9 Doppler Techniques

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9.1 Basic Principles

The Doppler method of measuring blood flow is based on generating high-frequency sound waves, or ultrasound, that are passed through the body and used to detect the flow of the red blood cells in the blood vessels such as the aorta. Unlike conventional ultrasound which images the underlying tissues by sending out pulses of ultrasound and detecting returning waves as they bounce off tissue interfaces at different distances from an ultrasound probe, the Doppler detects the shift in ultrasound frequency caused by movement. The faster the movement, the greater the frequency shift which is plotted on a vertical axis against time along a horizontal axis to produce a velocity profile. Positive frequency shifts arise from flow toward and negative shifts from flow away from the probe.

The probe contains a crystal that oscillates at a high frequency (*i.e.,* 2–4 MHz) when an alternating current is passed through it, the piezo-electric

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effect, and this generates an ultrasound beam. The same, or second, crystal produces an electric current when caused to vibrate by the reflected ultrasound waves. The crystal can be used as either a transmitter or a receiver. The resulting electrical signal is amplified to produce a Doppler velocity profile that represents the blood flow in the vessel. By measuring the area under the curve during one heartbeat cycle, a variable is derived known as the velocity time interval (VTI) or stroke distance (SD).

To measure stroke volume, one also needs to know (1) the cross-sectional area (CSA) of the vessel which is multiplied by the VTI. Multiplying by the heart rate gives cardiac output. The CSA is either measured by echocardiography or estimated from the subjects' age and height using an algorithm. If the direction of the ultrasound beam is at an angle (θ) to the direction of blood flow, the Doppler shift, and thus VTI, is reduced. The extent of attenuation is proportional to the cosine of θ; where in line with the direction of flow (*i.e.,* parallel), there is no attenuation (×1.0), but at right angles to the flow (*i.e.,* perpendicular), there is no detected Doppler shift (×0.0). A deviation (θ) from the line of flow of up to 25° produces an attenuation of <×0.9 or less than 10%.

Doppler ultrasound is considered to be safe. The heating effect on the insonated tissue is minimal. However, the insertion of an esophageal probe could potentially cause the patient mechanical harm, and the probe should be tested for electrical safety.

9.2 Methods in Clinical Use

Pulsed systems: Most echocardiographs also perform Doppler measurements. A region of interest is found using ultrasound imaging, and then the Doppler signal from the region is displayed. Often colors are used to display blood velocity. The diameter of the vessel, and thus the CSA, can also be measured. The most commonly used technique uses the apical window and measures flow exiting the left ventricle.

Continuous wave Doppler: This requires a probe with both transmitting and receiving crystals working simultaneously. Two methods are currently used clinically:

1. Transthoracic Doppler which uses either (a) the suprasternal route to measure from the aortic valve (AV) outflow and (b) the precordial route *via* the left third or fourth rib space to measure from the pulmonary valve (PV). The only available device that performs these measurements is the UltraSound Cardiac Output Monitor or USCOM (USCOM Ltd., Sydney, Australia). Its use is intermittent because a handheld probe is used that does not maintain itself in a focused position.
2. Esophageal Doppler which uses a flexible probe that passes through the nose or mouth and down the esophagus to lie beside the descending aorta in the lower thorax. It is the only truly continuous method because the probe remains in a focused position. The principle device currently being sold is the CardioQ (Deltex Medical Ltd., Chichester, UK). It uses a disposable probe. A reusable esophageal Doppler probe system is available, the Waki-To (Atys Medical, Soucieu en Jarrest, France). Arrow International produced a reusable probe system called the HemoSonic 100, but this was discontinued in 2006.

Measurements can also be made by placing a transducer directly on the aorta, pulmonary artery, or other vessel. Such measurements can only be made in special circumstances such as open-heart surgery or animal research. Directly placed probes provide more accurate readings. Strictly speaking these are not Doppler measurements as the current standard, Transonic probes, uses ultrasound transit time to detect blood flow. Previously electromagnetic flow probes were used.

