ABSTRACT

Patients who undergo inter-hospital transfer experience increased relative mortality, ranging from 10 to 100% higher than non-transferred patients. The high-cost, increased risk of complications and poor outcomes of transferred patients warrant the critical examination of potential causes. One of the major causes may be the external stressors that patients are exposed to during medical transport. To realize simultaneous measurements of external stressors, we developed a multi-sensor unit for measuring vibration, noise, ambient temperature, and barometric pressure. For preliminary evaluation, the sensor unit was tested on 29 medical transports, 11 air transports by a helicopter and 18 ground missions by an ambulance. The average whole-body vibration for each air and ground transport was calculated at 0.3510m/s$^2$ and 0.5871m/s$^2$ respectively. Air transports produced much higher level of noise than the ground transports. We found no significant difference between two modes in terms of average temperature and the temperature changes. Barometric pressure drops significantly during air transport, indicating potential use of this data for automatic mode classification.

INTRODUCTION

According to the American College of Surgeons National Trauma Data Bank, a total of 61,909 patients were transported by a helicopter and 161,556 patients were transported by ground between 2007 and 2009 (1). Despite the higher cost and limited availability of a helicopter transport, recent studies have supported the use of helicopters for the rapid transfer of patients that are experiencing a time-sensitive emergency such as trauma or myocardial infarction (2, 3, 4). Therefore, it was considered as a predictor of higher survival compared with ground transport (5). Among many time-sensitive emergencies, fast and safe medical transport of and traumatic patients is in particular important as they are more sensitive to time and vibration exposed during the transport (7, 8).

Despite the effort made for quick and safe transport, patients that undergo inter-hospital transfer for non-urgent conditions such as transfer between intensive care units, experience increased relative mortality ranging from 10-100% higher than non-transferred patients (7, 8). Identifying causes of the increased mortality has remained elusive. The high-cost, increased risk of complications and poor outcomes of transferred patients warrant the critical examination of potential causes.

Several studies have been conducted on measuring external stressors, such as vibration, noise, and temperature, using commercially available sensors. As an example, a set of sensors, a microphone, triaxial accelerometers, and electrocardiogram (ECG) device was used to measure the whole body vibration (WBV) and acoustic noise in relation to the rate and regularity of an infant’s heartbeat (9). The study found that both sound and WBV levels exceeded the recommended limits where higher WBV was associated with a lower heart rate, and a higher sound level was correlated with a higher heart rate (9). Another study used gyroscopes and a global positioning system (GPS) to measure gyration at each location/time (10).

In this study, we hypothesized that one of the major causes of increased mortality is the external stressors that patients are exposed to during medical transport. Several studies have investigated environmental stressors with commercially available sensors while only focusing on one specific stressor or a couple of external stressors using commercially available sensors (11, 12, 13, 14). Our study focuses on the development of a multi-sensor unit to realize simultaneous measurements of
multiple environmental stressors of transport, including temperature, noise, vibration, and barometric pressure. Integration of multiple sensors is not technically challenging. However, careful consideration is required to ensure low power consumption, proper circuit integration, and overall robustness of the device for repeated use by non-technical persons, such as nurses, in ground and air vehicles. In addition to successful development of the hardware, we also developed an easy user interface for data monitoring, graphical visualization and statistical analyses. Detailed description on the developed system is provided below followed by our preliminary evaluation results.

**SYSTEM DESCRIPTION**

For simultaneous measurements of the external stressors, we developed a multi-sensor unit that can measure vibration, noise, temperature, and barometric pressure simultaneously.

**Hardware Architecture**

![Figure 1. Multi-sensor unit for measuring external stressors of patients during transport.](image)

The portable multi-sensor unit consists of the following components (Fig. 1): (a) the embedded control unit with an Arduino Uno and custom electronic boards for integrating multiple sensors, a memory unit, and a battery; (b) the human-machine interface involving three switches, for turning on/off, data recording, and sending/deleting the stored data, and an LCD display indicating the current functional status and battery/memory capacities; and (c) an acrylic chassis capable of withstanding falls and crashes. It also has an external USB port for data transmission and a battery charging port for recharging the battery.

