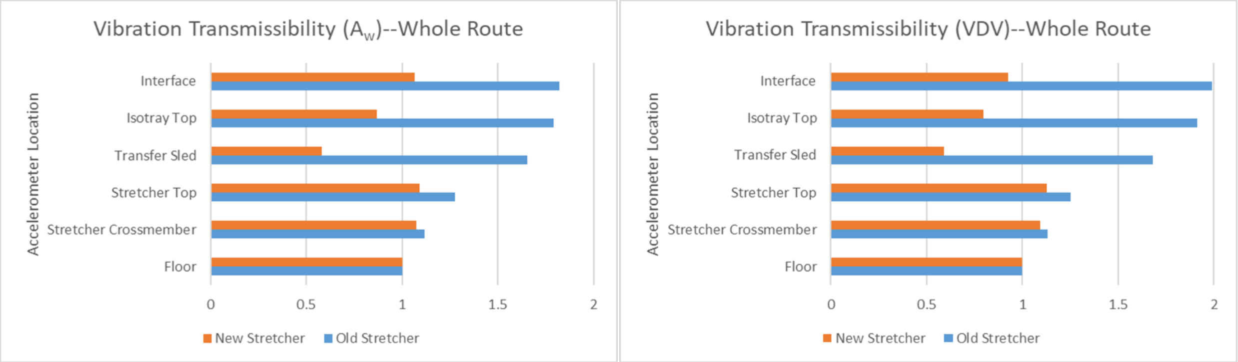

Figure 3.10. Median vibration transmissibilities relative to the floor for the standard (n = 2) and new (n = 4) stretcher systems showing the average continuous exposures (A_w, left) and cumulative, impulsive exposures (VDV, right). Measurements averaged over the inter-hospital routes which were ~46 minutes long.

Relative Transportation Times of the Standard and new Stretcher Systems

The average weighted vibrations and cumulative impulsive vibrations experienced with both the standard and new systems were then used to determine the relative length of time, normalized and compared to the vibration inputs at the floor, that an infant could ride in the isolette before reaching adult occupational Daily Vibration Action Limits (DVAL). As can be seen in Figure 3.11, average weighted vibrations and impulsive vibrations experienced by the simulated neonate in the standard system (blue lines in Figure 3.11) would reduce transportation times by 70% and 93%, respectively, due to the amplification of the vibrations through the stretcher system. With the new system (orange lines in Figure 3.11), the transmission of the floor measured vibrations through the stretcher system was reduced. For the average weighted vibration exposures, the transportation times were only reduced by 12%, and for the impulsive vibrations, the transportation times increased by 36%, due to the ability of the new system's built-in suspension to better absorb the bumps, jolts and jarring contained in the impulsive vibrations.

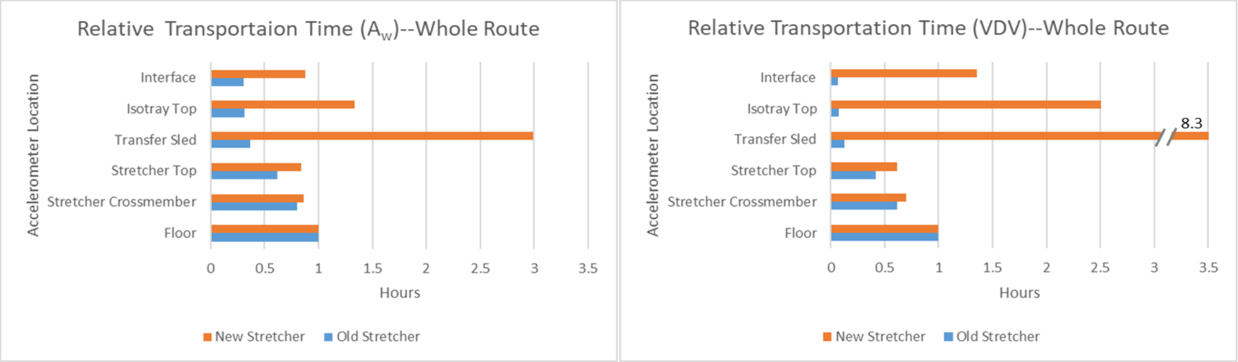

Figure 3.11. Median relative transportation times for the standard (n = 2) and new (n = 4) stretcher systems normalized relative to the input vibrations measured at the floor showing the average weighed vibration exposures (A_w, left) and cumulative, impulsive vibration exposures (VDV, right). Relative transportation times based on the inter-hospital routes which were ~46 minutes long.

Absolute Transportation Times of the Standard and new Stretcher Systems

To facilitate comparisons between the stretcher systems due to slightly different transportation times and different exposures at the ambulance floor, the exposures for each stretcher system were normalized to one hour of transport (Table 3.1). If the one-hour exposures were representative, with the standard system, the adult occupational daily vibration action limits would be reached in 4.6 and 3.5 hours respectively for the A_w and VDV exposures. For the new system, the adult occupational daily A_w and VDV vibration action limits would be reached in 8.7 and 25.3 hours respectively. Based on the exposures measured at the interface, for the A_w and VDV exposures the new stretcher system would increase transportation times 1.7-fold and 7.2-fold respectively relative to the standard system. These increases in transportation times would hold true for other transportation durations as well.

Table 3.1. Median A_w and VDV exposures at the floor and interface comparing the standard (n = 2) and new (n = 4) stretcher systems over the whole route, normalized to 1 hour of transportation time. In addition, the floor to interface transmissibility and transportation time (in hours) to reach Daily Vibration Action Limits (DVAL) is shown for comparative purposes.

		Floor	**Interface**	**Transmissibility**	**DVAL (hrs)**
A_w (1) m/s^2	**Standard System**	0.36	0.66	1.82	4.6
	New System	0.45	0.48	1.07	8.7
VDV (1) $m/s^{1.75}$	**Standard System**	5.9	11.7	1.98	3.5
	New System	7.3	6.8	0.93	25.3

3.4 DISCUSSION

The aim of this study was to compare the WBV exposures experienced by a simulated neonate using standard ground transportation ambulance stretcher to two potentially mitigating strategies: a standard stretcher with strut and a stretcher with a custom-built suspension system. We found that, although the simulated ambulance ride lasted less than an hour, the vibration exposures using the standard stretcher exceed the 8-hour occupational daily vibration action levels set forth for adults. Adult, occupational-based exposure standards may not be ideal for comparison purposes, however, no standards are available for comparison in neonates. Our results are consistent with previous research on this topic, which also presented comparisons to occupational-based standards (Sherwood et al., 1994; Macnab et al., 1995; Browning et al., 2008).

The standard stretcher with the addition of the stabilizing strut did not perform as expected. It was hypothesized that the addition of the stabilizing strut would reduce the overall ability of the system to vibrate, reducing the amplitude of the vibration exposures delivered to the interface where the neonate rested. However, the strut increased the overall amplitude of the vibration exposures compared to the standard stretcher system. It increased the amount of average weighted vibrations and cumulative, impulsive vibrations that were transmitted through the chain of equipment by almost 80% and 40%, respectively, when compared to the performance of the standard stretcher.

This is the first time the performance of a stretcher with a custom-built suspension system has been evaluated in the scientific literature. In contrast to the standard stretcher system and the stretcher with the strut, the new stretcher system substantially reduced both the overall average weighted vibrations and the cumulative, impulsive vibrations measured at the interface. The stretcher with the suspension was able to reduce the exposures measured at the interface to below the adult DVAL.

Differing levels of vibration input were measured at the floor of the ambulance when testing the different stretcher systems traveling over the same standardized route. Previous studies have looked at interface measurements as they related to the floor input (Sherwood et al., 1994; Sallee et al., 2016), and in order to improve this comparison in the current study, the measurements taken at all other levels of the transport system were normalized to the floor input measurements. Both the standard and new stretcher systems transmitted vibrations up the equipment chain. The standard system amplified the A_w and VDV floor-measured exposures by 1.8- and 2-fold respectively, whereas the new stretcher with the built-in suspension increased the A_w exposures by just 7% and reduced the VDV exposures by 7%.

Further, the vibration exposures measured at the level of the aluminum transfer sled in the new stretcher system (directly above the built-in suspension in the new system) were considerably reduced (~40%) relative to the input vibrations measured at the floor. Vibration exposures then increased above the transfer sled, indicating that equipment above the level of the suspension system was amplifying the vibration energy. The largest increase appeared to occur between the level of the transfer sled and the isotray top, indicating that the transfer sled was transferring vibration energy to the isotray. Further research into characterizing the frequency of the vibration energy transmitted through the system and decreasing the occurrence of this energy transfer is warranted.

The relative travel times that an infant could ride in the isolette compared to the floor level input measurements were also calculated. The allowable travel time markedly increased by 3- to 10-fold at the interface level when the simulated neonate was transported in the new stretcher system. It was again noted that the vibration exposures in the new stretcher were amplified above the transfer sled, again indicating that the transport equipment above this level was interacting and increasing the vibration delivered and measured at the interface. This is consistent with the results found in previous studies (Sherwood et al., 1994; Gajendragadkar et al., 2000; Sallee et al., 2016).

