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Original Contribution

A novel 4D volumetric M-mode ultrasound scanning technique for evaluation of intravascular volume and hemodynamic parameters

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ABSTRACT

Introduction: We use a novel 4-dimensional (4D) volumetric M-mode (VMM) ultrasound (US) technique to assess intravascular volume by monitoring the inferior vena cava (IVC). The VMM method expands the spatial coverage of standard M-mode scanning (depth vs time) by including lateral image direction and adds transducer tilt to cover the region surrounding the IVC. Current ultrasound methods for volume assessment suffer from intra- and inter-operator variability. The VMM technique aims to address these limitations, aiding in early detection of hypovolemia/hemorrhage and guiding resuscitation.

Methods/technical approach: The 4D VMM technique was used on animals that underwent a swine hemorrhagic shock protocol with fluid resuscitation. 2D ultrasound images obtained were formatted in a 3D volume to capture changes over time in vessel size with respiration and volume status. Planes were then extracted from the 3D volume at multiple lateral locations to find and track the IVC. The vessel walls were manually traced on vertical planes (depth vs. time) to determine mean IVC diameter and IVC collapsibility at each measurement time point in the shock/resuscitation protocol. Planes at constant depth (lateral vs. time) were selected to extract respiratory and cardiac cycle data.

Results: Mean IVC diameter in the baseline phase was significantly greater than in the hemorrhage phase ($p = 0.020$). There was no significant different in mean IVC diameter between baseline and resuscitation ($p = 0.064$) or hemorrhage and resuscitation phases ($p = 0.531$). There was no statistically significant difference in mean collapsibility or ΔIVC diameter between protocol phases. The 4D VMM technique effectively measured heart and respiratory rates, consistent with monitored vitals.

Conclusion: 4D VMM identified IVC changes corresponding to blood loss and resuscitation during hemorrhagic shock as well as heart/respiratory rates. This innovative approach holds promise in reducing operator variability and providing actionable information during treatment of shock.

1. Introduction

Volume assessment is critical in settings of hemorrhagic shock, sepsis, trauma, and surgery [1]. Point-of-care ultrasound (POCUS) is a noninvasive method of volume assessment that can be quickly performed and has the benefits of being low-cost and widely available. Though POCUS is easy to use, its diagnostic value is limited by high intra- and inter-operator variability [2–8]. Furthermore, POCUS provides a 'snapshot' of intravascular volume status and thus is limited in situations where continuous monitoring is required. To address the limitations of POCUS in the use for intravascular volume assessment, we devised a novel 4-dimensional (4D) volumetric M-mode (VMM) ultrasound scanning technique that allows for continuous measurement of the major venous structures [e.g., inferior vena cava (IVC) or internal jugular (IJ)]. Standard M-mode, which highlights target motion in the depth direction along a single ultrasound image line, has been used previously to measure IVC size changes associated with volume status [8,9]. Our approach extends the M-mode data to a 2D field of view

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rather than a single line and interrogates a volume by slow repeated tilting of the ultrasound scanhead, therefore eliminating the need for precise placement of the ultrasound transducer.

2. Methods

2.1. Swine model assessment

In a protocol development phase piloting our technique, 4D VMM was used to assess volume status on pigs that underwent a previously published swine model of pressure-controlled hemorrhagic shock with fluid resuscitation [10]. The experimental protocol was in accordance with ARRIVE 2.0 guidelines, and compliance with the Animal Welfare Act was maintained with institutional animal use committee approval according to the Guide for the Care and Use of Laboratory Animals, National Academy of Science, 2011 [11,12]. As part of the protocol development process, ultrasound scans from 7 animals were performed at least once per protocol phase (baseline, hemorrhage, or resuscitation). After protocol development was completed, scans for one animal were performed every 2–9 min for just over 1 h, which produced a total of 14 time-points. Images from this pig were selected for detailed analysis.

2.2. 4D VMM technique

The VMM technique expands the spatial coverage of the standard M-mode data acquisition (depth vs. time) to include depth, time, lateral direction, and tilt angle of the 2D image plane. A linear array ultrasound scanhead (9L, Logiq E9, GE HealthCare, Waukesha, WI, USA) was first positioned by hand to acquire a longitudinal view of the IVC with a trapezoidal scan format. The VMM scan was then performed with slow manual repeated tilting of the scanhead for at least 1 min from the left to right on the abdomen, and vice-versa. Each tilt scan in one direction took approximately 30 s. All 2D images over the course of the scan were recorded as a cine-loop on the ultrasound instrument.

