Doppler cardiac output monitoring: a tool for all physicians

This article introduces Doppler ultrasound cardiac output monitoring and outlines its increasing utility for managing patients with critical illness in the hospital environment.

Modern medicine is offering a wider and more complex range of treatments than ever before. Today's physician is caring for an increasingly elderly population who exhibit diminished physiological reserve.

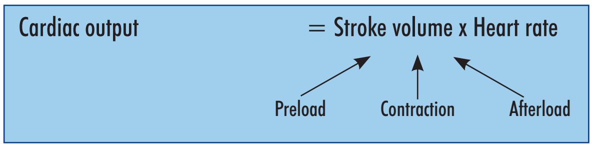
Cardiovascular disease is increasingly prevalent in hospital patients and when associated with low cardiac output states carries a high mortality (Tuchschmidt and Mecher, 1994). Where empirical treatment of haemodynamic compromise is unsuccessful, additional data are needed to guide and optimize the circulation, ideally before critical care admission. Doppler cardiac output monitoring (DCOM) is gaining popularity in this setting as it is both minimally invasive and easy to perform.

Background

The supply–demand relationship that ensures healthy organ perfusion relies upon coordinated cardiovascular system control to achieve adequate cardiac output during periods of fluctuating oxygen use. The endocrine and central nervous systems interact with local cardiac intrinsic mechanisms to adjust heart rate and stroke volume leading to immediate changes in cardiac output (*Figure 1*).

Cardiac output can be defined as 'the amount of blood ejected from the left ventricle in 1 minute' and is a measure of global blood flow. Surrogate markers of organ perfusion, e.g. skin temperature, capillary refill time, cognition and urine output, are of limited diagnostic value and insensitive to subtle changes in cardiovascular status (Eisenberg et al, 1984). In illness a patient's blood pressure may also be falsely reassuring because it assumes blood flow is related to blood pressure. This can be a flawed assumption in many clinical settings because compliance of the arterial system is not constant (*Figure 2*).

Figure 1. Determinants of cardiac output.



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Conversely, if mean arterial blood pressure and cardiac output are known, the systemic vascular resistance can be calculated and used to guide inotrope or vasopressor therapy. Problems are also encountered when central venous pressure is wrongly assumed to predict left heart blood flow, the former being a poor predictor of the latter.

To overcome these problems the pulmonary artery catheter has developed to be the current 'clinical standard' for cardiac output measurement. This technique, famously first described in clinical practice in 1970 by Swan, Ganz and colleagues, involves calculating cardiac output from a dye, or thermodilution, method by estimating the area under the curve of dye concentration, or temperature change, against time.

Concerns about the safety of the pulmonary artery catheter technique (Anonymous, 1997) cast doubt on the role of the pulmonary artery catheter in clinical practice, since when there has been a search for a safe and reliable minimally invasive form of cardiac output monitoring.

Doppler principle

In 1842 the Austrian mathematician Christian Doppler first proposed how 'the velocity of a moving object is proportional to the shift in reflected frequency of an optical wave of known frequency' in his paper 'On the coloured light of double stars and certain other stars of the heaven'. He tested his hypothesis 3 years later in 1845 by moving trumpeters playing a solitary note in an open freight carriage past other musicians who observed the apparent change in pitch produced by the approaching and receding train. The Doppler effect is described by a simple equation (*Figure 3*) which calculates the velocity of an object assuming a change in frequency is observed.

Figure 2. Determinants of mean arterial blood pressure.

Blood pressure = cardiac output x systemic vascular resistance

$$\Delta f = \frac{2fe.\ v.\ \mathrm{Cos}\theta}{c}$$

c = speed of wave; Δf = frequency shift; fe = emitted frequency; v = velocity; θ = angle between axis of wave and the velocity vector

Figure 3. The Doppler equation.

The Doppler effect and haemodynamic monitoring

The Doppler principle was first used to measure blood flow in 1961 by Franklin et al and has since been used widely in many areas of medicine. DCOM was first described by Light in 1969 using a non-invasive transthoracic view of the descending aorta. Ultrasound waves reflected off moving erythrocytes in the aorta cause a shift in reflected frequency proportional to their velocity. This shift is used to calculate blood flow from a displayed flow–velocity waveform when the diameter of the blood vessel is known. Light went on to modify his technique, describing a completely non-invasive suprasternal approach, but concerns about signal reproducibility as a result of probe angulation errors led to the distal oesophagus becoming the preferred anatomical site.

First described in 1971 by Side and Gosling, oesophageal positioning restricts probe movement and allows the possibility of continuous and reproducible data, albeit at the expense of it becoming an invasive tool and ideally therefore the patient must be sedated or unconscious to tolerate its insertion.

A call for the early recognition and proactive management of the critically ill (McQuillan et al, 1998; Cuthbertson, 2003) has led to the continued evolution of these tools. Now a smaller, more compliant and subsequently better tolerated probe allows its use in the non-sedated patient, often in non-traditional critical care environments.

Practical considerations

The distal oesophagus lies adjacent and parallel to the descending aorta at a depth of approximately 35–40 cm from the lips in adults and is readily accessed from the nose or mouth (*Figure 4*). The oesophageal Doppler monitor probe is passed into the distal oesophagus where it is manipulated to produce the optimal signal detection, primarily by audible detection of pulsatile flow and then by focussing the image to gain the maximum peak velocity (*Figure 5*). Familiarization of optimal waveform patterns before analysis is therefore essential and operator training crucial. However, learning curve analysis shows an acceptable degree of success after insertion of only 10–12 oesophageal Doppler monitor probes (Lefrant et al, 1998).