This study had several strengths. First, the use of a typical transport route and standard transport equipment improved the generalizability of results. Second, the use of the same driver and route for all test conditions reduced the variability that may be associated with changes to these factors. Third, the study benefited from the presence of a member of the neonatal transport team who was able to assess the feasibility of the new transport system and make recommendations for future use. It was determined that the increased height of the new system did not limit its usability in the ambulance tested but may be a consideration for other ambulances. Due to the increased height of the new system compared to the standard system, the transport team member did request that a cushion be added to the front of the isolette where the provider's forearms would rest during care of an infant. During transport, the team member subjectively noted the improved accessibility and stabilization of the simulated neonate in the new system as compared to the standard system.

The limitations of this study include the small sample size. Due to the standardized route, there was limited variability between measurements, and the measurements and behavior of the systems are fairly representative, minimizing the error normally associated with a small sample size. Additionally, utilizing a simulated newborn infant rather than a live newborn may have two different impacts. The materials of a manikin are different than a human body, resulting in a different resonance, and the manikin may have a different mass, causing the actual neonate vibration to differ. (Sherwood et al., 1994).

Further investigation may be merited to evaluate the structures at and above the aluminum transfer sled. Here, altering the weight and stiffness of the system components and/or adding vibration isolators between components may help mitigate exposures. Improvements may also be made by altering the vibration properties of the mattress and/or fluidized positioner that support the baby in the isolette. Future studies in this area may look at the comparison of tri-axial/vector measures and may look to further characterize the vibration exposures in the frequency domain. Future studies should also look at additional and alternative mitigating strategies to further improve the attenuation of the experienced vibrations.

3.5 CONCLUSION

The objective of this study was to characterize and compare WBV exposures experienced across three different test conditions, a standard stretcher system and two potentially mitigating strategies. The new stretcher system was effective at reducing average weighted and cumulative, impulsive vibration exposures measured at the level of the interface to below the adult, occupational-based action limits. The new stretcher had its lowest vibration at the level of the transfer sled, and then the vibration magnitudes increased above the transfer sled to the interface; however, unlike the standard stretcher, the vibration levels were below action limits. In contrast, the stretcher with the strut was not effective at reducing the WBV exposures, and at the level of the interface, it increased the exposures to above those of the standard system. These findings indicate there is still an opportunity and a need for further mitigation above the level of the suspension system. Further testing and validation of the effectiveness of this suspension system is also warranted. It is apparent that exposures are high. Future studies should prioritize characterizing these exposures in the frequency domain and mitigating exposures that may fall within the frequency range of concern.

Chapter 4. THE CHARACTERIZATION OF THE FREQUENCY PROFILE OF TWO INTERVENTIONS TO REDUCE NEONATE WHOLE BODY VIBRATION EXPOSURES DURING AMBULANCE TRANSPORT

4.1 INTRODUCTION

It is understood that humans are vulnerable to mechanical vibrations and that human sensitivity to vibration varies with the frequency of vibration (Campbell et al., 1984). The effects of whole body vibration (WBV) in adults has long been studied and classified, and exposure standards and limits have been put in place by the International Standards Organization (ISO) (1997) and by the European Union (EU) in the European Commission Directive (2002). Vibration is known to cause fatigue, interfere with visual acuity, and decrease response time (Floyd et al., 1973; Griffin, 1990). It has also been associated with change in heart rate and oxygen saturation (Bailey-Van Kuren & Shukla, 2005; Harrison & McKechnie, 2012), and it has been studied in association with increased risk of skeletal and muscle morbidities, specifically low back pain (Bovenzi, 2010). Floyd et al. (1973) reported decreases in body temperature in rhesus monkeys that were subjected even to relatively benign vibrations (12 Hz) and sharp increases in peripheral-nerve conduction time when they were subjected to severe, low-frequency (6-8 Hz) vibrations.

The United States has voluntary standards for the assessment and measurement of WBV but does not have regulations pertaining to human exposure to whole body vibration. In lieu of these regulations, we reference the EU Vibration Directives, adapted from the International Organization for Standardization (ISO 2631-1) standard. These standards specifically address the average weighted vibration exposures (A_w) and Vibration Dose Values (VDV) described in previous chapters, and they provide frequency weightings to help predict the severity of human response to vibrations (Ahn & Griffin, 2008). The frequency content is responsible for the way vibration exposures affect human health, comfort, perception, and even motion sickness (ISO, 1997). The prescribed frequency weightings are dependent on the direction of vibration. For the purposes of this study, the weighting for the vertical recumbent measurements will be utilized (ISO, 1997). When measuring these exposures, the frequency range of interest for this purpose is 0.5 Hz to 80 Hz as this is the range associated with human health effects (ISO, 1997). Of specific concern are vibrations in the range of 4-12 Hz as these vibrations are known to be resonance frequencies of the human body, potentially causing amplification of vibration to the internal tissues and organs (ISO, 1997; Macnab et al., 1995; Sallee et al., 2016).

These standards and guidance are applicable for adults in a seated position, but no standards exist for persons in a recumbent position or for children (Browning et al., 2008; ISO, 1997). Newborn infants delivered in a compromised state of health may require transport between point of delivery and an advanced care facility. This transfer is undertaken with the intent to improve the health outcomes for these fragile infants. However, the transport process may expose this vulnerable population to unnecessary external stressors. This is particularly concerning as exposure to whole body vibration (WBV) may impact the infants' near and longer-term health outcomes (Grosek et al., 2009; Macnab et al., 1995). Additionally, an increase in the morbidity and mortality of infants who are transported between hospitals was reported in 1988 by Bowman et al. They looked at the mortality rate of preterm infants who had been transferred between tertiary perinatal centers and found that the mortality rate for transferred infants was 50%, compared to 24% for a comparable group of infants who had not been transferred.

To better understand the influence that WBV may have on the problem, Shenai et al. (1981) measured the vertical accelerations experienced by neonates inside a transport isolette while being transferred by ground ambulance, and they found that vibrations were most substantial from 3 to 18 Hz. More recently, Karlsson et al. (2012) found that the WBV exposures in ground ambulance transport were predominantly in the 3-8 Hz frequency range. Campbell et al. (1984) also examined vibration within the isolette during ground transport and reported vibration acceleration of less than 10 Hz. In most of the studies on this subject, vibrations experienced by neonates during ground transport reach, and in many cases, surpass the recommended levels for adults (Campbell et al., 1984; Karlsson et al., 2012; Macnab et al., 1995; Shenai et al., 1981) and fall within the frequency range of concern.

To further characterize the role the transport equipment plays in these exposures, Sherwood et al. (1994) looked at the peak acceleration and vibration levels at four locations on the transport equipment and on the ambulance floor. Their results indicated an accentuation of vibration from the floor to the isolette – the life support system and housing in which the infants are transported—indicating the equipment may increase the amount of vibrations delivered to the neonates during transport. Additionally, Sallee et al. (2016) closely examined the patient tray within the isolette system. They determined the natural resonance frequency of the tray to be 8-10 Hz and found that there was a 1.6 magnification at the level of the tray between 5-9 Hz. This is particularly informative because of its overlap with the natural resonance frequency of the human body (4-12 Hz) and raises concern due to the potential for amplification of vibration exposures within this frequency range.

The purpose of this study was to characterize the vibration frequency spectra of the WBV exposures during simulated neonate inter-hospital ground transport along a typical transport route. Determining the vibration frequency spectra will inform decisions on vibration dampening equipment and materials that may be implemented. Further, determining which components of the transport system transmit vibration energy through the system will inform decisions on placement of vibration dampening materials. This manuscript aims to compare the frequency profiles of exposures using standard transport equipment and two potentially mitigating strategies and to characterize how the vehicle-based vibrations are transmitted from the floor of the ambulance through the chain of equipment used to support neonates (the stretcher, aluminum transfer sled, and isolette). *It is hypothesized that the proposed mitigating strategies will reduce overall WBV exposures experienced by neonates during ground ambulance transport.* This study examined WBV exposures from their current state through the implementation of mitigating strategies.

4.2 METHODS

Study Design

WBV exposures were collected when a 1.3 kg simulated newborn infant was repeatedly transported by ambulance over a 46-minute, 36 km route between two hospitals (Figure 4.1). Measurements were taken from three different stretcher configurations: 1) a standard neonate ground transport stretcher system (two times), 2) a standard neonate ground transport stretcher system where the base of the stretcher was modified with a strut to make the stretcher system more rigid (two times), and 3) a custom-made stretcher system with a built-in suspension (four times). The simulated neonate was transported in a standard isolette (Airborne Voyager Transport Incubator; International Biomedical; Austin, TX) with a mattress underlayer (Pressure diffusing mattress; International Biomedical; Austin, TX) and a fluidized positioner (Z-Flo; Molnlycke; Norcross, GA) on top. The simulated neonate was situated on top of the fluidized positioner inside the isolette. The isolette was transported on a power load cot (Power-PRO IT; Stryker; Kalamazoo, MI) (Figure 4.2) in a 12-year old ground ambulance (International 4300LP; Navistar; Lisle, IL) (Figure 4.3). The data were collected on dry road conditions with ambient air temperatures ranging between 9 to 24 Celsius (48 to 75 Fahrenheit).

