Real-Time Doppler-Based Arterial Vascular Impedance and Peripheral Pressure-Flow Loops: A Pilot Study

Robert H. Thiele, MD,* Karsten Bartels, MD,† Stephen Esper, MD, MBA,‡ Keita Ikeda, PhD,§ and Tong-Joo Gan, MD‖

Objective: **Arterial pressure-flow loops and vascular impedance provide additional data that could be used to assess the hemodynamic effects of therapeutic interventions in anesthetized patients. To evaluate the utility of such an approach, the authors sought to design a device that combines flow waveforms from an esophageal Doppler probe and pressure waveforms from a peripheral artery to produce real-time pressure-flow loops and estimates of arterial vascular impedance.**

Design: **Prospective, cohort study.**

Setting: **Single center, university-based teaching hospital.**

Participants: **Patients undergoing surgery in whom the attending anesthesiologist had opted to place an esophageal Doppler probe and a peripheral arterial catheter for hemodynamic monitoring.**

Interventions: **This was a non-interventional study designed to record pressure-flow loops and arterial vascular impedance intraoperatively using a novel, noninvasive device.**

Measurements and Main Results: **Pressure-flow loops and arterial vascular impedance were measured noninvasively using radial artery pressure and descending thoracic aorta flow waveforms in real time.**

Conclusions: **Real-time arterial vascular impedance and peripheral pressure-volume loops can be determined using available monitoring devices. Technical feasibility of this technology in patients is a crucial first step to permit meaningful evaluation of the clinical value of this approach for accurate determination of complex hemodynamic indices and, eventually, improvement of outcomes.**

KEY WORDS: doppler, impedance, pressure flow loops, hemodynamics, arterial waveforms, monitoring

ADVANCED UNDERSTANDING of cardiac physiology requires simultaneous measurement of arterial pressure and ventricular volume. Advanced understanding of vascular physiology requires simultaneous measurement of arterial pressure and vascular flow. Although this information currently is not available in routine clinical practice, the technical hurdles that would preclude real-time, simultaneous pressure and flow measurements largely have been overcome. Although knowledge of such data has the potential to provide additional insight into the cardiovascular physiology of a patient, further evaluation of this approach will first and foremost require a functional device. Pressure-length loop area (a unidimensional analog of pressure-volume loop area in which myocardial segment length is measured invasively) has been shown to decrease following coronary artery occlusion in animal models of ischemia.[1–3] There is a clear relationship between both coronary perfusion pressure and coronary blood flow and the area of pressure-length loops.[4] The myocardial response to various hemodynamic interventions (decreased ventricular afterload, increased contractility, increased preload, myocardial ischemia) has been linked to characteristic appearances of different loops.[5]

Ventricular pressure-volume loops describe the amount of mechanical work produced by the ventricle, and total pressure volume area (PVA) is related to myocardial consumption of oxygen (VO_2) in animal models.[6–10] Ventricular power (energy per unit time) can be calculated in both the time domain (pressure-flow [PQ] loop area divided by the R-R interval[11]) and the frequency domain.[12] Pressure and flow waveforms also can be combined to measure ventricular efficiency.[13–15]

The concept of systemic vascular resistance is based on a single-resistor model, is a poor measure of myocardial work, and can be misleading.[16–18] "Arterial vascular impedance," a bipartite relationship derived from a mathematic comparison of arterial pressure and flow waveforms in the frequency domain, which requires a computational technique known as "fast-Fourier transformation," is a more physiologically appropriate descriptor of ventricular afterload.[19–21] Changes in capacitance and changes in resistance affect vascular impedance differentially, and these changes can be detected by examination of the impedance spectra.[22] These discoveries have not been translated yet into meaningful clinical applications. The goal of this pilot study was to utilize existing clinical monitoring tools to integrate arterial pressure and flow waveforms in such a way that peripheral PQ loops and arterial vascular impedance could be displayed and analyzed, in real time. The authors hypothesized that the waveforms produced from an arterial pressure transducer and an esophageal Doppler monitor can be combined to produce real-time displays of both PQ loops and arterial vascular impedance.

METHODS

Device Development

Pressure waveforms were collected from a radial artery transducer (Transpac, ICU Medical, San Clemente, CA, www.icumedical.com). These transducers, which utilize a Wheatstone bridge to produce voltage differentials proportionate to measured pressure, were connected to a 12-bit USB-6008 Analog Input Module (National

*From the *Technology in Anesthesia and Critical Care Group, University of Virginia, Charlottesville, VA; †Department of Anesthesiology, University of Colorado Denver, Aurora, CO; ‡Department of Anesthesiology, University of Pittsburgh, Pittsburgh, PA; §Department of Anesthesiology, Duke University, Durham, NC; and ‖Department of Anesthesiology, Duke University, Durham, NC.*

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Address reprint requests to Robert H. Thiele, MD, Department of Anesthesiology, Box 800170, Charlottesville, VA 22908-0170. E-mail: rht7w@virginia.edu

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Instruments, Austin, TX, www.ni.com). The resonant frequency of this system (tested in vivo[23]) was 8 Hz.

The Deltex CardioQ esophageal Doppler monitor utilizes an Analog Devices (Norwood, MA, www.analog.com) AD557 8-bit digital-to-analog converter (DAC) to output flow waveforms as a voltage signal. These signals were retrieved by the USB-6008.