2.3. 4D VMM image processing and analysis

For each tilt scan, the sequence of 2D B-mode ultrasound images was formatted in a 3D volume to provide a time series that captured the changes in vessel size with respiration (Figs. 1–3). Custom software was developed with the MATLAB engineering software package (MathWorks, Inc., Natick, MA, USA) to create the volumetric M-mode data and extract 2D planes for analysis. Long-axis vertical planes (i.e. depth-time planes) were extracted from the volume at selected lateral locations (x-axis in Fig. 2) to track the IVC size. Scans at different stages of shock/resuscitation highlight the changes in the IVC size and collapsibility (Fig. 4).

The IVC was identified on long-axis vertical planes at 14 time points during the swine hemorrhagic shock protocol for one animal. At each study time point, three long-axis vertical planes were selected, offset in the lateral direction (x-axis in Fig. 2). This provided repeated size measurements over a segment of the IVC. The IVC walls were manually traced to identify maximum and minimum diameter during a single respiratory cycle. The measurements for the three long-axis vertical planes were averaged at each study time point. Mean IVC diameter was calculated at each measurement time point in the shock/resuscitation

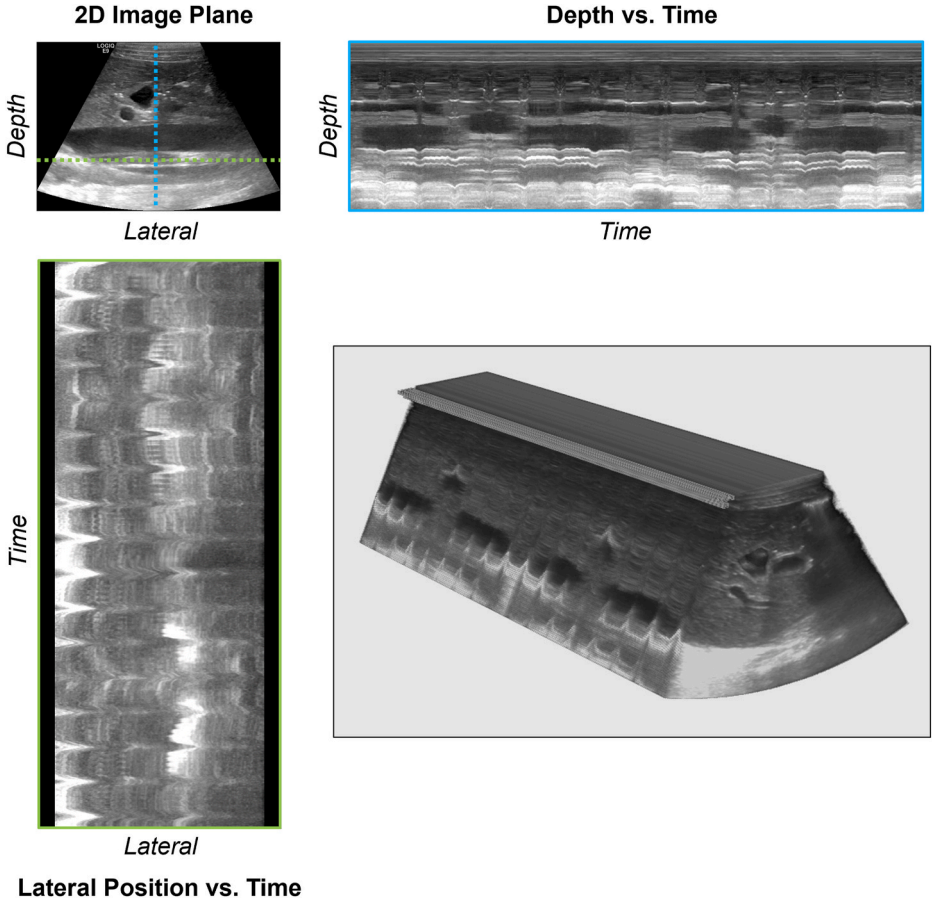

Fig. 1. Overview of the VMM data set. The bottom right image shows the reformatting of the 2D B-mode ultrasound images obtained into a 3D volume. The top left image shows a 2D B mode ultrasound image. The bottom left and top right images show 2D images over time as the scanhead is being tilted from left to right and vice-versa. The bottom left image is extracted at constant depth (green dashed line in B-mode image), and the top right image is extracted at constant lateral location (blue dashed line in B-mode image). (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