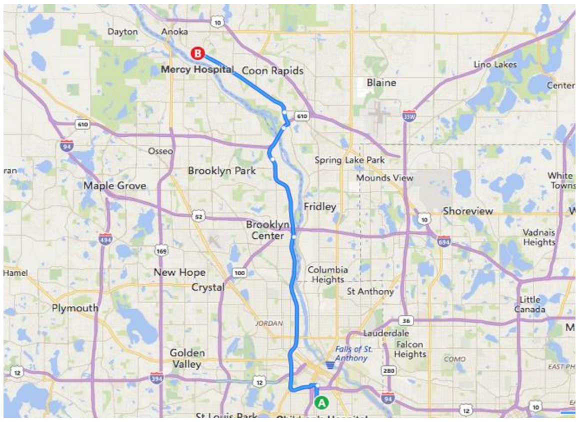

Figure 4.1. Transport Route—Route between inter-city hospitals

Figure 4.2. Standard Stretcher System

Figure 4.3. Ground Ambulance

Vibration Mitigation Approaches

The standard stretcher system consisted of a standard power load cot. The modified stretcher system was modified to be more rigid and consisted of the same power load cot system with the addition of a stabilizer bar affixed to the base of the stretcher and secured to the ambulance floor. Here, a metal strut, a non-compliant connection, was fabricated to join the front of the stretcher to the metal loops rigidly secured to the floor of the ambulance. The strut was designed to go into compression and tension with the movement of the ambulance floor instead of bending. The custom-made stretcher system utilized the same power-load cot, but it also contained a built-in suspension system on the top of the stretcher. This stretcher was fabricated by Bose Corporation, Framingham, MA. The prototype triaxial suspension system was placed between the power load cot and the detachable aluminum transfer sled which holds the medical equipment and the isolette. As shown in the photos of Figure 4.4, the prototype was designed to use compressed air and a scissor mechanism to attenuate vibrations in the up and down direction (vertical) and linear ball bearings to attenuate movement in the fore/aft and lateral, side-to-side directions.

Figure 4.4. New stretcher system with the built-in suspension (left) and with the transfer sled and isolette (right)

Instrumentation and Measurement

The instrumentation procedures for this study replicated the procedures previously used during the first phase of this study (Chapter 2) to ensure comparability of existing, modified/stiffened and new stretcher system measurements. The vibration data were measured using triaxial accelerometers (Model 356B41; PCB Piezotronics; Depew, NY), and single axis accelerometers (Model 352C33; PCB Piezotronics; Depew, NY) (Figure 4.5). Measurements were taken at six locations throughout the chain of transport equipment. Accelerometers were placed as depicted in the diagram below (Figure 4.6) (Shah et al., 2008). Single (vertical) measurements were taken at all locations. Accelerometers were magnetically mounted at the stretcher crossmember, stretcher top, and transfer sled with duct tape for added security. Accelerometers were firmly secured with tape at all other equipment locations.

Continuous vibration data were recorded using two eight-channel dataloggers (DA-40; Rion Co. LTD; Tokyo, Japan) (Figure 4.5). Vibration data were gathered at a sample rate of 1280 Hz and concurrent global positioning system (GPS) data were collected at 1 Hz utilizing a portable GPS unit (Model CR-Q1100P; Qstarz Co.; Taipei, Taiwan) (Figure 4.5). (Blood et al., 2011). Data loggers were secured to the top of the transport unit utilizing a combination of adhesive Velcro strips and duct tape, and GPS units were firmly secured with tape to the vehicle dashboard.

Figure 4.5. Data Collection System

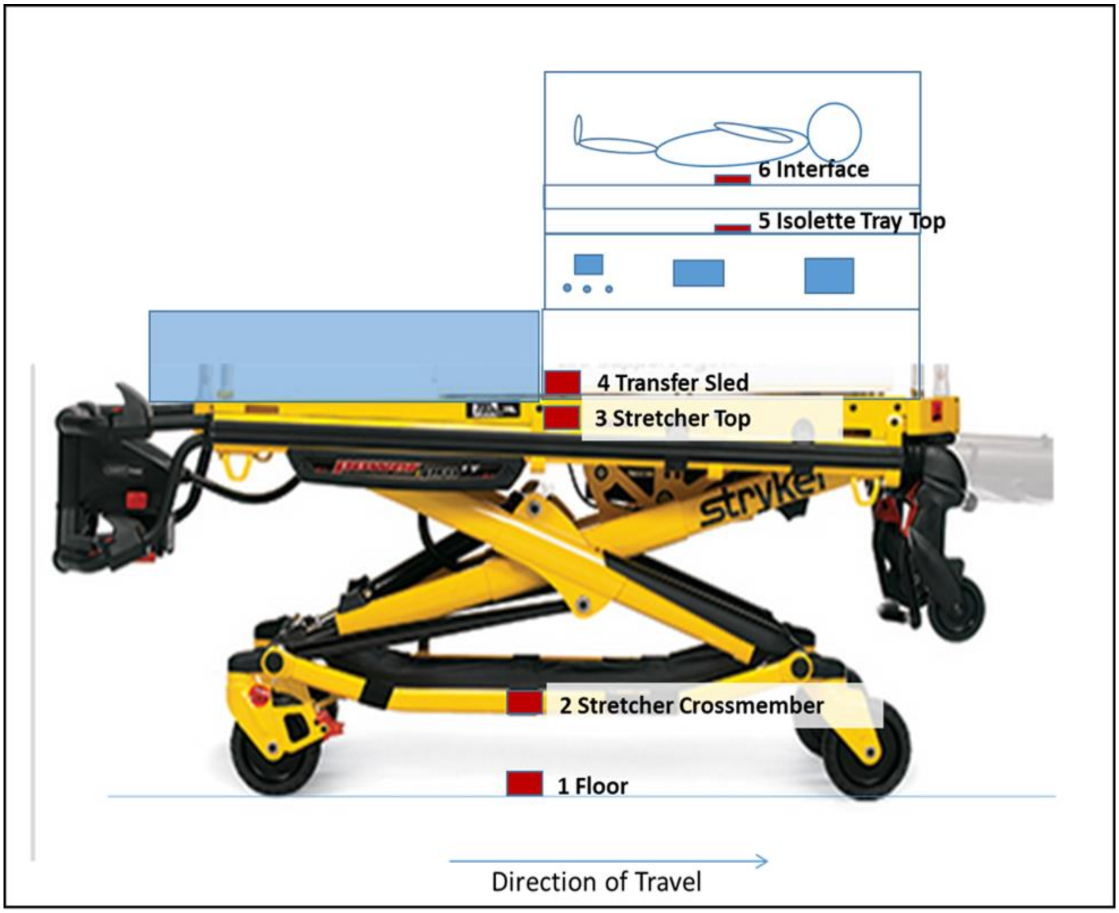

Figure 4.6. Instrumentation Diagram (Red rectangles indicate the position, number, and location of accelerometers on the three stretcher systems evaluated)

Data Processing

After the data collection, data were processed using a collection of interactive LabVIEW programs (Version 2016; National Instruments; Austin, TX), as previously described in the literature (Blood et al., 2011). Acceleration data were aligned with GPS data, and these were combined into one file to interpret acceleration data as it related to ambulance speed and type of road. GPS coordinates were used to separate acceleration measurements by road type (highway, freeway, city streets). A LabVIEW program was used to analyze the frequency content of the vibrations present during transport. Sixty-second segments of each road type were compared for each location across the three stretcher configurations.

Data Analysis

Data analysis was conducted using JMP Statistical Discovery Software (Version 14; SAS Institute; Cary, NC). Power Spectral Densities (PSDs) were used to represent the vibration frequency content the simulated neonate experienced during ground transport across the different test conditions. Four frequency ranges were used to characterize the frequency content: low (1-4 Hz), intermediate (4-8 Hz), high (8-16 Hz), and very high (16-30 Hz). The frequency content at the tested locations throughout the equipment chain were characterized, and PSDs were further compared across the three different stretcher configurations and across the three different road types. In addition, the frequency content at each location was analyzed as a function of the preceding level to determine what vibration frequencies and amplitudes were being transmitted between locations. The transmissibility of each system was examined to identify the difference in vibration magnitude (the amount of energy that is transferred) between the levels in the equipment chain. The full frequency profiles (floor to interface) of each stretcher configuration over the three road types were compared, and the transmissibilities were further narrowed by location interval to better understand the difference in vibration magnitude between measurement locations.