The USB-6008 was connected to a Windows-based PC running LabView 2009 (National Instruments, Austin, TX, www.ni.com; Fig 1). A custom software routine retrieved pressure and flow waveforms from the USB-6008 and converted it to units of mmHg and cm/s using calibration constants (display output divided by recorded voltage) that could be entered manually by the user (determined by comparing the LabView output to values provided by the Deltex and anesthesia monitoring systems). To remove high-frequency noise, an adjustable low-pass filter was applied to the arterial pressure waveform. Pressure and flow waveforms were displayed in real time. After alignment based on manual entry of a time delay (designed to account for the difference in response times between the pressure and flow signals), pressure and flow were plotted simultaneously. A fast-Fourier transformation was performed on the quotient of the pressure and flow waveforms and the amplitude spectra of the arterial vascular impedance waveform was displayed.

Data Acquisition

This study was approved by the Institutional Review Board at Duke University (IRB #Pro00036563). Adult patients for whom an esophageal Doppler monitor and a radial arterial catheter for hemodynamic monitoring were part of their anesthetic plan were eligible for the study. The need for informed consent was waived by the IRB, because the device involved only the recording and processing of information already available; no Health Insurance Portability and Accountability Act identifiers were recorded, and no clinical decisions were based on the resultant PQ loops and arterial vascular impedance waveforms (the screen was hidden from the anesthesiology providers). Data were recorded for patients who met the aforementioned eligibility criteria and for whom the anesthesiologist initiated pharmacologic or fluid replacement therapy.

Data Processing

In addition to displaying the original pressure and flow waveforms, PQ loops, and arterial vascular impedance in real time, the device stored all waveforms as .csv files at 1,000 Hz resolution. Data surrounding hemodynamic interventions (at least 10 seconds) were imported into MATLAB (Mathworks, Natick, MA, www.mathworks.com) for off-line analysis and initial processing. After visual inspection of flow and pressure waveforms, data were down-sampled to 50 Hz temporal resolution and exported based on a time-stamped event marker. Down-sampled data were imported into Excel (Microsoft Corporation, Redmond, WA, www.microsoft.com) and a trough detection algorithm was applied to align both waveforms.

Using a series of iterative functions, average pressure and flow were calculated for the entire data sample. Pressure-flow area (PQA, the total area inside the pressure-flow curves) was calculated and utilized in 2 measures of ventricular efficiency: Traditional ventricular efficiency (external power divided by PQA) and functional ventricular efficiency (flow divided by PQA) were calculated. External power was defined as the product of flow and peak-systolic pressure (of note, while external power is defined traditionally as the product of flow and end-systolic pressure [P_{es}], invasive studies have revealed little difference between peak-systolic and P_{es}[24]).

RESULTS

A screen shot taken from one patient is shown in Figure 2. Of 6 patients studied thus far, 1 subject received multiple boluses of vasopressors, the results of which are available in Table 1. Two selected hemodynamic interventions were graphically displayed. The effect of 150 μg of phenylephrine on real-time PQ loops (demonstrating a decrease in height, a rightward shift, and an increase in width, consistent with decreased aortic velocity, higher systolic and diastolic blood pressure, and increased pulse pressure), as well as arterial vascular impedance are shown in Figure 3. The effect of 10 mg of ephedrine on real-time PQ loops (demonstrating an increase in height, no shift, and no change in width, consistent with increased aortic velocity and stable systemic blood pressure), as well as arterial vascular impedance are shown in Figure 4.

DISCUSSION

The authors describe the development of a device designed to display peripheral pressure-flow loops and real-time arterial vascular impedance derived from data obtained with commonly used clinical monitoring tools: A radial arterial catheter and an esophageal Doppler monitor. The device as described poses no additional risk to patients already receiving esophageal Doppler and intra-arterial pressure monitoring. Although the device was not validated using an invasive measure of aortic blood flow,

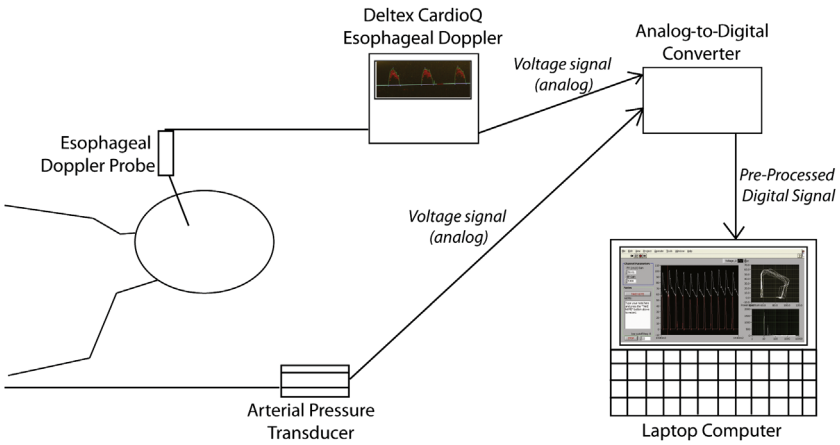

Fig 1. Schematic displaying the flow of data from the intraoperative monitoring equipment to the device. (Color version of figure is available online.)