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RESEARCH ARTICLE

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# A wearable carotid Doppler tracks changes in the descending aorta and stroke volume induced by end-inspiratory and end-expiratory occlusion: A pilot study

Jon-Émile S. Kenny[1] | Igor Barjaktarevic[2] | Andrew M. Eibl[1] | Matthew Parrotta[1] | Bradley F. Long[1,3] | Joseph K. Eibl[1,3]

[1]Health Sciences North Research Institute, Sudbury, Ontario, Canada

[2]Division of Pulmonary and Critical Care, Department of Medicine, David Geffen School of Medicine at UCLA, Los Angeles, California

[3]Northern Ontario School of Medicine, Sudbury, Ontario, Canada

**Correspondence**
Jon-Émile S. Kenny, Health Sciences North Research Institute, 56 Walford Rd, Sudbury, ON P3E 2H2, Canada.
Email: jon-emile@heart-lung.org

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## Abstract

**Background and Aims:** To test the feasibility of a novel, wearable carotid Doppler ultrasound to track changes in cardiac output induced by end-inspiratory and end-expiratory occlusion tests.

**Methods:** We observed the pattern of Doppler change of the common carotid artery during a simulated end-inspiratory and expiratory occlusion test (sEIOT/sEEOT) in 10, nonventilated, healthy subjects. Simultaneously, we measured the Doppler signal of the descending aorta using duplex ultrasound (Xario, Toshiba Medical Systems) and stroke volume (SV) using noninvasive pulse contour analysis (Clearsight, Edwards Lifesciences, Irvine, California).

**Results:** During sEIOT, SV, maximum velocity time integral (VTI) of the descending aorta, and common carotid fell by 25.7% ($P$ = .0131), 26.1% ($P$ < .0001), and 18.5% ($P$ < .0001), respectively. During sEEOT, SV, maximum VTI of the descending aorta, and common carotid rose by: 41.3% ($P$ = .0051), 28.3% ($P$ < .0001), and 41.6% ($P$ < .0001), respectively. There was good correlation between change in aortic VTI and carotid VTI ($r^2$ = 0.79); SV and aortic VTI ($r^2$ = 0.82), and SV and carotid VTI ($r^2$ = 0.95).The coefficient of variation of the VTI measured by the Doppler patch was roughly 60% less than that of the duplex system.

**Conclusions:** The pattern of SV change induced by a sEIOT/sEEOT in non-mechanically ventilated volunteers is reflected in the common carotid artery and descending aorta. The VTI variability of the Doppler patch was less than that of the traditional, duplex Doppler.

KEYWORDS

carotid artery, corrected flow time, end-expiratory occlusion test, fluid responsiveness, Valsalva maneuver, velocity time integral

## 1 | INTRODUCTION

The use of functional hemodynamic indices to identify preload responsiveness has been of growing interest for nearly two decades in the intensive care unit.[1,2] One such measure, the end-expiratory occlusion (EEOT) test, is based upon transient preload augmentation following the release of inspiratory intra-thoracic pressure during mechanical ventilation.[3] In general, an increase in cardiac output of at least 5% following a 12 to 30 second EEOT reliably detects patients who are preload responsive.[4]

More recently, however, Doppler ultrasound has been used as a means to assess the change in cardiac output—or its surrogate—induced by an EEOT. For example, both the left ventricular outflow tract (LVOT)[5] and transesophageal Doppler ultrasound of the descending aorta[4] have been used successfully to infer fluid responsiveness in critically ill patients. Interestingly, in both of the aforementioned studies, the addition of an end-inspiratory occlusion test (EIOT) to the EEOT accurately detected fluid responsiveness with a diagnostic threshold more compatible with the precision of Doppler ultrasound than EEOT alone. The basis of the EIOT is the converse of the EEOT; the EIOT requires transient preload reduction consequent to the inspiratory rise in intra-thoracic pressure.[4,5] When summing the fall and rise in Doppler-derived stroke volume (ie, from the LVOT) during the EIOT and EEOT, respectively, a threshold of 13% was found to predict fluid responsiveness with good sensitivity and specificity.[5] A similar analysis was performed with transesophageal Doppler; likewise, when summing the fall and rise in descending aortic blood flow during an EIOT and EEOT, respectively, a threshold of 9% demonstrated excellent sensitivity and specificity for predicting fluid responsiveness in critically ill patients.[5]

Given that trans-esophageal Doppler has been used to track change in cardiac output during a combined EIOT and EEOT, we conducted a proof-of-concept study in human volunteers. We hypothesized that the pattern of change in the carotid artery—measured by an adhered, continuous wave Doppler ultrasound patch—would match that of the descending aorta measured by a traditional, duplex ultrasound system. To confirm that the pattern of change observed in the descending aorta reflected cardiac output, we also measured stroke volume by noninvasive pulse contour analysis in a subset of volunteers. Lastly, given that human factors are known to increase the variability of Doppler ultrasound measurement,[6] we compared the coefficient of variation of the velocity time integral (VTI) from the hand-held, pulsed wave Doppler ultrasound system to the adherent ultrasound patch.