4.3 RESULTS

Power Spectral Densities

Power Spectral Densities (PSDs) as seen in Figure 4.7, Figure 4.8, andFigure 4.9 were used to characterize the energy and frequency content of the exposures. These PSDs were calculated for all accelerometer locations across each stretcher configuration from the sixty-second segments while the ambulance traversed the city street, freeway, and highway roads. The array of figures demonstrates that there is different frequency input into the stretcher system based on road type and that the frequency content varies across the different locations throughout the equipment chain. As outlined in the methods, four frequency ranges will be used to characterize the frequency content: low (1-4 Hz), intermediate (4-8 Hz), high (8-16 Hz), and very high (16-30 Hz). Figure 4.7 presents the median floor input spectra for all three stretcher systems for each of the three road types. The city streets (left, Figure 4.7) had a relatively narrow and primarily low frequency vibration spectra at the floor due to the slower speed (20 km/h). The highway (middle, Figure 4.7) has the broadest spectrum of frequency with the vibration input profile measured at the floor spanning all four frequency categories. Finally, the freeway (right, Figure 4.7) predominantly had three peaks in the low, high, and very high frequency ranges likely associated with the fast speed of travel (100 km/h).

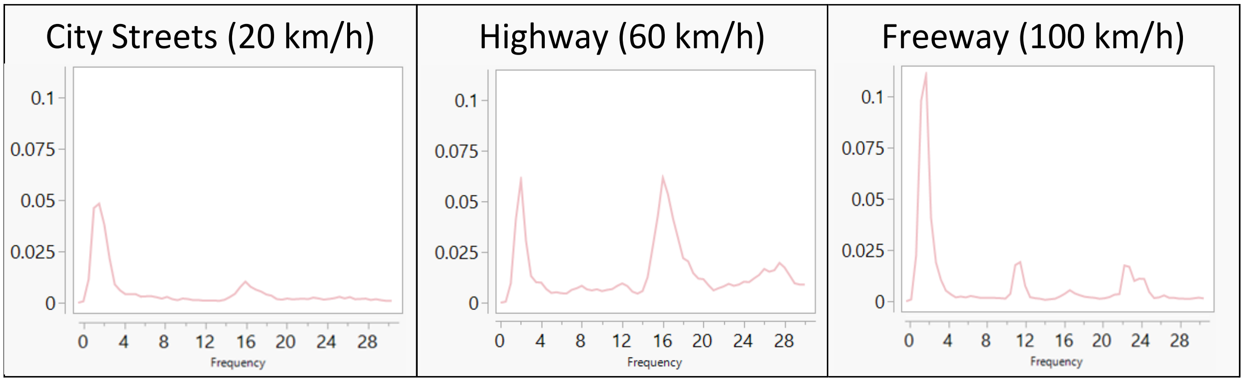

Figure 4.7. Median weighted floor input spectra for each road type (speed in km/h). Y-axis units is power in $m/s^2/Hz^3$ (n=8)

Figure 4.8 presents the weighted Power Spectral Densities (PSDs) for each of the stretcher configurations across the three road types. In the city street segments shown in the top row of Figure 4.8, the low frequency floor vibration spectra in the standard stretcher were amplified and projected into the intermediate frequencies (4 – 8 Hz) at the isotray top and interface levels. In contrast, the standard stretcher with the strut greatly amplified the low frequency floor vibrations and projected the vibration energy into both intermediate (4 – 8 Hz) and high (8 – 16 Hz) frequency at the stretcher top and interface (top left, Figure 4.8). Finally, the new stretcher with the built-in suspension did not alter the low frequency floor vibration spectra and most of the vibration energy from the floor stayed in the low frequency ranges when measured at the transfer sled and interface levels

In the highway segments in the middle row of Figure 4.8, we again see the broad spectrum of exposures experienced on this road type. The low (1-4 Hz) frequency floor vibration spectra in the standard stretcher were amplified and projected into the intermediate (4-8 Hz) and high frequencies (8-16 Hz) at all the other locations. The standard stretcher with the strut cancelled out the intermediate frequencies (4-8 Hz) but at the expense of greatly amplifying the high (8-15 Hz) and very high range of frequencies (16-18 Hz). The new stretcher successfully negated the intermediate (4-8 Hz) frequencies and reduced the high (8-16 Hz) frequencies but transferred some of the vibration energy to the very high frequency range (16-30 Hz).

The freeway segments (bottom row, Figure 4.8) demonstrate a similar trend as identified in the highway road segments. The low frequency floor vibration spectra in the standard stretcher system were again amplified and projected largely into the high frequency range (8-15 Hz). The standard stretcher with the strut cancelled out the intermediate range of frequencies (4-8 Hz) but again greatly amplified the high range frequencies. In contrast, the new stretcher system continued to perform well in the intermediate frequency range, cancelling out most of the vibration energy between 4-8 Hz. However, the new stretcher did project energy to the high and very high frequency ranges, but as shown in Chapter 3, the vibration amplitude measured across all frequencies was almost an order of magnitude lower when compared to the standard stretcher. For all three stretchers, across all the components in the stretcher systems, the vibration input measured at the floor influenced and projected vibration energy into higher frequency ranges, predominantly centered around 11 Hz and 22 Hz.

To generalize performance across all road types, the standard stretcher system (center, Figure 4.8) can be viewed as the baseline measurements for this comparison. The standard stretcher with the strut (left, Figure 4.8) and new stretcher (right, Figure 4.8) characterize the changes these potential mitigation strategies had on the vibration frequency spectra. The stretcher with the strut worked well at attenuating vibration content in the intermediate frequency range (4 – 8 Hz) but at the expense of creating vibration energy in the high frequency (8 – 16 Hz) range, resulting in a net increase in the vibration exposure as demonstrated in the results section of Chapter 3. In the frequency domain, the new suspension got rid of most of the vibration energy in the 4-10 Hz range and mitigated some of the vibration energy in the high frequency range (8-12 Hz). The new stretcher system with the built-in suspension removed almost all the vibration energy content in the intermediate frequency range (4 – 8 Hz), similar to the standard stretcher with the strut. However, in contrast to the standard stretcher with the strut, the new stretcher did not create as much vibration energy in the intermediate frequency range (4 - 8 Hz) and spread much of the vibration energy into the very high frequency ranges (16 – 30 Hz). Compared to the standard system, the new system removed almost all of the intermediate frequency vibration energy (4 - 8 Hz) and created less high frequency energy (8-16 Hz). The end result, as shown in Chapter 3, was the new stretcher system cut the overall vibration exposures in half relative to the standard system.

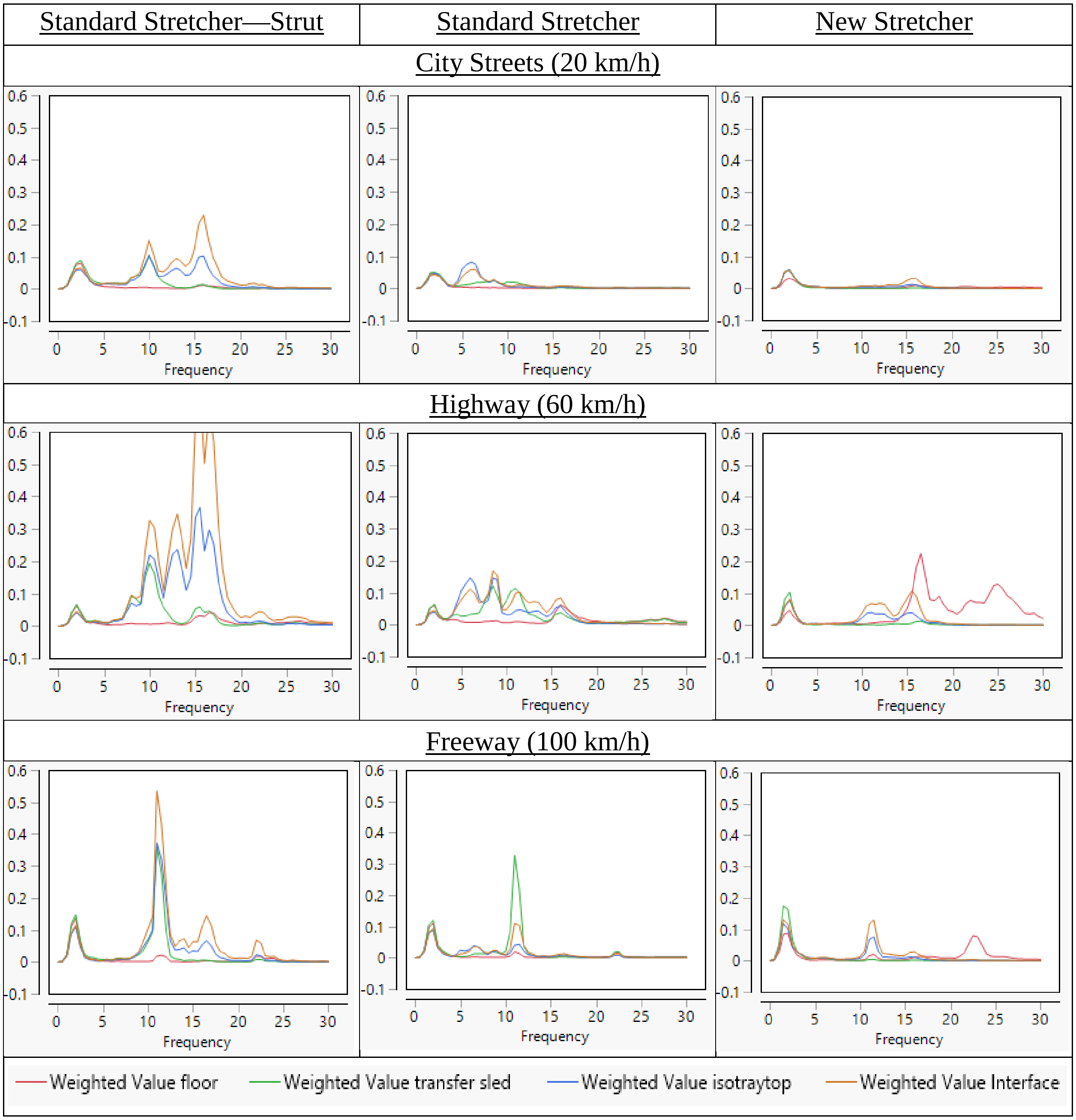

Figure 4.8. Median Weighted Power Spectral Densities by road type and stretcher system across select locations in the stretcher equipment chain. Standard stretcher with strut (n = 2) Standard stretcher (n = 2) New stretcher (n = 4). Y-axis units is power in $m/s^2/Hz^3$