9.3 The USCOM

The USCOM 1A was launched in 2003 and since then its design has not changed significantly. It is a robust, lightweight (6.5 kg), portable stand-alone unit with batteries and plug in handheld probe (Fig. 9.1). It produces both a visual and

Fig. 9.1 USCOM monitor and handheld probe. The screen shows velocity profiles outlined by flow trace software. Beneath are four selected parameters and trend plot

Table 9.1 Factors that improve performance

1.	The USCOM uses a divergent beam (*i.e.,* cone shaped), so its area of capture is larger than a conventional ultrasound imaging beam. The CardioQ probe is sited in close proximity to the descending aorta within the thorax
2.	Flow detection is continuous as two Doppler crystals, transmitter and receiver, are used
3.	Both the USCOM and CardioQ use the peak flow signal to outline and perform calculations. When using the USCOM, the peak signal comes from the narrowest point in the aortic outflow track proximal to the valve where flow rate is greatest. Because the flow is pulsatile and originates from the left ventricle, the laminar flow does not form, and all the red blood cells move at the same velocity. Beyond the outflow the thoracic aorta distends which slows the flow rate
4.	The USCOM relies on the beam being parallel to aortic outflow. Having a divergent beam helps in this respect. Furthermore, misalignments of up to 25° cause only minor attenuations of the Doppler signal (*i.e.,* ×0.9 or <10%)
5.	Training to ensure proper focusing of the beam and correct recognition of aortic or pulmonary blood flow plus well-designed software that allows a good operator to device coordination help to guarantee good signal acquisition

audible Doppler signal. It has a touch screen display which provides three screen views including (1) waveforms, (2) trends, and (3) patient reports. Measurements are made on the screen by outlining the captured velocity profile, which is done either automatically by flow tracking software or by hand using a touch point function. By inputting the measured variables such as blood pressure, oxygen saturation, and hemoglobin level a number of other circulatory parameters are generated which facilitate the use of decision charts. The USCOM can be used to measure the flow from either the aortic or pulmonary outflow tracts. During anesthesia the suprasternal approach (AV) is preferred, while the precordial approach (PV) is used in more ambulatory situations.

9.4 Velocity Profile Acquisition

Aortic measurement: The USCOM in AV mode uses a 2.2-MHz handheld probe which is applied on the patient's suprasternal notch. The transmitter/receiver surface is circular and makes a right angle with the handle. The direction of the beam is aimed toward the root of the heart and aortic outlet. The beam is focused to obtain the maximal resolution Doppler signal either visually or by listening to the audible sound. Focusing involves rotating the probe head in both the (1) anterior-posterior and (2) right-to-left lateral directions. Once focused the probe is held in position until a series of velocity profiles are saved on the screen. One screen sweep takes 7.5 s. Cardiac output and other parameters are calculated in real-time. The probe and software are designed to provide optimum readings (Table 9.1). However, in some patients, the velocity profile is suboptimal and provides unreliable data (Table 9.2: USCOM 1–6). The velocity profile can be score for its quality and reliability [1, 2].

Pulmonary artery measurement: The USCOM in PV mode uses the same 2.2-MHz handheld probe. The third or fourth left intercostal space beside the sternum is insonated. The flow in the pulmonary artery is away from the probe, giving an inverted velocity profile. It helps to have the patient in a left lateral position (Table 9.2: USCOM 2, 7). Focusing the probe is similar to the suprasternal approach and is better tolerated. The PV and AV readings should be similar, which is a useful check for correct signal acquisition.

Table 9.2 Common problems encountered when using continuous wave Doppler devices

	Site	USCOM
1	AV	In some patients it can be difficult to insert the probe far enough into the sternal notch and the beam is block by the sternal bone
2	AV	When probe placement and signal detection proves to be difficult, it can be quite uncomfortable and painful for the patient. Even when anesthetized the patient may be stimulated which leads to higher-than-resting readings. Heart rate increases provide a good guide to probe causing stimulation
3	AV PV	There are many flow signals that arising within the thorax, the largest being from the aortic outflow. Unfamiliarity with the technique can lead to the wrong signal being selected and the device underreading
4	AV	Calcification of the aorta can prevent sufficient beam energy reaching the aortic outflow and a greatly attenuated Doppler signal results. This is commonly encountered in elderly patients [5]
5	AV	Age-related tortuosity of the aortic arch can also effect signal detection [6]
6	AV	In high cardiac output states such as sepsis or anemia, the USCOM can overread because spikes in the velocity profile occur that are caused by turbulence. The flow-tracking function is particularly susceptible, and re-outlining the flow profile using touch point can help
7	PV	In some patients it can be difficult to insonate the pulmonary artery because the highly echogenic lung edge obstructs the beams passage, and this can be made worse when the lungs are hyperinflated by positive pressure ventilation
		CardioQ
1	OES	The esophageal probe is uncomfortable restricting its use to anesthetized, sedated, and unconscious patients. Furthermore, the patient needs to have a normal esophagus, and the presence of oro−/nasogastric tubes and devices may block the probe's beam
2	OES	A recognizable Doppler flow profile is not always detected, and this is probably due to air or esophageal spasm. There may also be a morphological reason resulting in the esophagus not lying adjacent to the descending aorta. If available, reviewing a thoracic CT scan can help to identify a reason
3	OES	The probe can pick up signals from the pulmonary or celiac vessels if wrongly positioned. The Deltex medical website provides good information on the correct signal identification
4	OES	The aorta becomes wider and longer with aging, and this effects the angle made by the ultrasound beam with the aorta. Unfolding of the aorta can be seen on the chest radiograph. Small movements in the insertion depth can cause significant changes in the size of the velocity profile due to changes in the insonation angle [7]
5	OES	The aorta becomes wider with age, and the rate of flow within the aorta becomes less for the same cardiac output. The CardioQ adjusts for this aging effect when calibrated. However, conditions such as hypertension can cause the aorta to age faster than predicted by the algorithm