## 2 | MATERIALS AND METHODS

### 2.1 | Clinical setting

We obtained a convenience sample of 10 healthy adult volunteers with no known cardiovascular history and on no regular cardiovascular medications.

### 2.2 | Simulated end-expiratory occlusion test

All subjects performed a simulated EEOT as follows: following 15 seconds of recorded, resting baseline, the subjects were instructed to take a tidal breath in and contract the diaphragm against a manometer placed at the lips to maintain an airway pressure of 20 to 25 cm $H_2O$ for 15 seconds; this was termed the "simulated end-inspiratory occlusion test" (sEIOT). Immediately following the sEIOT, the pressure and tidal breath were released to functional residual capacity and this was held for an additional 15 seconds before another breath was taken; this was termed the simulated "end-expiratory occlusion test" (sEEOT). Finally, beats were recorded for an additional 15 second recovery phase.

### 2.3 | Stroke volume measurements

Subjects were monitored with a noninvasive, FDA-approved pulse contour method (Clearsight, Edwards Lifesciences, Irvine, California) enabling measurements of SV every 20 seconds. Briefly, Clearsight uses a "volume clamp" method for transducing the digital artery waveform. Using an algorithm, the digital artery waveform is transformed into a brachial artery waveform and then analyzed using pulse contour analysis to derive stroke volume.[7] A number of studies have evaluated the ability of Clearsight to track changes in cardiac output with agreement values ranging between 84% and 100% compared to a gold standard.[7] The study protocol did not begin until there was adequate Clearsight signal as measured by the Physiocal metric (ie, ≥50); the third digit was used in all volunteers, as recommended by the manufacturer. Subjects were monitored quietly with the Clearsight device for at least 3 minutes prior to the onset of the sEIOT/EEOT protocol. Only five subjects had their stroke volume measured due to availability of the pulse contour analysis device in the physiology lab.

### 2.4 | Descending aorta VTI measurement

A traditional, hand-held, duplex ultrasound imaging system (Xario, Toshiba Medical Systems, Otawara, Tochigi, Japan) was employed to acquire simultaneous pulsed wave (PW) Doppler from the descending aorta. The PW Doppler velocity measurements in the descending aorta were measured by a trained sonographer blinded to the velocity data acquired simultaneously from the hands-free Doppler ultrasound patch. The duplex system was set up to obtain a view of the descending aorta via the supra-sternal notch, confirmed by identification of the left subclavian artery and pulsatile flow away from a phased array cardiac probe (7.5 MHz), as previously described.[8] The sample volume was 4 mm long and positioned mid-vessel. The angle of insonation was 0°, as flow was directly away from the probe.

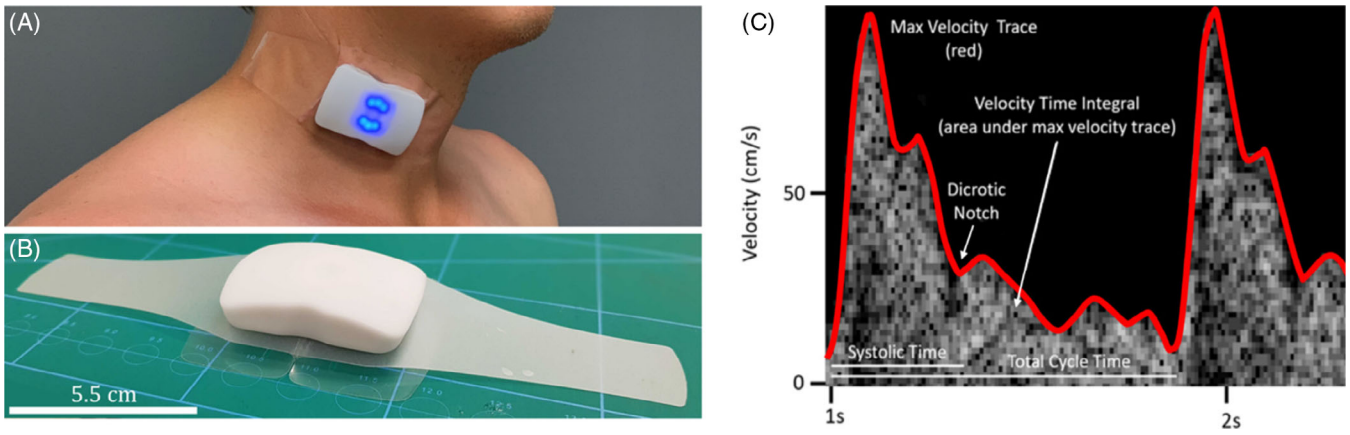


**FIGURE 1** The wireless Doppler ultrasound patch. A, Wireless, hands-free Doppler patch placed over common carotid artery of a healthy volunteer. B, Scaled image of the Doppler patch. C, Metrics obtained from wearable Doppler

## 2.5 | Carotid VTI and carotid corrected flow time measurements

The FDA-approved, carotid ultrasound patch (FloPatch, Flosonics Medical, Sudbury, Ontario) (Figure 1) was placed by palpation over the carotid artery below the angle of the jaw in an effort to ensure Doppler sampling below the bifurcation.