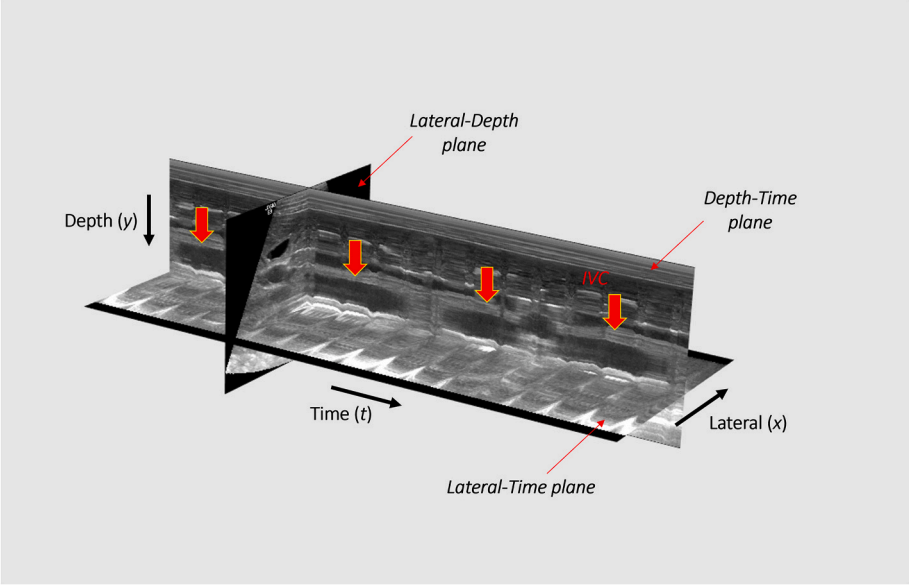

Fig. 2. Depiction of IVC visualization via the VMM method. The IVC appears intermittently in the long-axis vertical plane (depth-time plane) as the tilt scan passes across the vessel. The lateral-depth plane (x-y axis) shows a 2D B-mode image at a selected time. The horizontal lateral-time plane (x-t axis) visualizes the data at a selected depth.

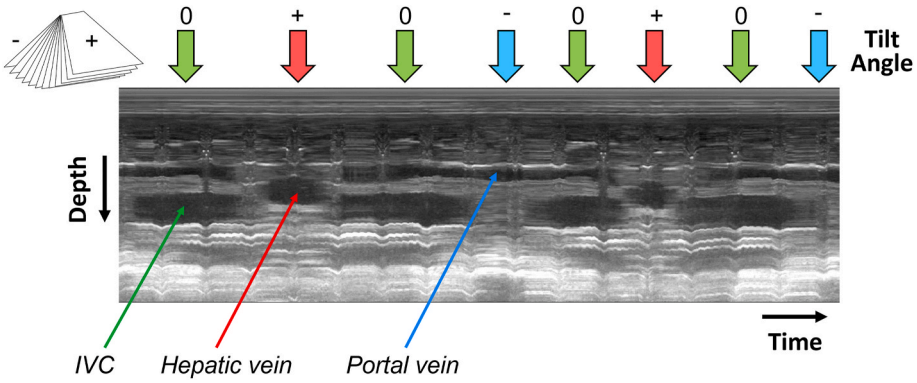

Fig. 3. The tilting of the scanhead is indicated by the + and – signs with 0 being a neutral position over the IVC. The bottom part of this display shows the vertical plane (i.e. depth-time plane). Throughout the tilting of the scanhead from + positioning to – positioning the hepatic and portal veins can be seen, respectively.