The embedded sensors include digital thermometer, barometric pressure sensor, microphone, 9-degree-of-freedom Inertial Measurement Unit (IMU), and real-time clock. We used a commercially available IMU unit (9DOF Razer IMU) incorporating three sensors, a triaxial gyroscopic sensor (ITG-3200, ~1KHz), triaxial accelerometer (ADXL345, ~100Hz), and triaxial magnetometer (HMC5883L, ~160Hz). The temperature sensor (Texas Instruments, TMP102 Low Power Digital Temperature Sensor) provides an accuracy of 0.5 °C and a resolution of 0.0625 °C with the range of -40 to +125 (15). The barometric pressure sensor (Bosch BMP085) provides a resolution of 0.01hPa with a relative accuracy pressure at ±0.5 hPa for the range of 300 to 1100 hPa. The microphone has a frequency range of 100 – 10,000Hz, sensitivity ~46 ± 2.0 at 1KHz. The maximum input sound pressure level (SPL) is 100 dB at 1.0 KHz.

Since each commercial sensor operates on its own clock, time synchronization is needed. We added a real-time clock to synchronize the sensor data. It provides absolute seconds, minutes, hours, day, month, and year. Time synchronization among the multiple sensor data is an important criterion for our application in order to allow appropriate sensor fusion and data comparisons with patients’ physiological data, such as blood pressure and heart rate in a long term. The sensor unit uses a rechargeable 7.4V Li-Po battery with its operation time up to 20 hours. It also contains a 16 GB of onboard memory to store measured sensor data.

Human-machine interface is realized by three toggle switches with high durability and an LCD screen installed on the top of the unit. The LCD displays the current status of the unit, either recording, downloading, or charging, and the memory and battery capacities. The entire unit is encased in a plastic case made of 6mm acrylic sheets. The device is about $17 \times 10 \times 6$ cm$^3$ in its size and weights about 500g.

**Graphical User Interface**

![Figure 2. GUI for visually displaying selected or cumulative sensor data and statistical results.](image)

The Graphical User Interface (GUI) is designed in MATLAB for non-technical users to easily access the measured sensor data and graphically visualize these data either for each individual mission or several missions for a specific sensor. The GUI is designed using MATLAB, which serves as an easy computing and visualization tool. Once the user opens an executable file, it will open the GUI with a button on the top to select an appropriate folder that contains the data. Once the folder is selected, the user may choose the entire folder or a specific data set within the folder to analyze.
As shown in Fig. 2, the GUI consists of a select menu bar (left), descriptive statistical data for selected data (middle), and a graph (right) for plotting the data set. It also contains icons for editing the specific parameters, saving graphs in the MATLAB Figure format, or changing display parameters. Once the user runs an executable MATLAB GUI file, the above window (Fig. 2) will open. First, the user selects a folder that contains one or more data files in the .csv format by clicking the Choose Folder button. The list of files in the selected folder will be then displayed on a drop-down menu. The user can choose a specific data file for a single mission or the entire folder for statistical analyses and graphical visualization.

Descriptive statistical analysis, including average, maximum and minimum values, and duration and the number of transports, will appear at the middle column. If the user selects a specific mission from the drop down menu the statistics will change to represent the selected file’s data. The main select bar on the left column allows the user to choose specific sensor data. The current format of the GUI allows individual analyses and display of each sensor data and some preprocessed data, including time duration, temperature in Celsius, noise, barometric pressure, integrated/raw accelerations, rotation, and integrated/raw gyroscopic data.

**PRELIMINARY EVALUATION**

This small-scale clinical evaluation focuses on testing technical functionality of the sensor unit, usability for non-engineering end-users, and preliminary evaluation on the sensor data in terms of the patient’s whole body vibration (WBV), noise, barometric pressure, and temperature exposures during air and ground medical transports by a helicopter or ground ambulance.