As can be seen in Figure 4.9 when going up the chain of equipment in the stretcher systems, the floor vibration input excited and created vibration energy in the transfer sled centered around 10 Hz in both the standard stretcher and the standard stretcher with the strut. In contrast, with the new system, because of the built-in suspension, there is no vibration amplification in the transfer sled at 10 Hz. Going up to the isotray top, the next level up in the equipment chain, in the standard stretcher with the strut, it can be seen that the high (8 – 16 Hz) frequency vibration content in the transfer sled was substantially amplified by the isotray top. At the isotray level in the standard stretcher, the vibration content in the high frequency range measured at the transfer sled was attenuated by the iso tray and transferred into the intermediate frequency ranges. Finally, with the new stretcher system, the vibration spectra from the transfer sled excited and created high frequency vibration energy (8 – 16 Hz) in the isotray top. At the terminal level of the equipment chain, the interface, both the standard stretcher with the strut and the new stretcher amplified the high frequency vibration energy that was measured at the isotray top. In contrast, at the interface level, the standard stretcher only slightly altered and slightly amplified the high frequency vibration energy measured at the isotray top.

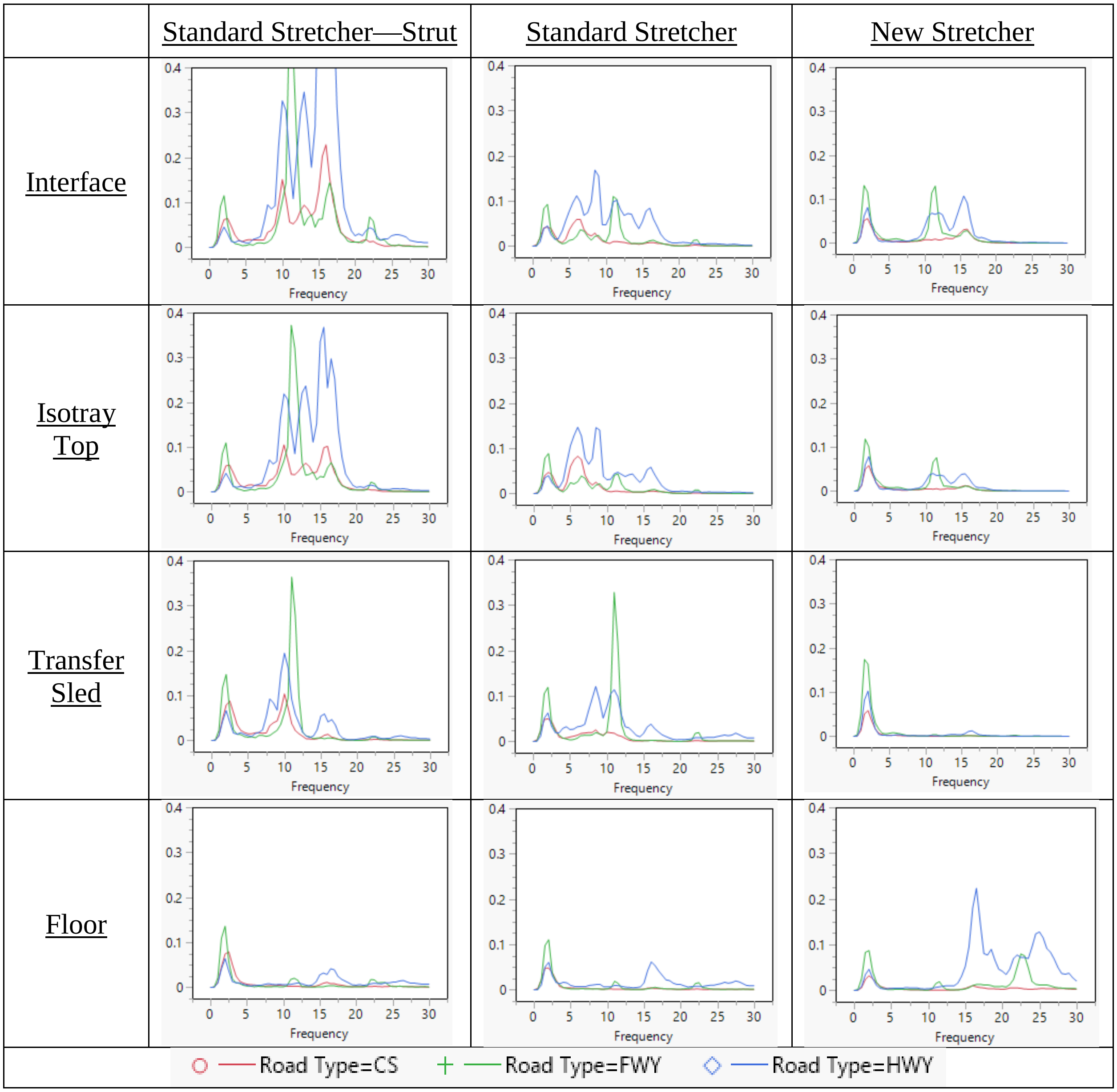

Figure 4.9. Median Weighted Power Spectral Densities by selected locations across the stretcher equipment chain and stretcher system, compared by road type. Standard stretcher with strut (n = 2) Standard stretcher (n = 2) New stretcher (n = 4). Y-axis units is power in $m/s^2/Hz^3$

Transmissibilities

Figure 4.10 displays the transmissibility values across all frequencies for all three stretcher configurations across the three road types. The transmissibility between locations is compared between standard stretcher, standard system with the strut, and the new stretcher system. The transmissibility values represent the difference in vibration magnitude (amount of energy that is transferred) between the different levels in the equipment chain. In the areas where there is attenuation, the horizontal bars will decrease. In the case of amplification, the horizontal bars will increase.

As seen in Figure 4.10, the frequency range problem areas were 7.5-12 Hz for the transfer sled and 12-20 Hz for the isotray top. On the freeway, the isotray top was amplifying across a wide range of frequencies (7.5-18 Hz). In the case of the strut system, the floor to interface transmissibility had the greatest amplification of the three systems tested, whereas from the level of the transfer sled to interface the new system had the greatest amplification of the vibration energy; amplifying the vibration energy between 10-15 Hz 50-fold compared to the floor. Amplification was also occurring between the floor to isotray top, but this was likely due to the influence of the transfer sled.