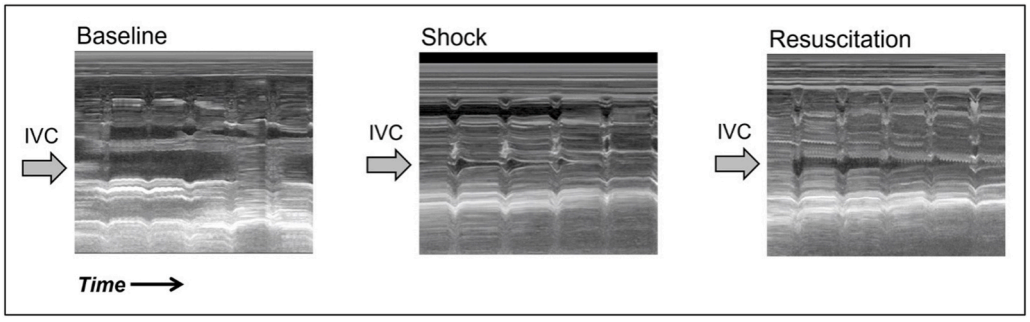

Fig. 4. VMM visualization of IVC (arrows) size changes that correspond with volume status in a swine trauma model. Note the IVC collapse within the shock phase and the expansion of the IVC after resuscitation.

protocol. IVC collapsibility was calculated using the equation CI = 100* [(Dmax-Dmin)/Dmax)] to measure respiratory variation of the IVC. ΔIVC was calculated as Dmax-Dmin.

Horizontal planes (lateral-time planes) at constant depth (y-axis in Fig. 2) were used to extract respiratory and cardiac cycle data (Fig. 5). Peaks in lateral offset were manually marked and the heart rate and respiratory rate were calculated from the average time intervals.

2.4. Statistical analysis

One-way ANOVA was performed to compare differences in mean IVC diameter and collapsibility between protocol phases. The Tukey post-