**Design and Methods**

Medical transport is conducted by a ground vehicle, helicopter, or jet. Due to high frequencies of helicopter and ground transports, we selected these two for technical evaluation of the sensor unit and data comparison. For technical evaluation, we analyzed the battery operations and counted any sensor malfunction during recording. Data analyses focused on the following:

a. Difference in WBV between two transportation modes;  
b. Statistical analyses on noise, barometric pressure, and temperature data; and  
c. Preliminary validity evaluation of the sensor collected data by comparing with the results from the previous studies.

For measured triaxial acceleration data, the average, maximum, and minimum values of WBV were calculated and compared between the two modes. The calculation for WBV was conducted only for the period when the patient is being transported in the vehicle while the sensor is recording well before the departure of the transport vehicle. We also analyzed the noise, barometric, and temperature data as potential distinguishing or shared characteristics between the two transportation modes.

The data measured in each mission is saved in a single excel file with 16 columns: Year, Month, Date, Hour, Minute, Second, Temperature, Noise, Barometric Pressure, Acceleration about x-axis \((a_x)\), Acceleration about y-axis \((a_y)\), Acceleration about z-axis \((a_z)\), Magnetometer Data, Gyro\(_x\), Gyro\(_y\), and Gyro\(_z\) at the sampling rate of 50 Hz. We conducted descriptive data analyses for each temperature, noise, barometric pressure, and magnetometer data by calculating the average, maximum, minimum, and standard deviation.

**Whole-body vibration (WBV) calculations:**

The triaxial accelerometer embedded in the sensor unit produces g-force (gravitational force) rather than accelerations \((\text{m/s}^2)\). The conversion of the raw sensor data to accelerations \((\text{m/s}^2)\) is made by

\[
a_k = \frac{a^{raw}_k \times V_{ref}}{B}
\]

where \(k = x, y,\) or \(z,\) \(a^{raw}_k\) is the raw sensor data, \(V_{ref}\) is the reference voltage, and \(B\) is the bit resolution. In our case, \(V_{ref} = 3.3\text{V}^\prime\) and \(B = 1024\).

According to the European Committee for Standardization (CEN) (16), an axis is regarded as dominant when the weighted root-mean-square (RMS) value in each of the other two axes, multiplied by 1.4 in the case of \(x\) and \(y\) axes, is less than 66% of that in the dominant axis. Since our results found that there was no dominant axis among the three frequency-weighted RMS accelerations, the vector norm of the frequency-weighted RMS accelerations was calculated to evaluate the health risk from exposure to whole-body vibration (WBV), according to the following formula (ISO2631-1:1997):

\[
a = \sqrt{1.4^2 a_x^2 + 1.4^2 a_y^2 + a_z^2} \text{ [m/s}^2]\]

Since there is no dominant direction of accelerations during transport by an ambulance or helicopter, WBV in medical transportation research uses the above frequency weighted WBV formula (17).

Although many researchers use the \(k\)-factor (i.e., 1.4) for the accelerations along the \(x\) and \(y\) axes when evaluating WBV noted in the application of ISO2631, there is a debate for this number due to ambiguity regarding the axes to be evaluated. The ambiguity comes from the anomalous use of a multiplying factor of 1.4 for \(a_x\) and \(a_y\). The guidance is only provided regarding the evaluation of health effects of WBV, not the effects of WBV on comfort (18). As an alternative, the vector sum of the RMS accelerations with no weighing factor can be used (ISO 2631-1:1997):

\[
a = \sqrt{a_x^2 + a_y^2 + a_z^2} \text{ [m/s}^2]\]

This formula is being used in many machinery devices to measure the acceleration.

**Directional variation measure:**

The triaxial magnetometer measures the absolute angles from the North Pole, ranging from 0 to 360°. While the accelerometer provides information about translational motion, it does not effectively capture rotational motion. In particular, inclusion of a magnetometer can determine 1) differences in the overall rotational/directional variations between air and ground transports and 2) differences between different routes that the ground vehicle may take during transport. In this study, we
only examined the average and standard deviation of each air and ground transport.