Once an adequate spectrogram signal was visualized in an open-access audio-recording program (Audacity) and a satisfactory Physiocal value was obtained on the Clearsight device, the protocol was initiated. The maximum velocity of the continuous wave (CW) Doppler waveforms was automatically traced using an algorithm based on the approach described by Steinman et al.[9] The automated maximum velocity estimation for each timepoint in the waveform was used to calculate the VTI as the area under the curve. The duration of systole (ie, from systolic velocity upstroke to the dicrotic notch, in milliseconds) was recorded from the CW Doppler patch and corrected for heart rate using Wodey's Formula[10] to obtain the carotid corrected flowtime (FTc):

$$\text{FTc} = \text{systolic flow time} + [1.29 \times (\text{HR} - 60)]. \quad (1)$$

Figure 1C describes the metrics derived from the continuous wave Doppler patch.

The real-time spectral Doppler signals from the descending aorta (PW system) and the CW Doppler ultrasound patch were fed into a two-channel audio recorder (Roland Corporation, Los Angeles, California) and then visualized with the Audacity software. This approach ensured synchronous recording of Doppler waveform signals from the hands-free patch and aorta from the duplex imaging system.

## 2.6 | Statistical analysis

For carotid and descending aorta Doppler, time 1 (T1) was the average of all cardiac cycles between 5 and 10 seconds of the 15-second resting baseline. Time 2 (T2) was the average of all cardiac cycles contained within the terminal 5 seconds of the 15-second sEIOT. Finally, time 3 (T3) was the terminal 5 seconds of the 15-second sEEOT. We created four quadrant plots and correlated change in VTI of the aorta and VTI of the carotid as well as change in SV compared to change in VTI of the aorta and carotid.

Because the Clearsight device updates SV every 20 seconds, we chose resting baseline (T1) as the SV value immediately prior to the onset of the 15 second resting baseline recorded for the descending aorta and carotid artery. T2 was therefore recorded 20 seconds into the protocol. T3 was measured at the end of the 60 second protocol to reflect a complete return to baseline. A Smirnov-Kolmogorov test was performed to assess for a normal distribution for VTI, FTc, and SV. Values obtained for stroke volume, maximal carotid VTI and carotid FTc, descending aortic VTI and FTc were compared using a paired sample *t* test.

For each individual, the coefficient of variation (CV) of the carotid VTI, FTc and aortic VTI and stroke volume were measured for each 5-second time window (ie, T1, T2, and T3). The average CV amongst all subjects for each metric at each time interval is reported.

## 2.7 | Ethical considerations

The procedures followed were in accord with the ethical standards of the committee on human experimentation at our institution. Written and informed consent was obtained for all subjects, and the study was approved by the Research Ethics Board of Health Sciences North. Consent to publish data was obtained for all subjects.

# 3 | RESULTS

Ten healthy volunteers were recruited to complete the 60 second simulated EIOT/EEOT. Nine of the 10 volunteers were included in the study results. One volunteer was unable to perform the simulated EEOT/EIOT correctly and was excluded from analysis. Baseline characteristics of the nine healthy subjects studied are described in Table 1. The Clearsight device was available for only five of the nine subjects studied, thus the SV data represents an n = 5.

Smirnov-Kolmogorov testing revealed that at all three time points, carotid VTI, carotid FTc, aorta VTI, and stroke volume did not differ significantly from the normal distribution.

### 3.1 | Hemodynamic effects of the simulated EIOT (T1-T2)

There was a statistically and clinically significant fall in stroke volume, aortic VTI, carotid VTI, and carotid FTc during the sEIOT, that is from T1 to T2 (Table 2).

### 3.2 | Hemodynamic effects of the simulated EEOT (T2-T3)

There was a statistically and clinically significant rise in stroke volume, aortic VTI, carotid VTI, and carotid FTc during the sEEOT, that is from T2 to T3 (Table 2).

**TABLE 1** Characteristics of healthy volunteers

| Demographic variable (n = 9); mean ± SD | |
|---|---|
| Average age in years | 34.5 ± 2.9 |
| Percent female | 56 |
| Average BMI | 26 ± 2.1 |
| Mean heart rate (bpm) | 69 ± 11.9 |
| Systolic blood pressure (mmHg) | 118.5 ± 12.4 |
| Diastolic blood pressure (mmHg) | 79 ± 9.7 |
| Mean arterial pressure (mmHg) | 78.5 ± 11.0 |

### 3.3 | Summary of hemodynamic effects during entire sEIOT and sEEOT

Four-quadrant plots using VTI of the descending aorta and SV by pulse contour analysis as the gold standard (on x-axis) are presented[11]; all included a 10% exclusion zone, but no data points landed within this zone. Comparing the change in VTI of the descending aorta to VTI of the carotid, there was 94% concordance with a correlation coefficient of 0.79 (Figure 2A). In the subset of patients who had their SV measured, there was 100% concordance between change in SV and VTI of the aorta with a correlation coefficient of 0.82 (Figure 2B). Finally, there was 100% concordance between change in SV and VTI of the carotid with a correlation coefficient of 0.95 (Figure 2C).