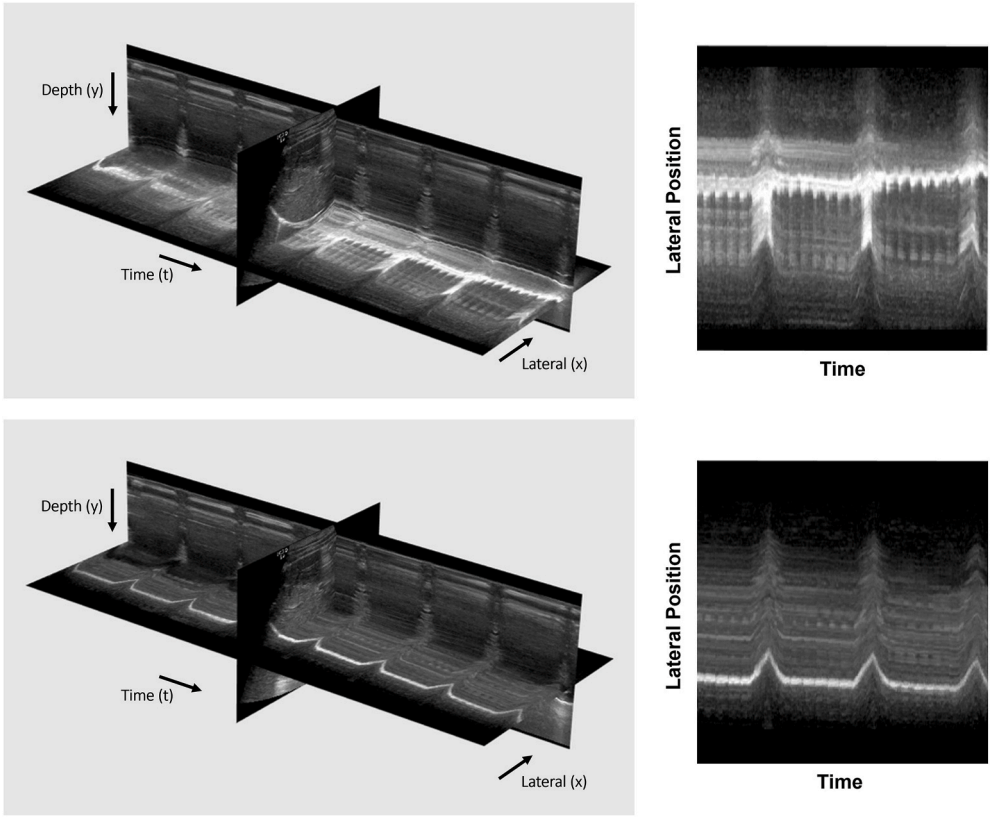

Fig. 5. Illustration of the physiologic signals captured by the VMM display. Top left: The specific horizontal plane (i.e. lateral-time plane) selected shows the heart rate measurement; Top right: The cardiac cycle is displayed as pulsatile wall motion of the vessel; Bottom left: The specific horizontal plane (ie lateral-time plane) selected shows the respiratory rate measurement; Bottom right: The respiratory cycle is displayed as a cyclical lateral shift in multiple anatomic structures. The triangular pattern is due to ventilator-controlled respiration in the animal model.

hoc test was utilized to assess differences between pairs of phases. P values ≤ 0.05 were considered significant. Data are reported as mean or percentage $\pm$ standard deviation (SD).

3. Results

Mean IVC diameter in mm (SD) was 5.39 during baseline (0.63), 2.77 (0.91) during shock, and 3.40 (1.05) during resuscitation, and differed significantly between these three protocol phases as demonstrated by one-way ANOVA ($F(2,11) = 5.23$, $p = 0.025$) (Fig. 6 top). Mean collapsibility (SD) was 26.14 % (4.11), 48.64 % (10.52), and 45.27 % (13.36) (Fig. 6 bottom), and mean ΔIVC (SD) was 1.71 (0.52), 1.96 (0.28), and 2.06 (0.88) during baseline, shock, and resuscitation, respectively. Neither mean collapsibility nor ΔIVC differed significantly between protocol phases.

Heart rate and respiratory rate were successfully measured from the constant-depth planes. The respiratory rate measured using VMM images was 13.09 breaths per minute, which was consistent with the ventilator rate of 13 breaths per minute. The heart rate measured using VMM images showed an increase in heart rate after hemorrhage and decrease in heart rate after a period of resuscitation (Fig. 7).

4. Discussion

Our novel ultrasound method, 4D volumetric M-Mode was applied in a swine model of hemorrhage to provide a proof-of-concept of clinical utility of such an approach on large vessel monitoring. Volumetric reconstruction of spatial data over time in our VMM technique simplified serial scanning and data collection. The scanhead tilting increased spatial coverage, thereby negating the need for precise scanhead placement to identify the vessel of interest. When the vessel is not parallel to the skin surface, the planes are extracted with arbitrary orientation as needed to ensure IVC diameter measurements are made perpendicular to its center axis.

Previous studies have shown poor reliability and reproducibility when measuring IVC diameter and measuring respiratory variation within the IVC [2,3,13,14],. The ability to identify and measure vessels from planes at multiple lateral locations over time provides a greater number of data points for trending IVC parameters. By running each scan over multiple respiratory cycles repeated measurements of the vessel of interest will be obtained, thereby decreasing intra- and inter-operator variability. In addition, extended data in the lateral direction (x-axis in Fig. 2) would allow for tracking of the IVC during large respirophasic shifts.

Automated feature tracking and calculation may be applied to the analysis portion of our technique given our multi-dimensional dataset in combination with repetitive visualization of anatomic motion patterns over an extended scanning period. Automation of ultrasound scanning and/or analysis with integrated heart and respiratory rate monitoring would offer providers in resource-limited environments an invaluable tool for data-driven fluid management of critically ill patients.

4.1. Limitations

Our preliminary study has several limitations that will be addressed in future experiments. We cannot comment on the degree to which the VMM technique minimizes inter- and intra-operator and interpreter variability, as VMM has not been validated against human sonographers or interpreters. Another limitation of this study was the small sample size. We analyzed images from only one subject simply as a proof of concept. While the trends of mean IVC diameter and IVC collapsibility throughout the various protocol phases were as expected, with diameter