**Noise, barometric pressure, and temperature data analyses:**

Our initial expectation of the maximum noise range was around 80–100dB. However, collected data revealed that the actual noise level exceeded 100dB occasionally during transport. To compensate the error due to such limitation, signal restoration can be applied for the distorted data using filters that perform signal separation and restoration (19). We first tried a simplified Kalman filter by tuning covariance values arbitrarily to match the original signal and filtering signals for the period of correctly collected signals. However, these covariance values are chosen with a trial and error method by looking at the signal. Therefore, it was not appropriate without reference data.

Instead, a Butterworth filter was used with a corner frequency, which is the same as a sampling frequency of the data (19). As a result, the same amplitude for the collected signal and the restored signal was achieved while restoring cutoff data. Fig. 3 (top) shows an example original noise data measured during an air transport with the maximum sensing range of 100dB. It shows significant noise increase between about 550 and 1,550 seconds where the high frequency values were cut off at 100 dB. Fig. 3 (bottom) shows the restored data using the Butterworth filter.

![Figure 3](image)

**Figure 3.** Original noise data (top) and restored data (bottom). Truncated noise level at 100dB from about 550 second to 1550 second are restored by the Butterworth filter.

For the restored noise, temperature, and barometric pressure data, we calculated the average, maximum, and standard deviation. For the noise data, since the acoustic noise forms a wave of collected data that shows oscillation with amplitude which is the difference between the high and low noise level.

**Experimental Protocol**

Experiments were conducted by the following protocol:

1. The user, a registered transport nurse in our study, turns the unit on by closing the red switch, waits for a few seconds until the system performs internal configurations and is ready for data recording.
2. The unit is installed before the patient is moved to a transfer bed in his/her room before being transported. The unit is placed facing upward between the patient’s legs.
3. The user turns off the sensor unit by opening the orange switch once the transport is completed.
4. To download the collected data, the user connects the unit to a computer using a USB-2 cable and turns on the white switch. The LCD screen will then display “downloading”.
5. To delete the data in the onboard memory, the user turns on the clear switch and leaves it on for 10 seconds. It will automatically initiate memory formatting.
6. To charge the battery, the power switch must be turned off and the battery charger cable should be connected to the battery charging part.

**Results**

The sensor unit was tested on total 29 medical transports, 11 by a helicopter and 18 by a ground vehicle. Average duration of each transport was 656 seconds for a helicopter and 1,222 seconds for a ground vehicle.

**Whole-body vibration (WBV):**

**Table 1.** Average and maximum vibrations [m/s²] and standard deviation (SD) using Eq. (1) for air transport by helicopter and ground transport by ambulance.

<table>
<thead>
<tr>
<th></th>
<th>Average</th>
<th>Maximum</th>
<th>SD</th>
</tr>
</thead>
<tbody>
<tr>
<td>Air</td>
<td>0.3510</td>
<td>1.0917</td>
<td>0.1988</td>
</tr>
<tr>
<td>Ground</td>
<td>0.5871</td>
<td>2.8052</td>
<td>0.2619</td>
</tr>
</tbody>
</table>

**Table 2.** Average and maximum WBV [m/s²] and standard deviation (SD) using Eq. (2) for air transport by helicopter and ground transport by ambulance.

<table>
<thead>
<tr>
<th></th>
<th>Average</th>
<th>Maximum</th>
<th>SD</th>
</tr>
</thead>
<tbody>
<tr>
<td>Air</td>
<td>0.3035</td>
<td>0.7042</td>
<td>0.1794</td>
</tr>
<tr>
<td>Ground</td>
<td>0.5381</td>
<td>2.5356</td>
<td>0.2817</td>
</tr>
</tbody>
</table>

**Table 3.** Comparison with other studies by Karlsson et al. (9) and Raffler et al. (17).

<table>
<thead>
<tr>
<th></th>
<th>Our study (Table 1)</th>
<th>Karlssons et al</th>
<th>Raffler et al</th>
</tr>
</thead>
<tbody>
<tr>
<td>Air</td>
<td>0.3510</td>
<td>0.12</td>
<td>0.37</td>
</tr>
<tr>
<td>Ground</td>
<td>0.5871</td>
<td>0.25</td>
<td>0.53</td>
</tr>
</tbody>
</table>