With descending aorta VTI as the gold standard, a fall in carotid VTI of 10% detected a 10% decrease in VTI of the aorta with a sensitivity of 73% and a specificity of 100% (Figure 2A). In the subset of five subjects with SV as the gold standard, a 10% decrease in VTI of the either the descending aorta or carotid both correctly identified a 10% fall in SV with perfect sensitivity and specificity (Figure 2B,C).

### 3.4 | Variability of hand-held Doppler and Doppler patch (T1, T2, and T3)

The average coefficient of variation at all three time points was less for the Doppler patch than the hand-held, duplex system. These averages were based on an analysis of 5 to 10 cardiac cycles for each volunteer at each time point. For the Doppler ultrasound patch, the average coefficient of variation for all nine subjects was 0.053, 0.096,

**TABLE 2** Changes in stroke volume, VTI, FTc, during the sEIOT/sEEOT maneuvers, and *P*-values for all subjects

| Simulated EIOT (↓cardiac preload) T1 to T2 | | | | |
|---|---|---|---|---|
| **Metric (mean)** | **T1** | **T2** | **% change** | ***P*-value** |
| Stroke volume (mL) | 104.2 | 77.4 | −25.7 | *P* = .0131 |
| Aortic VTI (cm) | 15.3 | 11.3 | −26.1 | *P* < .0001 |
| Carotid VTI (cm) | 36.3 | 29.6 | −18.5 | *P* < .0001 |
| Carotid FTc (ms) | 334.8 | 296.7 | −11.4 | *P* = .0048 |
| Mean arterial pressure (mmHg) | 78.5 | 86.5 | +10.4 | *P* = .0610 |
| Heart rate (bpm) | 72 | 90 | +25 | *P* < .0001 |
| **Simulated EEOT (↑cardiac preload) T2 toT3** | | | | |
| **Metric (mean)** | **T2** | **T3** | **% change** | ***P*-value** |
| Stroke volume (mL) | 77.4 | 109.4 | +41.3 | *P* = .0051 |
| Aortic VTI (cm) | 11.3 | 14.5 | +28.3 | *P* = .0005 |
| Carotid VTI (cm) | 29.6 | 41.9 | +41.6 | *P* < .0001 |
| Carotid FTc (ms) | 296.7 | 319.4 | +7.7 | *P* = .082 |
| Mean arterial pressure (mmHg) | 86.5 | 102.6 | +18.5 | *P* = .011 |
| Heart rate (bpm) | 90 | 70 | −22.2 | *P* < .0001 |

Abbreviations: EEOT, end-expiratory occlusion test; EIOT, end-inspiratory occlusion test; FTc, carotid corrected flow time; sEEOT, simulated end-expiratory occlusion test; sEIOT, simulated end-inspiratory occlusion test; VTI, velocity time integral.