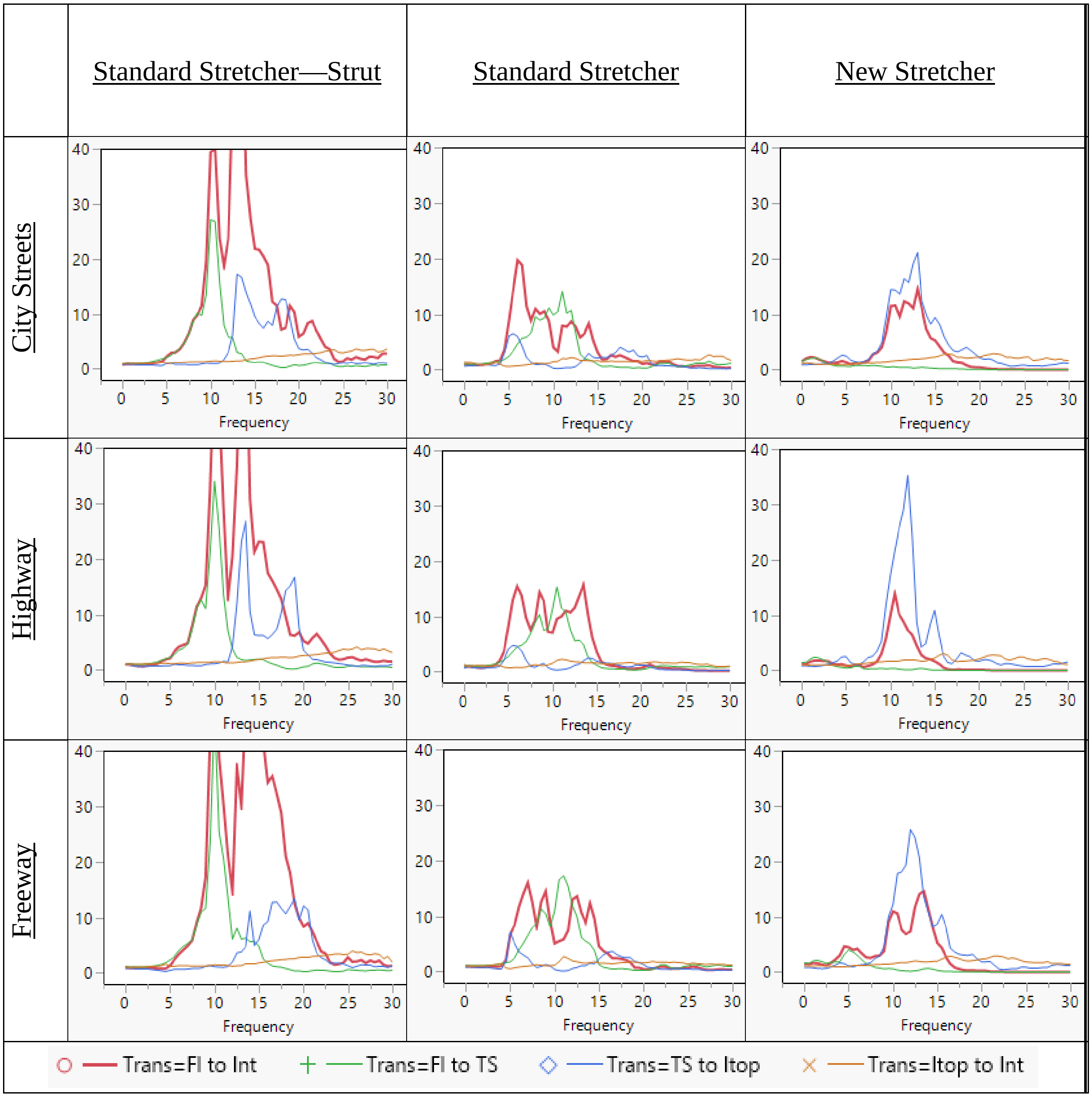

Figure 4.10. Transmissibility between select locations in the stretcher equipment chain for each stretcher system by road type. Standard stretcher with strut (n = 2) Standard stretcher (n = 2) New stretcher (n = 4). Y-axes represents transmissibility a measure where 1 = 100% transmission.

In order to further compare and understand the difference in vibration magnitude between locations, the transmissibilities were presented by the locations across the equipment chain where there was noticeable amplification (floor to transfer sled, transfer sled to isotray top and isotray top to interface. The transmissibilities for all three stretchers on the highway road segment, spanning the prominent locations in the equipment chain, is presented in Figure 4.11. The overall transmissibilities are represented by the floor to interface comparison (bottom row, Figure 4.11). As noted previously, the overall exposures were highest in the stretcher system with the strut (bottom left, Figure 4.11) and were lowest in the new stretcher system (bottom right, Figure 4.11). The floor to transfer sled transmissibility between 5-15 Hz in the stretcher system with strut was more than double the transmissibility measured in the standard stretcher system at the same level. In contrast, the new stretcher nearly eliminated all the vibration energy in this frequency range. However, the transfer sled to isotray top transmissibility in the new system was higher than the other two systems with a 30-fold amplification of transmitted vibration energy between 7-12 Hz. In all three system configurations, the isotray does not transmit notable energy to the mattress (not shown in the figure) and the mattress does not amplify (transmit) any additional energy to the interface.

As mentioned previously, there were four frequency ranges of interest. The low range amplification in the standard system and stretcher with strut appeared to be the result of resonant frequencies emanating from the floor exciting the transfer sled. The intermediate frequency amplification in the standard stretcher appeared to be the result of resonant frequencies emanating from the floor exciting the transfer sled and the intermediate frequency amplification in the stretcher with the strut appeared to be the result of resonant frequencies emanating from the transfer sled exciting the isolette tray (isotray). Finally, the high range amplification in the new stretcher system appeared to be the result of resonant frequencies emanating from the floor exciting the isotray top (Figure 4.11).

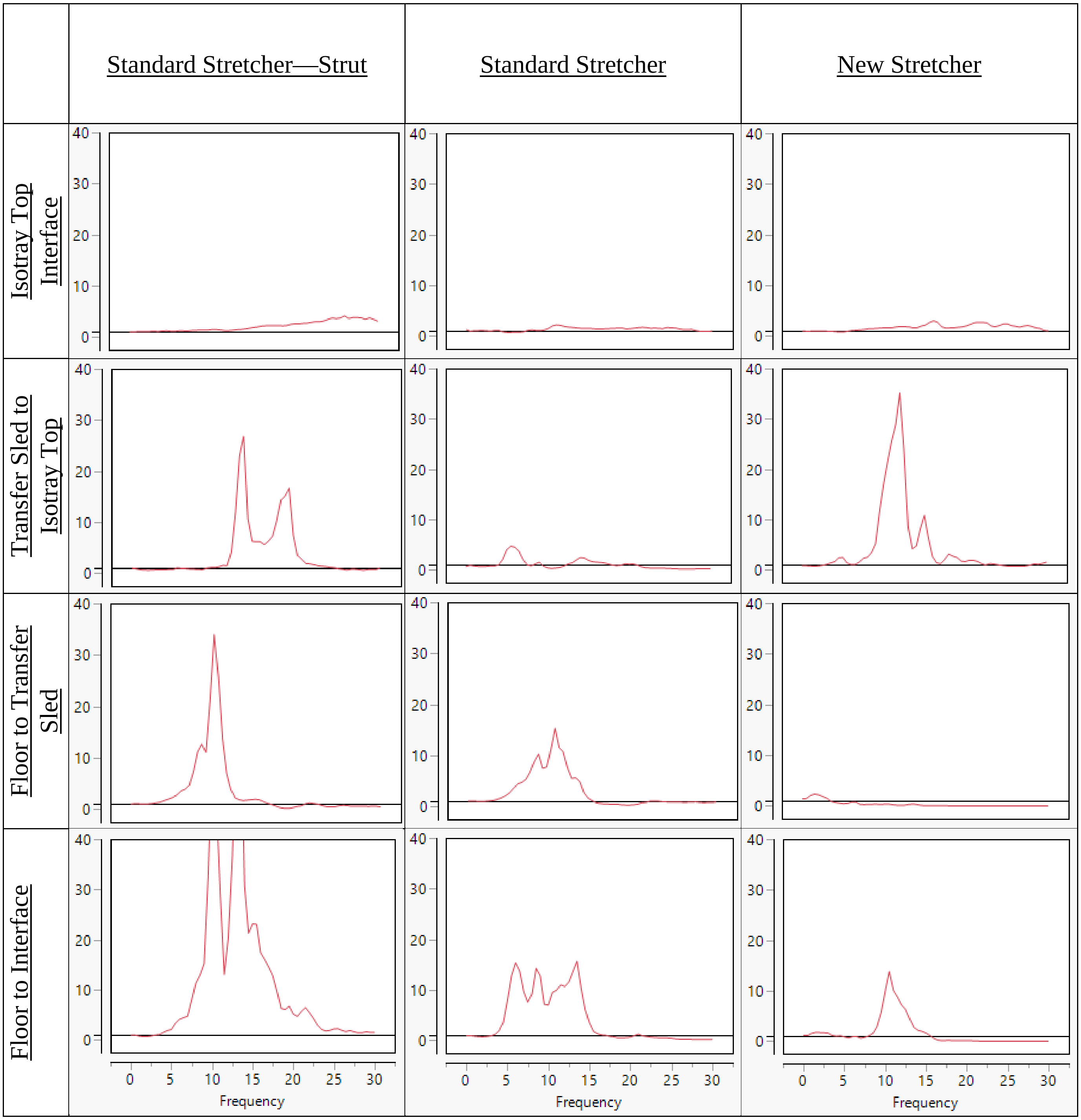

Figure 4.11. Transmissibilities compared across the stretcher systems, between selected locations in the stretcher equipment chain on highway road segment. Reference line is at 1; lines below 1 signify attenuation, lines above 1 signify amplification. Standard stretcher with strut (n = 2) Standard stretcher (n = 2) New stretcher (n = 4). Y-axes represents transmissibility a measure where 1 = 100% transmission.