WBV using Eq. (1) and (2) was calculated for each mission. The calculation of WBV was conducted only for the in-transit period in order to focus on the patient’s vibration exposure inside the vehicle for comparison between two different modes. As shown in Table 1, the descriptive statistical analysis revealed that the average WBV calculated by Eq. (1) was 0.3510 m/s² with the standard deviation of 0.1988 by a helicopter and 0.5871 m/s² with the standard deviation of 0.2619 by a ground vehicle. The maximum WBV was recorded at 1.0917 m/s² and 2.8052 m/s² for each helicopter and ground transportation, respectively. The results show that the ground vehicle generates higher average, maximum and standard
deviation of WBV. Table 2 shows the results when we used Eq. (2) for calculating vibration. While the calculated values are smaller than that in Table 1, the results reserves the same characteristics as the one using Eq. (1), such as higher average, maximum and standard deviation of WBV in ground transports.

Table 3 compares our data with the results from the previous studies (9, 17). These previous works used Eq. (2) and therefore comparisons were made for the values in Table 1. In all three studies, air transport resulted in a lower average WBV than ground transport.

**Directional variation:**

Table 4 shows the statistical results of directional changes during air and ground transports. We found no difference in the average and maximum angles measured from the North Pole, while the helicopters showed somewhat higher standard deviation (94.6617) than the ground ambulances (70.7502). It was hard to determine which type of transport is better in terms of generating less directional changes because it highly depends on the routes and street/traffic conditions. However, this data can be useful when the study involves different routes, in particular for ground transport, to examine differences in rotational acceleration change and its effect on patients’ health outcomes and comfort.

**Table 4.** Average and maximum angles measured from the North Pole and the standard deviation for air transport by helicopter and ground transport by ambulance.

<table>
<thead>
<tr>
<th>Sensor data</th>
<th>Ave</th>
<th>Max</th>
<th>Min</th>
<th>SD</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Air</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Barometric</td>
<td>89,236</td>
<td>92,083</td>
<td>86,268</td>
<td>2,326</td>
</tr>
<tr>
<td>Noise (in-transit)</td>
<td>47.3 (60.5)</td>
<td>185.7 (148.7)</td>
<td>-</td>
<td>43.6 (30.9)</td>
</tr>
<tr>
<td>Temperature (change)</td>
<td>28.02 (5.93)</td>
<td>29.98 (1.6)</td>
<td>24.05 (8.63)</td>
<td>1.65 (2.47)</td>
</tr>
<tr>
<td><strong>Ground</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Barometric</td>
<td>91,773</td>
<td>92,861</td>
<td>90,902</td>
<td>505</td>
</tr>
<tr>
<td>Noise (in-transit)</td>
<td>37.5 (34.8)</td>
<td>181.6 (134)</td>
<td>-</td>
<td>38.6 (26.4)</td>
</tr>
<tr>
<td>Temperature (change)</td>
<td>25.51 (8.06)</td>
<td>28.16 (2.81)</td>
<td>20.1 (14.12)</td>
<td>2.16 (3.24)</td>
</tr>
</tbody>
</table>

**Barometric pressure, noise, and temperature data:**

As shown in Fig. 5, barometric pressure data can be used to classify between air and ground transports. As summarized in Table 5, the transports by a helicopter resulted in lower average and maximum values where the standard deviation was significantly higher than the ground transports. This indicates that the patients transported by a helicopter are exposed to lower air pressure with higher variance.

We also calculated the average, maximum and standard deviation of the restored noise data. The average noise level was 47.3dB and 37.5dB for each air and ground transports, respectively, when the entire duration of measurement was considered. The in-transit noise level for air transports was 60.5dB while it was 34.8dB for the ground transport. The standard deviation was also higher in air transports ground mission, such that 60.5dB during air transport and 34.8dB during ground.