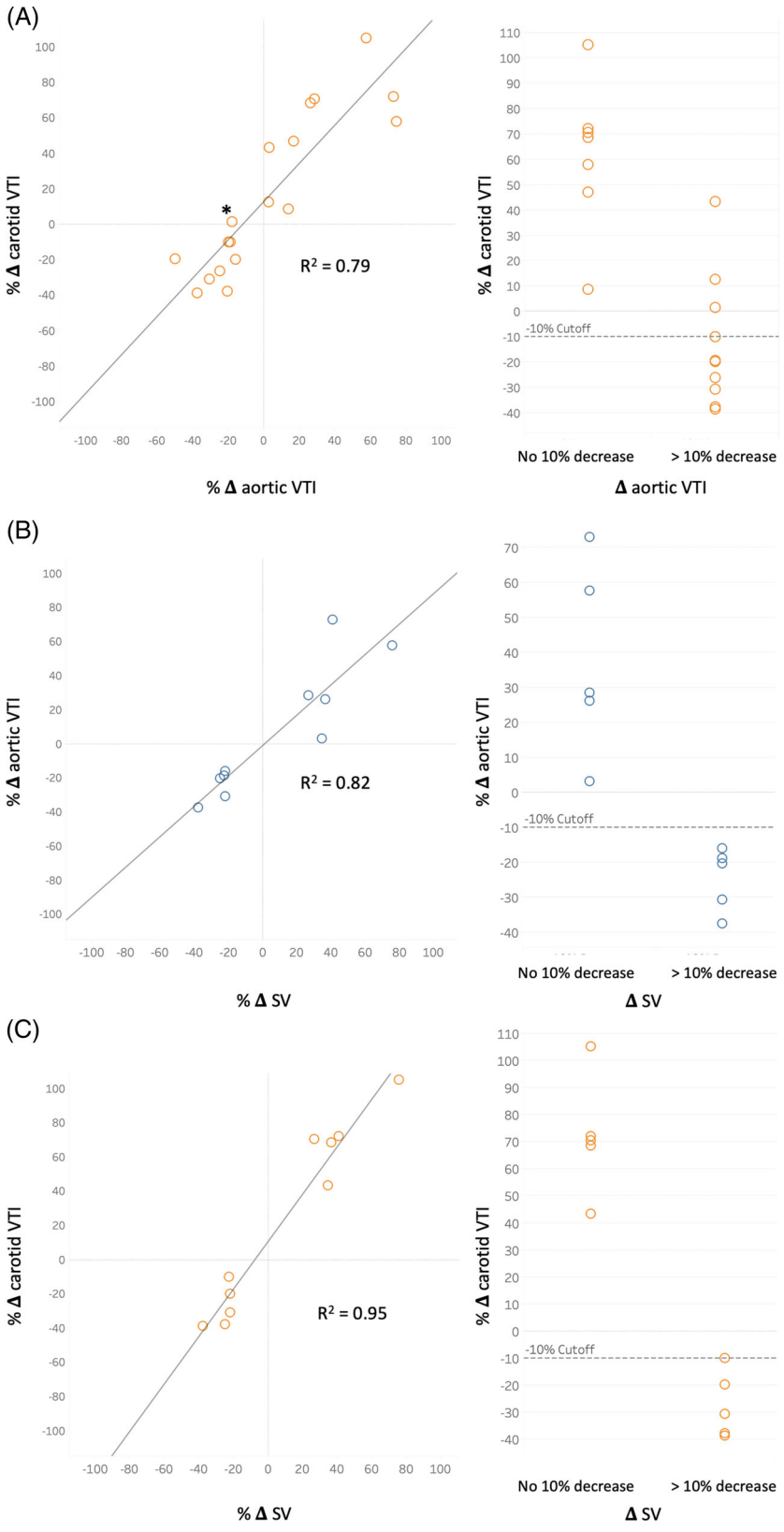


**FIGURE 2** Relationships between carotid VTI, aortic VTI, and SV. A, Relationship between aortic VTI as gold standard and change in carotid VTI. The asterisk notes the single point of discordance on the four-quadrant plot. B, Relationship between SV as gold standard and change in aortic VTI. C, Relationship between SV as gold standard and change in carotid VTI. The y-axis is percent change for all panels. See text for details. SV, stroke volume; VTI, velocity time integral

and 0.063 for T1, T2, and T3, respectively. By contrast, for the handheld duplex system employed by the trained sonographer, the coefficient of variations obtained were 0.096, 0.135, and 0.113 for T1, T2, and T3, respectively (Figure 3B).

## 4 | DISCUSSION

We demonstrated that the qualitative and quantitative change in VTI and FTc of the common carotid artery follows the VTI of the