Calibration: The USCOM measures flow (VTI) and cross-sectional area (CSA) of the vessel has to be derived from a height-based algorithm [3]. The algorithm is only accurate up to 16% (95% confidence limits) which contributes to the reported percentage error (PE) in Bland-Altman style comparative studies.

9.5 Esophageal Doppler

Development of esophageal Doppler by Deltex Medical, formerly Doptek, dates from the late 1980s [4]. The CardioQ is a portable bedside monitor that attaches to a disposable esophageal probe. Over the years there have been a number of soft and hardware modifications, and it now accommodates other hemodynamic monitoring modalities. Early prototypes had an additional external transthoracic probe, the SupraQ. Today the system supports pulse pressure using the Liljestrand–Zander algorithm and impedance cardiography in their ODM+ and TrueVue models. It displays the Doppler velocity profile in real time which is outlined to measure cardiac output. Trends are also displayed. Data can be downloaded. Operation is by knobs and buttons (Fig. 9.2).

The Waki-To is made by a French company, Atys Medical, that produces a range of clinical ultrasound devices. It has a reusable esophageal probe with higher-quality crystals than dispos-

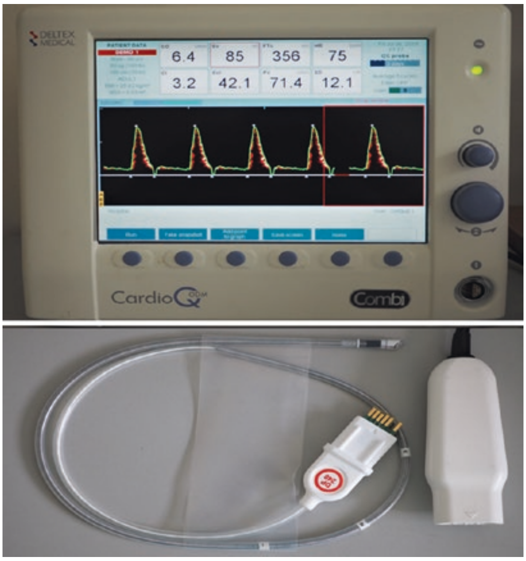

Fig. 9.2 CardioQ and esophageal probe. COMBI research model. The screen shows outlined flow profiles with measured parameters displayed above which is controlled by knobs and buttons. Beneath flow profile an arterial pressure trace can be displayed. Probe has sealed tip with two transducers at 45°, flexible wire stalk with depth markers and plug connector with computer memory chip

able probes. The display and velocity profile analysis function are similar to the CardioQ.

The CardioQ probe has a flexible wire stalk that facilitates insertion and positioning with markers to indicate insertion depth. The tip has two ultrasound crystals (4 MHz), transmitter and receiver, that are set at a 45-degree angle. The tip is sealed and tested for electrical safety (Fig. 9.2). A memory chip records calibration data, time and date. Probes range between 6-h and 10-day use. They are sterile packed and designed for single use.

The probe is inserted to 35–45 cm so that the tip lies about the level of the sixth thoracic vertebrae behind the heart. It is focused by rotation and adjusting depth. Both visual and audible signals can be used. An acceptable visual flow profile has a well-formed crescent shape with no diastolic extension. However, the alignment of the probe's beam can move and refocusing is required. A nose clip can be used to maintain insertion depth. Flow profile morphology can be used to diagnose different hemodynamic states.

Calibration: The CardioQ is calibrated using an internal algorithm based on the height derived from population data. Age is needed because the descending aorta widens with age and loss of elasticity (Table 9.2: CardioQ 4, 5). Accuracy relies on the descending aorta and esophagus lying parallel and the split ratio (*i.e.,* 0.3:0.7) between the aortic blood flow to the upper body (*i.e.,* subclavian and jugular arteries) and lower body remaining constant. It is worth noting that a significant proportion (*i.e.,* 25–30%) of the descending aorta's blood flow occurs during diastole due to elastic recoil, and the proportion varies with changes in afterload.