4.4 DISCUSSION

In the previous phase of this study (Chapter 3), the median WBV exposures were compared across all three stretcher configurations. All the measurements at the level of the interface in the standard stretcher exceeded the ISO and EU adult daily occupational exposure action values. The objective of this phase of the study was to further compare the WBV exposures measured using a simulated neonate across the same three ground ambulance stretcher configurations. These further comparisons were made in the frequency domain in order to better characterize the exposures across the systems and determine whether the exposures experienced in transit were within the frequency range of concern. The frequency range of concern according to the ISO 2631-1 (1997) standard is 0.5-80 Hz, as this range is known to have human health effects. Exposure in the natural resonant frequency of the human body, which is between 4-12 Hz (ISO, 1997; Macnab et al., 1995; Sallee et al., 2016), may amplify the damage done to human tissues. Though the three stretcher systems also had distinct frequency profiles, they all had predominant frequency content between 0-30 Hz, falling within the range of concern (ISO, 1997).

The PSDs demonstrated that a low frequency resonance was present when traveling over all road types and that each road type had a distinct and different vibration energy profile. The city streets had a predominantly low frequency vibration spectra due to the lower travel speeds and the freeway predominantly had three peaks in the low, high, and very high ranges, likely associated with the higher speed of travel. The highway segments had the broadest frequency spectrum, essentially spanning all four frequency ranges of interest.

The standard stretcher performed consistently across the three road types and is used as the baseline for comparison to the two other stretcher systems. The low frequency vibration spectra measured at the floor of the standard stretcher was amplified and projected to the intermediate and high frequency ranges at the isotray top and interface locations. These frequency profiles corroborate the results found by Shenai et al. (1981) and Gajendragadkar et al. (2000) who found the exposures measured at the level of the infant were in the mid to high frequency ranges. These findings were also in agreement with previous studies (Campbell et al., 1984; Karlsson et al., 2012; and Sallee et al., 2016) that found that measures taken at the isotray level fell within the intermediate range. These exposures are concerning, as they fall in the frequency range of concern containing many of the natural resonant frequencies of the human body (4-12 Hz).

The other two stretcher configurations examined here were novel approaches which were designed to attenuate road-induced vibrations passing through the stretcher systems. The stretcher system with the strut did not perform as expected. It cancelled out the intermediate frequencies measured but at the expense of greatly amplifying the frequencies in the high and very high ranges, leading to an overall increased amplitude. It is unknown what the health impacts of these higher frequency exposures may be on an infant in transport. However, it appears best to err on the side of caution and decrease the overall exposure where possible, especially considering these frequencies remain in the frequency range of concern.

In contrast, the new stretcher system with the custom-built suspension was effective across all three road types and performed as hypothesized. The new stretcher did not amplify the low frequencies experienced on the city streets, slightly amplifying the vibration exposures at the interface below 4 Hz and not amplifying the overall exposures between the floor and interface levels. Over the highway and freeway roads, the new stretcher successfully negated the intermediate frequency exposures and reduced the high frequency exposures. The built-in suspension predominantly reduced the large displacement vibrations; however, as can be seen in the vibrations measured above the aluminum transfer sled, the vibration exposures monotonically increased. This increase was likely due to the smaller displacement, higher frequency vibrations passing through the built-in suspension and causing the components above the aluminum transfer sled to resonate and amplify the higher frequency vibration content. The low frequency vibration amplification was still present with the new stretcher; this low frequency resonant vibration could possibly be reduced with an active suspension. Additional controls are needed to decrease the very high frequency presence with the new system. This warrants further testing of foam washers between equipment pieces and assessment of different gel and foam layers within the isolate.

To further understand how the equipment was interacting, how it may be contributing to the measured exposures, and the difference in vibration magnitude between locations in the equipment chain, the transmissibilities between the locations were calculated. Again, the standard stretcher was used as the baseline comparison measure. As mentioned previously, there were four frequency ranges of interest. The low frequency vibration energy appears to be the result of floor resonance, the medium frequency vibration energy appears to be the result of isolette tray resonance (isotray), and the high frequency vibration energy appears to be the result of transfer sled resonance. It appears that the low frequency vibration energy that starts at the floor is transformed into higher frequency energy as it passes through the transfer sled; this energy is then transferred to the isotray and then ultimately reaches the interface (where the simulated neonate is supported). The high frequency resonance of the transfer sled excites and causes resonance at the interface level. This overall profile supports the findings of Sherwood et al. (1994), Gajendragadkar et al. (2000), and Sallee et al. (2016) who reported that vibration energy is transmitted up the chain of the equipment to the level of the infant.

The floor to transfer sled transmissibility in the strut system was more than double the transmissibility at the same level in the standard stretcher system. In contrast, the new stretcher attenuated this same frequency range to negligible levels, eliminating the low frequency content of the vibration exposures. However, the transfer sled to isotray top transmissibility in the new system was higher than the other two systems with a 30-fold amplification of transmitted vibration energy in the intermediate frequency range. In all three system configurations, the isotray does not appear to transmit notable energy to the mattress and the mattress does not amplify (transmit) any additional energy to the interface. These measures are multiplicative and indicate interactions that are occurring between individual levels. These measures indicated where amplification of the exposures occurred and where attenuation of exposures occurred. In the standard stretcher and stretcher with strut, the biggest contributor to the overall exposure was the energy being transmitted from the floor to the transfer sled. However, in the new stretcher, the biggest offender was the amplification of the vibration between the transfer sled and isotray. This is the first that implication up the various components in the equipment chain has been presented in the literature.

The number of locations assessed and the ability to identify the vibration frequency content at each level was a unique contribution of this research. Additional strengths of this study include the use of a typical transport route and standard transport equipment which improved the generalizability of our study results. The use of the same driver and route for all test conditions reduced the variability that may be associated with changes to these factors.

The limitations of this study include the small sample size. Due to the standardized route, there was limited variability between measurements, and the measurements and behavior of the systems are fairly representative, minimizing the error normally associated with a small sample size. Additionally, utilizing a simulated newborn infant may have two different impacts. The materials of a manikin are different than a human body, resulting in a different resonance, potentially causing the actual exposures to differ. Additionally, the manikin may have a different mass, causing the actual neonate vibration to differ (Sherwood et al., 1994; Gajendragadkar et al., 2000; Prehn et al., 2015). Further investigation may be merited to evaluate the structures at and above the aluminum transfer sled. Here, altering the weight and stiffness of the system components and/or adding vibration isolators between components may help reduce hazardous exposures.

4.5 CONCLUSION

The results of this study provide invaluable information on vibration frequency content of the neonate transport system and may assist in future development of mitigating strategies and design of improved stretcher systems to reduce road-induced vibration. These results provide a greater understanding of the mechanisms behind the vibration exposures during ground ambulance transport and the effect of different existing potential mitigating strategies. Although it seems intuitive that stabilizing the base of the stretcher would reduce the stretcher system’s vibration, we found that the stabilizing strut did not reduce the vibration exposures, but actually amplified the higher frequency vibration content resulting in overall higher exposures. However, the built-in suspension system did attenuate the vibrations and deserves further validation in the field. The work presented here can be built upon in future research to determine what standards and controls should be put in place to reduce exposures and improve health outcomes for neonates requiring transport.

Chapter 5. CONCLUSION

This study was motivated by concern that infants may be exposed to elevated levels, and potentially damaging levels, of WBV in transport between hospitals. This study examined the WBV exposures in existing transport equipment and compared those exposures to comparison activities (car seat and stroller) and potentially mitigating strategies (a stretcher with a strut and a stretcher with a built-in suspension). This chapter concludes the dissertation with a summary of how the dissertation addressed gaps in the literature, contributions of the work, and limitations and future directions of this research.

5.1 RESEARCH GAPS ADDRESSED

Previous research indicates that the potential exposure of neonates to WBV during ground ambulance transport has long been a concern. The earliest studies examining the WBV exposures of neonates in ground transport (Shenai et al., 1981; Campbell et al., 1984) found that vibrations experienced where the infant was located were above those levels recommended for adults. Further, they describe vibration frequency profiles within the range of concern for human health related impacts. Several studies have looked at potentially mitigating strategies and have made recommendations for changes to transport equipment based on their results. The mitigating strategies examined range from alternative mattress options (Prehn et al., 2015; Sherwood et al., 1994; Gajendragadkar et al., 2000; Shah et al., 2008; Bailey-Van Kuren & Shukla, 2005) to adding vibration isolating pads to the isolette structures (Prehn et al., 2015; Sherwood et al., 1994). Macnab et al. (1995) compared a new isolette system in 1995 with a model that was 15 years older and found that the vibration exposures in both models were comparable, indicating that recommended changes from previous research had not been implemented. More recent work by Sallee et al. (2016), Prehn et al. (2015), and Blaxter et al. (2017) again found elevated exposure levels that were similar to previous research. Our baseline results further corroborate these findings, indicating that the current isolette structure and transport system in use has not been sufficiently improved to reduce vibration exposures to neonates in transit.