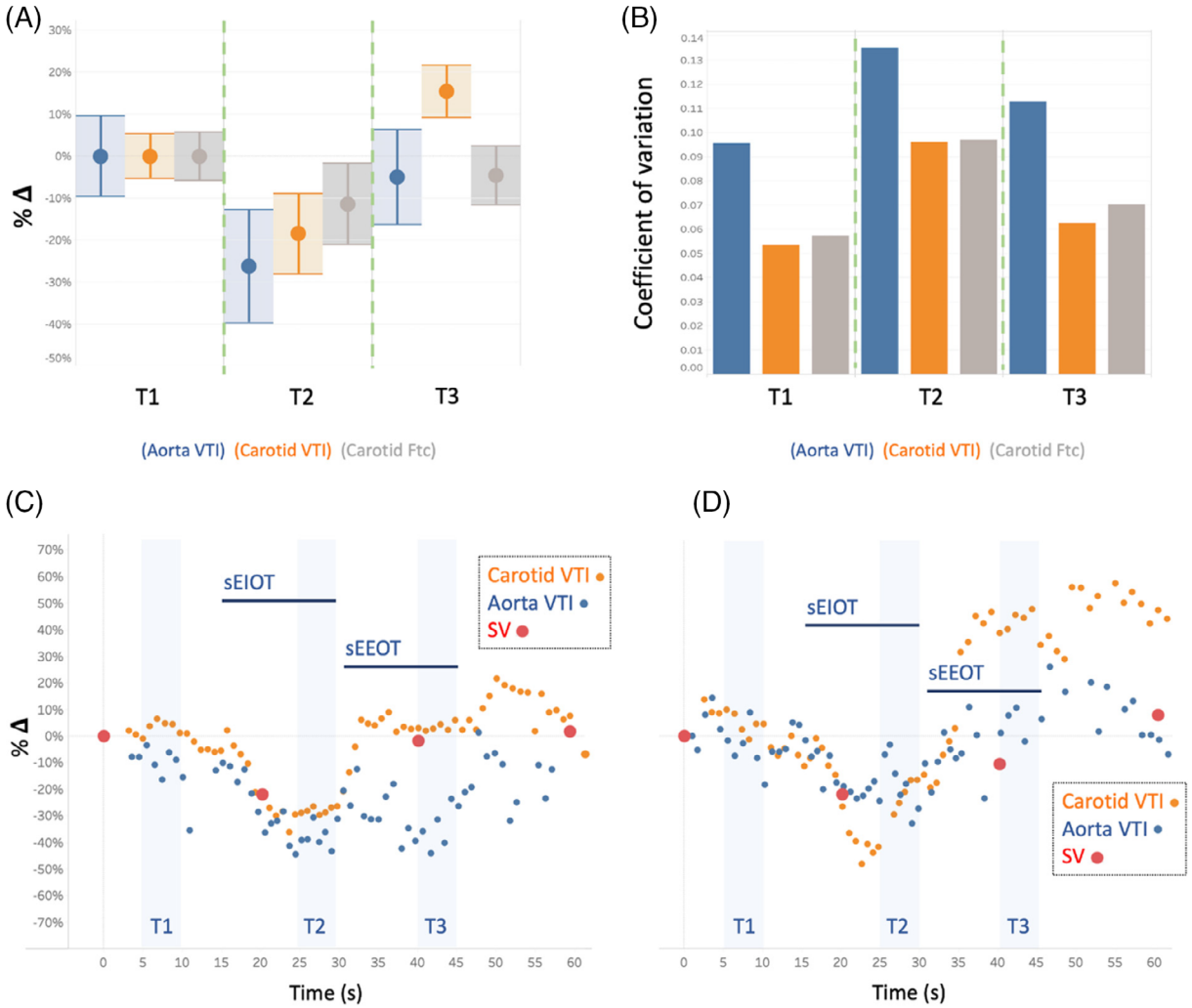


**FIGURE 3** Summary data from simulated occlusion tests. A, Percent change on the y-axis for all subjects for all Doppler metrics, across T1, T2, and T3 on the x-axis; bars represent SE. B, Coefficient of variation on the y-axis for all subjects for all Doppler metrics across T1, T2, and T3 on the x-axis. C, Data from an individual with a slow aortic response across the entire maneuver; each dot from the carotid and aorta represent one heartbeat, while the SV represents 20 second data points from the pulse contour analysis device. D, An individual with carotid "overshoot" early in the sEEOT. The y-axis is percent change and the same for both subjects; T1, T2, and T3 are highlighted for clarity. sEEOT, simulated end-expiratory occlusion test; sEIOT, simulated end-inspiratory occlusion test; SV, stroke volume; VTI, velocity time integral

descending aorta during a simulated end-inspiratory/end-expiratory occlusion test. In a subset of subjects, stroke volume measured by noninvasive pulse contour analysis followed a similar pattern of change. These findings are congruent with previous studies in the critically ill using transthoracic echocardiography[5] and transesophageal Doppler.[4] Further, we found that the variability, as defined by the coefficient of variation, was less with the Doppler patch compared to the traditional, hand-held, duplex system.

While it is tempting to directly compare the values obtained in healthy volunteers to the thresholds achieved from the LVOT and descending aorta in the critically ill, they are not interchangeable. The average fall in aortic VTI during the sEIOT added to the average rise in aortic VTI during the sEEOT was 54.4% in our study; this is much larger than the change observed from the LVOT and descending aorta, in the critically ill. The reason for this discrepancy is likely that our simulated maneuver is different from the EIOT/EEOT performed in passive patients on a mechanical ventilator. In our paradigm, 20 to 25 cm $H_2O$ during the EIOT was chosen to mimic a clinically relevant plateau pressure, however, achieving this value likely required greater pleural pressure than in ventilated patients. Thus, the fall in stroke volume and descending aortic VTI were much larger than those values observed in patients receiving an EIOT.[4,5]

Additionally, we observed an "overshoot" in the common carotid artery from T2 to T3 (Figure 3D). The common carotid VTI rose by 41.6% during the simulated EEOT; comparatively, the VTI rise of the descending aorta was only 28.3%. This explains the slightly diminished sensitivity of carotid VTI in detecting a fall in aortic VTI. Three subjects maintained a decreased aortic VTI at T3 of at least 10% but were judged by the carotid VTI to be higher. We suspect this was

consequent to intracerebral vasodilation during the preceding sEIOT, as previously described.[12] This could be mitigated if the EIOT and EEOT are not performed in immediate succession as they were in our paradigm. Moreover, as above, because the sEIOT likely exaggerated the fall in cardiac output, cerebral autoregulatory changes may have been heightened; in the clinical setting, this is probably less pronounced.

Previous studies have associated carotid blood flow and cardiac output over relatively long measurement time (eg, hours) with mixed results.[13,14] It is expected that flow in the common carotid artery will diverge from the left ventricle over time because of auto-regulation; indeed, we observed the effects of cerebral autoregulation within 15 to 30 seconds. Nevertheless, our data is consistent with previous work[15] showing robust correlation between abrupt changes in carotid VTI compared descending aorta VTI and stroke volume. This suggests value in tracking immediate change—where the carotid artery acts as a transient window to the left ventricle.