The average temperature was 28.02 °C and 25.51 °C for each air and ground transport. The average temperature change was 5.93F (SD: 2.47) by air transport and 8.06F (SD: 3.24) by ground transport. The ground transport showed higher temperature changes and variation. However, since our study was conducted over several months and the number of missions per each transit mode for the same time period was not controlled. Therefore, the comparison is inconclusive from this preliminary study. In general, patients undergo a rather sudden temperature change when they exit the hospital to be moved to the vehicle especially when the weather is hot or cold.

Fig. 5 shows an example of acceleration data (m/s²) measured during air and ground missions. It also shows the barometric pressure multiplied by 10⁴. The calculation of WBV was conducted only for the boxed area in order to focus on the patient’s vibration exposure inside the vehicle for comparison between two different modes.

**Table 5.** Barometric pressure [hPa], noise [dB] and temperature [°C] data.

<table>
<thead>
<tr>
<th>Sensor data</th>
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<td>2.16 (3.24)</td>
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</tbody>
</table>
DISCUSSION
Findings
A multisensory unit that can measure WBV, temperature, barometric pressure, and noise was developed and clinically tested for technical functionality and data validation. The sensor unit functioned well without any operational errors, validating its technical robustness and usability. The users (a transport nurse or a student majoring in nursing) had no difficulty operating the device, including data measurement, transfer, and analyses, formatting the memory, and charging the batteries.

The developed sensor unit was tested on 29 medical transports, 11 air transports by a helicopter and 18 ground transports by an ambulance. We observed significantly higher average WBV during the ground transport than during the air transport, primarily due to the varying road conditions and rapid changes in speed and orientation while driving. WBV was analyzed only for the in-transit period. However, the raw vibration data showed high acceleration for a short period of time, when the patient is moved from his bed to the transport stretcher prior to transport, when the patient is loaded into the transport vehicle, and when the patient is unloaded from the transport vehicle.

The study also found that a helicopter produces much higher noise than a ground ambulance possibly causing discomfort to patients. Furthermore, patients were exposed to lower and more varying air pressure during air transports as expected.

Limitations
Our initial expectation of the maximum noise range was around 80–100dB. However, most of helicopter missions in our experiments exceeded this limit during flight, resulting in the high frequency values cut off at 100dB. Therefore, the current microphone was chosen due to its light weight and small size with relatively broad range of measurements, but was not sufficient for our purpose. We applied the second order Butterworth filter for high-frequency data restoration as reported above. However, data restoration presents its own numerical errors and it is hard to project how close the restored data would be to the real data. Another study reported higher noise levels for ground transport ranging from 50-80 dB, and between 70-90 dB for helicopter transport. To overcome this limitation, we are replacing the current microphone by one that can measure up to 200dB.

Potential and Future Work
This paper reports our first clinical trial of the new sensor device developed for measuring environmental stressors during medical transport. Therefore, we first focused on evaluating technical feasibility and usability of the device. The overall goal of this research is to determine how environmental stressors influence patient’s health outcomes in order to discern how best and when to move patients that require medical transport. To do so, our next step is to evaluate correlations between the sensor data and the patients’ physiological data and identify high-correlation factors, including the type, intensity/strength, and duration of exposure. In addition, the barometer data clearly distinguished between the air and ground missions, implying its potential use for automated data classification. As a part of our ongoing work, we are developing an algorithm to automatically label events (e.g., loading, unloading, etc.) with time stamps.

Once fully tested, this sensor unit can serve as a stand-alone, integrated sensor unit that can measure multiple environmental stressors, including noise, vibration, air pressure, and ambient temperature, simultaneously during medical transport. While one or some subsets of these measures have been considered in previous studies, these data have not been collected and analyzed as a whole.

ACKNOWLEDGMENTS
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15. Texas Instruments Datasheet, Low-Power Digital Temp Sensor w/SMBus/Two-Wire Serial Interface in SOT563 (Rev. C)