Researchers have begun to more closely examine the individual components of the transport system to determine if the system itself is contributing to the increased exposures experienced by the neonates in transport. However, measurement methods have not been standardized, making it more difficult to translate results across studies. Browning et al. (2008) and Sallee et al. (2016) specifically looked at the impact of the isolette tray on vibration exposures but did not use a mattress in their studies. Campbell et al. (1984) measured the exposures at the tray underneath a mattress. Sherwood et al. (1994) looked at the isolette exposures and compared them to the vibration measures from the floor of the transport vehicle. In contrast, Gajendragadkar et al. (2000) measured the exposures experienced at the head of a simulated neonate to those exposures measured at the base of the incubator. While their methods were different, they were able to replicate the same accentuation of exposures at the head of the infant compared to the base of the isolette as was seen in the study completed by Sherwood et al. (1994). Previous research does not appear to include investigation of potential changes or improvements to the structures beneath the isolette. These structures appear to be delivering an increased level of vibration to the isolette and should be examined. No one to date has examined the vibration exposures as they are transmitted from the floor of the ambulance to points vertically aligned on the transport system.

Additionally, there has been inconsistency with how to best characterize and describe these exposures. Many previous studies have reported average weighted vibrations and compared the neonate exposures to the adult, occupation-based standards as put forth by the ISO (1997) and EU Directives (2002). However, others have utilized the comfort ratings as put forth in the ISO 2631-1 (1997) standards as their comparison, and still others have described their results in peak exposures. As there is no standard for limiting exposures and there is no guidance or prescribed method for presenting results in this population, interpretation of the results to date is challenging.

5.2 STUDY CONTRIBUTIONS

Intellectual and technical merits

The health impacts associated with ground ambulance transport of neonates are concerning. Neonates are often neurologically immature and/or physiologically compromised (Macnab et al., 1995), and they have an increased sensitivity to external stimulation (Browning et al., 2008). The health impacts associated with transport of these vulnerable patients range from an unexplained deterioration in condition (Macnab et al., 1995) to an increased risk of mortality compared to infants who have not undergone transport (Bowman et al., 1988). One of the difficulties with identifying the impact of WBV exposures in this field is the inability of the patients to vocalize their discomfort. These infants cannot express the pain they may be feeling. They cannot advocate for themselves. It is up to us as researchers and scientists to commit to investigating and solving the problem. The health and well-being of this vulnerable population should be a priority.

The research approach used in this dissertation was unique, as measurements were taken over typical transport routes and exposures were assessed at six different levels of potential interaction within the chain of equipment. The methods used in the current study allowed for a more precise characterization of exposures and provided a greater understanding of the mechanisms behind the transmission of energy from the floor of the ambulance through the transport equipment. These methods will contribute to improved, reliable method for evaluating neonate ground ambulance transport WBV exposures.

This study also used a novel approach for measuring the interface exposures. Previous studies used an accelerometer within a seat pad for measuring the interface measurements or placed under a mattress. The current study did not use seat pad due to ISO (1997) guidance that persons shall adopt the normal position for the environment. The simulated neonate was cradled by the fluidized positioner, and the narrow stature of the infant made it impractical to use a seat pad between the manikin and positioner. Further, placing the seat pad between the isotray and the mattress would not have allowed the mattress to rest naturally on the tray and it would not have been an adequate substitution for a direct interface measurement. Using standard triaxial accelerometers in this case seemed the most logical as they were small and could be secured to the structures in the chain of equipment without interrupting the natural alignment of the transport equipment.

The mitigating strategies examined here are also unique approaches to decreasing vibration exposures. This is the first study that has investigated a custom-built suspension system. The suspension system built for this study was designed specifically for this purpose utilizing vibration measurements taken during a pilot study to characterize the vibration exposures of a standard ground ambulance transport system. The strut was also a novel approach to decrease the vibration exposures, though it did not counter the vibrations as expected. This study has shown that a custom-built suspension system can cut vibration exposures in half compared to the standard, existing equipment.

Implications

This research allowed us to examine and isolate amplification points in the chain of equipment and route of transport, and it also allowed us to identify and test mitigating strategies to reduce the overall WBV exposure to neonates in transport. This study found meaningful differences in the exposures experienced by neonates in the existing transport equipment and the comparable exposures in a car, stroller, and evaluated mitigating strategies. The exposures measured using the current, standard equipment were above the standards set forth for adults, which is consistent with the previous research in this area. These findings further supported the efforts of Macnab et al. (1995), demonstrating that the elevated levels of exposure remain and indicating that still, 23 years later, sufficient changes have not been implemented in neonate transport equipment. These implications bring to light the importance of interdisciplinary work and coordinated efforts between research and industry.

This study benefited from coordination with an industry engineer, who designed and built the custom suspension system, and a member of the neonatal transport team, who was able to assess the feasibility of the new stretcher configuration. In working closely together, the engineer and transport team member were able to identify potential issues, solve issues as they arose, and discuss further improvements that may be beneficial. One potential issue that was raised was the height that the built-in suspension added to the overall stretcher system. It was determined that the height of the new system, while greater than the standard system, did not limit its practicality. The new stretcher configuration fit through the standard ambulance door, but its use may be limited in nonstandard ambulances. The team member subjectively noted the improved accessibility and stabilization of the simulated neonate in the new system as compared to the standard system.

The findings of this research pointed to the need to further focus efforts on decreasing the vibrations experienced above the level of the transfer sled. The results indicated that, using the standard stretcher system, vibration exposures were elevated 20% between the transfer sled and the interface, and, using the new stretcher, the same vibration exposures were elevated 49%. Overall exposures were reduced with the new stretcher system and could be further reduced if exposures above the transfer sled were effectively mitigated. The frequency range of interest at this point in the system was between 7-12 Hz, indicating that efforts to reduce the exposures at this level should look to dampen vibrations in this range. This is consistent with recommendations from Macnab et al. (1995) who recommended close study of the efficacy of vibration reducing modifications and that efforts be directed at reducing vibration in the low frequency range.

The current standards for WBV exposure are not necessarily protective for populations outside of the working adult population. The current research has contributed to the body of research by identifying the current level of exposure during a typical ground ambulance transport and examining how it can be mitigated. This knowledge will aid in developing further research to determine the physiological impacts of vibration to the vulnerable neonate population. This research and determination of exposure limits will enable healthcare providers to measure exposures and limit exposures to an allowable range in order to protect neonates in transport.

5.3 CONSIDERATIONS AND RECOMMENDATIONS

Study Limitations

The limitations of this study include the small sample size which may yield a higher error rate compared to a larger sample. However, due to the standardized route, there was little variability between measurements, and the measurements and behavior of the systems are fairly representative, decreasing the potential for errors. Additionally, utilizing a simulated newborn infant may have several different impacts. The materials of a manikin are different than a human body and may have different mass and resonance, causing the actual neonate vibration to differ (Sherwood et al., 1994). Also, as noted by Shah et al. (2008), the simulated neonate would not provide spontaneous movement or the balancing force of muscle use as may be expected from a live infant.

The comparison of these results to the existing standards should be cautiously interpreted. The existing standards are designed to limit exposures that usually occur over an 8-hour period, daily, for the life of a worker. Infants will not be experiencing the same duration of exposure, but as these are the only standards in place they can be used as a metric for relative comparison (Bailey-Van Kuren & Shukla, 2005; Blaxter et al., 2017). However, health-related effects are already occurring during transports that are typically less than an hour (Bailey-Van Kuren & Shukla, 2005). This the primary motive to establish appropriate and applicable standards to limit the exposures to WBV that neonates encounter during transport. The results presented here represent an important step in the development and validation of applicable standards for human vibration exposure, across the lifespan.

Future Research

Measuring and characterizing the WBV exposures of neonates during ground transport is an issue that deserves further investigation. Future studies in this area may look at the comparison of tri-axial/vector measures to further assess multi-directional exposures. An increased sample size and sampling of exposures experienced by live infants may improve the validity and generalizability of future studies. Future studies should also look at additional and alternative mitigating strategies to further improve the attenuation of the experienced vibrations. Potential next steps include evaluating the structures at and above the aluminum transfer sled. Here, altering the weight and stiffness of the system components and/or adding vibration isolators between components may help to reduce vibration. Researchers should consider materials that may work to decouple the equipment above the level of the built-in suspension. This work should be undertaken presently due to the implications it may have in reducing vibration exposures even in the existing stretcher system.

Future research may also further examine the use of different mattress types in combination with a fluidized positioner and suspension system. Our research did not indicate that the current mattress or positioner were accentuating vibration exposures but use of a heavier mattress may serve to dampen vibrations as they are delivered to the isotray. Additionally, researchers should continue to examine the effects that the weight of the infant has on vibrations experienced. This study utilized a 1.3 kg manikin which would closely equate to an infant of very low birth weight. As described by Gajendragadkar et al. (2000) and Prehn et al. (2015), the effectiveness of mitigating strategies may be impacted by the weight of the infant. Though, in contrast, Blaxter et al. (2017) found that patient mass only weakly impacted dampening efforts. This factor is worth examining further.

The use of a repeated typical transport route and standard transport equipment improved the generalizability of this study, and the use of the same driver and route for all test conditions reduced the variability that may be associated with changes to these factors. These attributes should be continued in future studies.

Finally, the stretcher system with the built-in suspension presents a viable method of reducing concerning vibration exposures. Follow-on studies should look to further validate its performance. Researchers should work with industry contacts to pursue the manufacture of a viable model that can be tested for crashworthiness and, when appropriate, can be utilized with live infants.

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