We believe that a wearable Doppler has potential clinical benefits. First, as we observed, the measured VTI variability of an adherent Doppler was better than a hand-held, duplex system (Figure 3B). This occurred despite the parabolic velocity profile in the carotid artery. As compared to the uniform (i.e., plug) velocity profile of the descending aorta,[16] one might expect the aortic VTI variability to be less. Nevertheless, we observed the opposite, suggesting that an adherent Doppler mitigates human factors that contribute to Doppler measurement variability.[6,17] Second, a wearable Doppler can monitor a patient over extended periods, giving beat-to-beat, noninvasive surrogates of stroke volume. Finally, the hands-free nature of the device frees up the clinician to perform interventions on a patient such as a passive leg raise or fluid challenge.

A number of important limitations of our study must be addressed. First, we measured the VTI and not absolute flow. Because vascular diameter is prone to measurement error and amplified to the second power when calculating area,[16] we did not measure flow. Nevertheless, the VTI of the descending aorta followed common carotid artery Doppler indices in addition to noninvasive pulse contour-derived SV, intimating that changes in absolute flow—in this healthy cohort—can be inferred from changes in velocity. In addition, the transesophageal Doppler system used in a recent study in the critically ill does not measure vascular diameter—inferring change in flow from measured velocity; despite this limitation, transesophageal Doppler had an excellent sensitivity and specificity for diagnosing fluid responsiveness.[4] Second, our sample size was small, yet the observed trends were strong and in-line with expected physiology in healthy volunteers; thus, our findings should hold within a relatively healthy adult patient population with stable hemodynamics. Third, we measured stroke volume only in five subjects due to logistical constraints in the physiology lab where the study was performed. Fourth, we studied the descending aorta rather than the LVOT VTI. While we understand that LVOT has previously been studied with known precision, we find that this approach frequently requires placing the subject in left lateral decubitus position—a challenging view to maintain for the sonographer and volunteer. Further, the descending aorta should approximate transesophageal Doppler as described above. Lastly, there has been conflicting data regarding the correlation between SV from noninvasive pulse contour analysis and thermodilution-based methods; however, the ability of the former to track intra-individual change is clinically adequate.[7,18-22]

In this proof-of-concept study, we have shown that a novel ultrasound patch can monitor hemodynamic changes in the carotid artery. Transient alteration of stroke volume and VTI of the descending aorta were reflected in the common carotid artery of healthy volunteers during a simulated end-inspiratory/expiratory occlusion test. Accordingly, a wearable, Doppler ultrasound patch may be useful to assess the effects of end-inspiratory and end-expiratory occlusion in patients. Further evaluation in the emergency department, operating theater and in the intensive care unit is warranted.

## AUTHOR CONTRIBUTIONS

Conceptualization: Jon-Émile S. Kenny
Data curation: Jon-Émile S. Kenny, Andrew M. Eibl, Matthew Parrotta
Formal analysis: Jon-Émile S. Kenny, Igor Barjaktarevic, Andrew M. Eibl, Matthew Parrotta, Joseph K. Eibl
Investigation: Jon-Émile S. Kenny, Igor Barjaktarevic, Andrew M. Eibl
Methodology: Jon-Émile S. Kenny, Joseph K. Eibl
Project administration: Bradley F. Long
Resources: Bradley F. Long, Joseph K. Eibl
Software: Andrew M. Eibl, Matthew Parrotta, Joseph K. Eibl
Supervision: Bradley F. Long, Joseph K. Eibl
Validation: Andrew M. Eibl
Writing – Original draft preparation: Jon-Émile S. Kenny
Writing – Review and editing: Jon-Émile S. Kenny, Igor Barjaktarevic, Andrew M. Eibl, Matthew Parrotta, Bradley F. Long, Joseph K. Eibl

All authors have read and approved the final version of the manuscript.

Jon-Émile S. Kenny had full access to all of the data in this study and takes complete responsibility for the integrity of the data and the accuracy of the data analysis.

## TRANSPARENCY STATEMENT

Jon-Émile S. Kenny affirms that this manuscript is an honest, accurate, and transparent account of the study being reported; that no important aspects of the study have been omitted; and that any discrepancies from the study as planned (and, if relevant, registered) have been explained.

## CONFLICT OF INTERESTS

Jon-Émile S. Kenny, Joseph K. Eibl, Andrew M. Eibl, and Matthew Parrotta, are working with Flosonics Medical, a start-up developing a commercial version of the Doppler patch. Igor Barjaktarevic has received grants and consulting fees for GE Healthcare. These sources played no role in study design; collection, analysis, and interpretation

of data; writing of the report; or the decision to submit the report for publication.

## DATA AVAILABILITY STATEMENT

The authors confirm that the data supporting the findings of this study are available within the article (and/or) its supplementary materials.