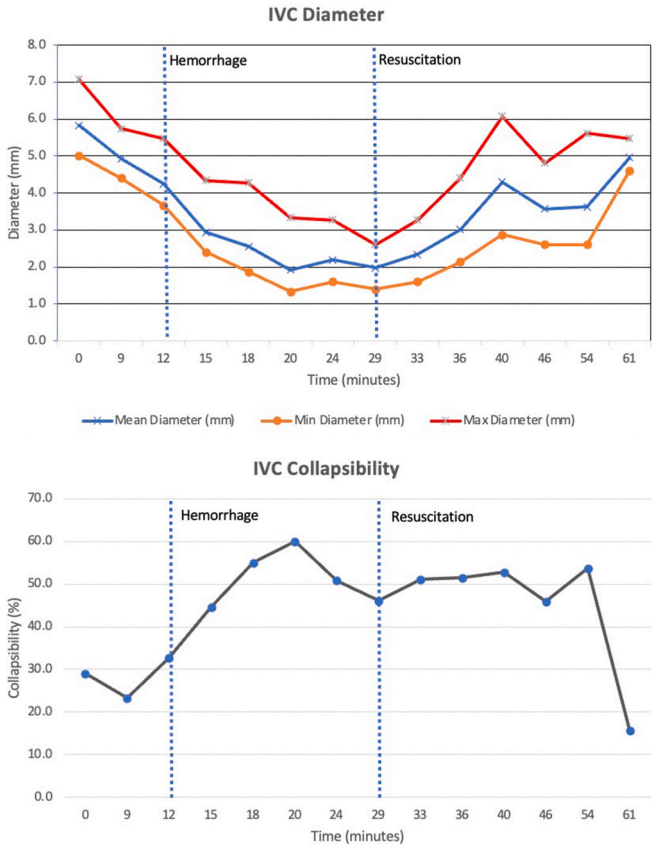

Fig. 6. IVC metrics obtained throughout hemorrhage/resuscitation protocol. Top - IVC diameter (mm) over time; Bottom- IVC collapsibility measured as 100*(Dmax-Dmin)/Dmax.

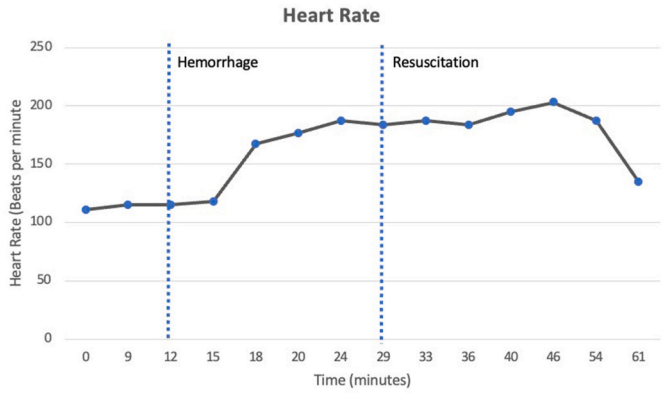

Fig. 7. Heart rate obtained by VMM technique throughout hemorrhage/resuscitation protocol.

decreasing and collapsibility increasing with more blood loss, more data needs to be obtained to be able to determine any statistical significance to these findings.

4.2. Future experiments

In future experiments, we plan to correlate specific large venous parameters (i.e. diameter, collapsibility, and spectral Doppler) with exact amounts of blood loss. This study will have more subjects allowing us to determine greater statistical significance and clinical relevance regarding our findings. These future experiments will also allow for more data to compare the VMM technique with standard M-mode images.

Though scanning for this study was performed manually as a proof-of-concept, we intend to develop a precise mechanical (or electronic) scanning method. The effects of scan speed will be tested in the future with a motorized ultrasound system. Also, automated image analysis will allow us to compile more locations along the IVC, with around 200–300 lines spanning the IVC included in pilot scans. While we hypothesize that multiple samples along the length of the IVC will provide a more robust measurement, this will need to be tested in future studies.

5. Conclusion

This novel 4D VMM technique shows promise in minimizing inter- and intra-operator variability and has favorable data storage requirements over prolonged continuous longitudinal monitoring. VMM is amenable to low-cost hardware implementation and automated analysis, thereby providing a means for cost-effective extended monitoring of intravascular volume status and wearable device integration.

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Data availability statement

The data that support the findings of this study are available from the corresponding author upon reasonable request.

Declaration of competing interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: Shahram Aarabi, Daniel F. Leotta has patent #18/259,388 pending to Shahram Aarabi, Daniel F. Leotta. If there are other authors, they declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.wfumbo.2024.100058.

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