9.6 Readings

In addition to stroke volume and cardiac output, the USCOM measures stroke volume variation (SVV) and an inotropy index (ION). The CardioQ measures Flow Time corrected (FTc) to a 60-s period, which is used like SVV to drive goal-directed fluid therapy.

9.7 Clinical Utility and Reliability

The USCOM is sold worldwide. It has a wide range of reported applications including hemodynamic evaluation of athletes in training, medical patients, emergency room assessment and resuscitation, intraoperative fluid management, critical care, and pediatric/neonatal use. Over 500 papers have been published on its reliability and clinical utility. The vast majority of validation studies have been Bland-Altman style comparisons with other methods. A meta-analysis of data from these studies has found the USCOM to be no more precise than other methods with a PE of 43% [8]. Errors that arise from its method of calibration and faults with operator technique rather than the lack of soundness of the Doppler method may account for the high PE [9].

The USCOMs ability to track changes in cardiac output has been under researched, presumably because of the difficulties in performing suitable studies, especially in the clinical setting.

The authors of this chapter performed a number of studies published between 2013 and 2016 that concluded that (1) with cross checking and (2) attention to detail Doppler methods can provide reliable trend data in the clinical setting [10, 11] and (3) that the shifts in calibration found with other methods are less common [12, 13].

The CardioQ is also sold worldwide. Its main clinical application has been to guide fluid therapy by optimizing the Frank–Starling curve. Boluses of intravenous fluid (*i.e.,* 200 mL over 5 min) are recommended, and an increase in stroke volume of greater than 10% shows fluid responsiveness which initiates further boluses. An alternative test is to raise the legs. In 2011, NICE (National Institute for Health and Care Excellence, UK) recommended using the CardioQ as part of an ERAS (Enhanced Recovery After Surgery) program, notably bowel surgery. More recent publications that support using the CardioQ during surgery include the FEDORA trial [14].

9.8 Obstacles to Clinical Acceptance

Doppler techniques that monitor cardiac output have been available for over 20 years, yet they have never been fully accepted into clinical practice. Possible reasons include (1) a lack of development and marketing, (2) poor financial model, (3) high operator dependency, (4) does not work in every patient, and (5) a lack of familiarity with using Doppler data by clinicians (Table 9.3).

Table 9.3 Reasons for the lack of acceptance of the continuous wave Doppler monitoring

1.	Currently marketed Doppler flow devices are produced by small independent companies that lack the finance to develop fully the potential of their product
2.	The USCOM has minimal running costs to support suppliers financially, whereas the CardioQ requires a costly single-use disposable probe which limits clinical use. Neither is a good financial model
3.	Using Doppler devices to measure cardiac output reliably is highly operator dependent. Both the USCOM and CardioQ have learning curves of 10–20 examinations before they can be used with any confidence. Furthermore, performing measurements is time-consuming and distracts the clinician from other important tasks
4.	Currently available systems fail to provide an acceptable Doppler signal, and thus reliable readings, in a significant proportion of patients, especially the elderly
5.	Cardiac output and associated parameters are not regularly used today and hospital doctors lack training in their use. Furthermore, the development of bedside echocardiography has eclipsed the need for routine cardiac output monitoring. Thus, there is little incentive to use Doppler monitoring except by a few enthusiasts

Practical Advice

- Continuous wave (CW) Doppler is an underused hemodynamic monitoring modality.
- Two Doppler modalities are used: (1) Transthoracic (USCOM) and (2) Doppler (CardioQ & Waki-To).
- One has to gain proficiency in the uses of these CW Doppler techniques to obtain reliable data.
- In some patients an inadequate Doppler flow profile is obtained and the data is unreliable. The user needs to be able to recognize such cases. Aging is the main cause of calcification, enlargement, and tortuosity of the aorta.
- Single readings may be inaccurate because of inherent calibration errors. However, when Doppler is used to assess changes in stroke volume and cardiac output in response to treatment (*i.e.,* trending), the data is much more reliable.
- Using readings from several monitoring sources improves user ability to determine the true value of cardiac output.

Keynotes

- Continuous wave Doppler is underused technique.
- Both transthoracic and esophageal modes are used.
- Measurements are highly operator dependent.
- Reliability is affected by age-related changes to the aorta.
- More reliable when used to monitor trends.

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