## ORCID

*Jon-Émile S. Kenny* https://orcid.org/0000-0002-3654-1146
*Igor Barjaktarevic* https://orcid.org/0000-0002-8096-0858

## REFERENCES

1. Michard F, Boussat S, Chemla D, et al. Relation between respiratory changes in arterial pulse pressure and fluid responsiveness in septic patients with acute circulatory failure. *Am J Respir Crit Care Med*. 2000;162(1):134-138.
2. Michard F, Teboul J-L. Using heart-lung interactions to assess fluid responsiveness during mechanical ventilation. *Crit Care*. 2000;4(5):282-289.
3. Monnet X, Osman D, Ridel C, Lamia B, Richard C, Teboul JL. Predicting volume responsiveness by using the end-expiratory occlusion in mechanically ventilated intensive care unit patients. *Crit Care Med*. 2009;37(3):951-956.
4. Dépret F, Jozwiak M, Teboul J-L, Alphonsine JE, Richard C, Monnet X. Esophageal Doppler can predict fluid responsiveness through end-expiratory and end-inspiratory occlusion tests. *Crit Care Med*. 2019;47(2):e96-e102.
5. Jozwiak M, Depret F, Teboul J-L, et al. Predicting fluid responsiveness in critically ill patients by using combined end-expiratory and end-inspiratory occlusions with echocardiography. *Crit Care Med*. 2017;45(11):e1131-e1138.
6. Lui EY, Steinman AH, Cobbold RS, et al. Human factors as a source of error in peak Doppler velocity measurement. *J Vasc Surg*. 2005;42(5):972.e1-972.e10.
7. Ameloot K, Palmers P-J, Malbrain ML. The accuracy of noninvasive cardiac output and pressure measurements with finger cuff: a concise review. *Curr Opin Crit Care*. 2015;21(3):232-239.
8. Ranjan R, Valez EM, Haldipur A, Schiller NB. Relation of velocity-time integral of the left ventricular outflow tract to that of the descending thoracic aorta and usefulness of a fixed ratio for internal validation. *Am J Cardiol*. 2018;122(1):166-169.
9. Steinman A, Tavakkoli J, Myers J, et al. A new approach for determing maximum frequency in clinical Doppler ultrasound spectral estimates. *Proceedings of the 22nd Annual International Conference of the IEEE Engineering in Medicine and Biology Society (Cat. No. 00CH37143)*. Chicago, IL: IEEE; 2000. https://ieeexplore.ieee.org/document/901402.
10. Wodey E, Carre F, Beneux X, Schaffuser A, Ecoffey C. Limits of corrected flow time to monitor hemodynamic status in children. *J Clin Monit Comput*. 2000;16(3):223-228.
11. Saugel B, Grothe O, Wagner JY. Tracking changes in cardiac output: statistical considerations on the 4-quadrant plot and the polar plot methodology. *Anesth Anal*. 2015;121(2):514-524.
12. Xiong L, Liu X, Shang T, et al. Impaired cerebral autoregulation: measurement and application to stroke. *J Neurol Neurosurg Psychiatry*. 2017;88(6):520-531.
13. Weber U, Glassford NJ, Eastwood GM, Bellomo R, Hilton AK. A pilot assessment of carotid and brachial artery blood flow estimation using ultrasound Doppler in cardiac surgery patients. *J Cardiothor Vasc An*. 2016;30(1):141-148.
14. Gassner M, Killu K, Bauman Z, Coba V, Rosso K, Blyden D. Feasibility of common carotid artery point of care ultrasound in cardiac output measurements compared to invasive methods. *J Ultrasound*. 2015;18(2):127-133.
15. Kenny J-ÉS, Barjaktarevic I, Eibl AM, et al. A carotid Doppler patch accurately tracks stroke volume changes during a preload-modifying Maneuver in healthy volunteers. *Crit Care Explor*. 2020;2(1):e0072.
16. Gill RW. Measurement of blood flow by ultrasound: accuracy and sources of error. *Ultrasound Med Biol*. 1985;11(4):625-641.
17. Kenny J-ÉS, Barjaktarevic I, Eibl AM, et al. The feasibility of a novel, wearable Doppler ultrasound to track stroke volume change in a healthy adult. *J Emerg Crit Care Med*. 2020;17:4.
18. Bogert L, Wesseling K, Schraa O, et al. Pulse contour cardiac output derived from non-invasive arterial pressure in cardiovascular disease. *Anaesthesia*. 2010;65(11):1119-1125.
19. Hofhuizen C, Lansdorp B, van der Hoeven JG, Scheffer GJ, Lemson J. Validation of noninvasive pulse contour cardiac output using finger arterial pressure in cardiac surgery patients requiring fluid therapy. *J Crit Care*. 2014;29(1):161-165.
20. Broch O, Renner J, Gruenewald M, et al. A comparison of the Nexfin® and transcardiopulmonary thermodilution to estimate cardiac output during coronary artery surgery. *Anaesthesia*. 2012;67(4):377-383.
21. Bubenek-Turconi SI, Craciun M, Miclea I, Perel A. Noninvasive continuous cardiac output by the Nexfin before and after preload-modifying maneuvers: a comparison with intermittent thermodilution cardiac output. *Anesth Analg*. 2013;117(2):366-372.
22. van der Spoel AG, Voogel AJ, Folkers A, et al. Comparison of noninvasive continuous arterial waveform analysis (Nexfin) with transthoracic Doppler echocardiography for monitoring of cardiac output. *J Clin Anesth*. 2012;24(4):304-309.

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