A continuous real-time waveform is produced with wave contour analysis producing valuable circulatory information. This information can be used to guide and monitor therapeutic interventions such as fluid therapy, inotrope and vasopressor administration.

Oesophageal Doppler monitoring is minimally invasive thus few contraindications exist to its use. Coagulopathy, oesophageal varices and other significant oesophageal pathology are only relative contraindications. Data interpretation must be tentative in the presence of significant aortic valve disease, coarctation of the aorta and if an intra-aortic balloon pump is in place (Al-Khafaji and Webb, 2004).

Oesophageal Doppler monitor probes have been used in the unconscious patient for up to 14 days without

Figure 4. Position of oesophageal Doppler monitor probe.

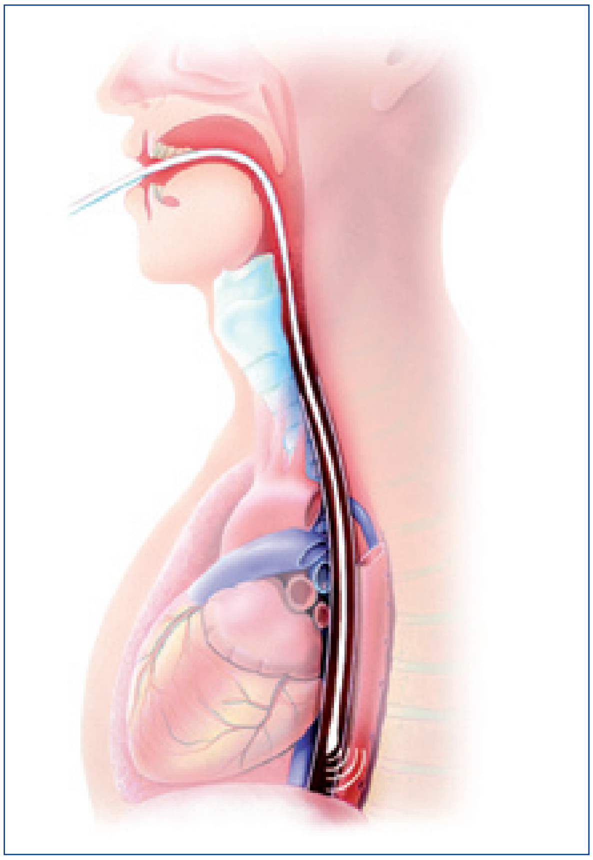
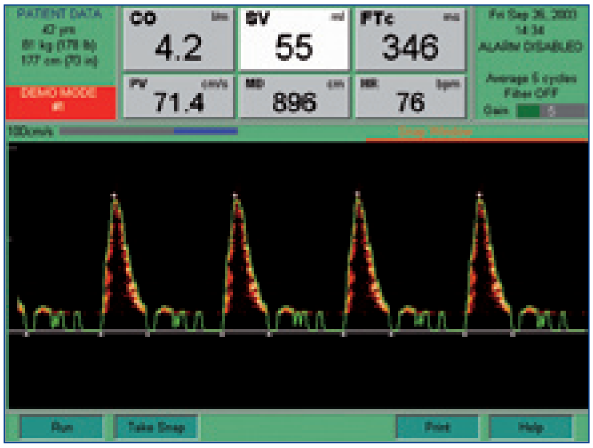


Figure 5. Normal oesophageal Doppler trace.



complication and there appears to be reasonable tolerability to insertion and continued use in the awake patient (Atlas and Mort, 2001; Walker et al, 2004).

DCOM is less accurate when estimating flow in pre-eclampsia or where a functional epidural is in place. This may be a result of the aortic root dilatation associated with pregnancy in the former, or secondary to vasodilatation of the splanchnic circulation in the latter. In both these situations using trend analysis to direct treatment is best and probably still of some benefit.

Practical Doppler cardiac output monitoring

The area under each wave is the velocity time integral and represents the distance travelled by a column of blood during each ventricular contraction known as the stroke distance. The product of stroke distance and heart rate is the distance travelled in 1 minute by that column of blood and called the minute distance.

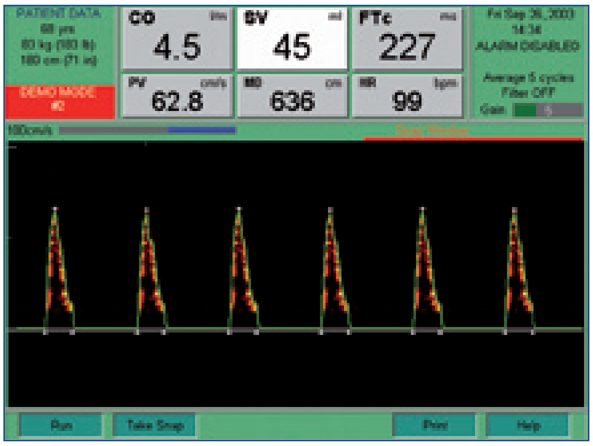
If the cross-sectional area of the aorta is known, either by transoesophageal ultrasound measurement or from a nomogram based on height, weight and age (Singer et al, 1989), then the stroke volume can be derived from the product of the cross-sectional area of the aorta and stroke distance (Huntsman et al, 1983).

Calculating stroke volume, and hence cardiac output, assumes that cross-sectional area of the aorta is constant which may not occur at extremes of blood pressure. However, it is a response to changes in trends of these parameters rather than to a single result that influences clinical management and DCOM has the advantage of producing continuous data.

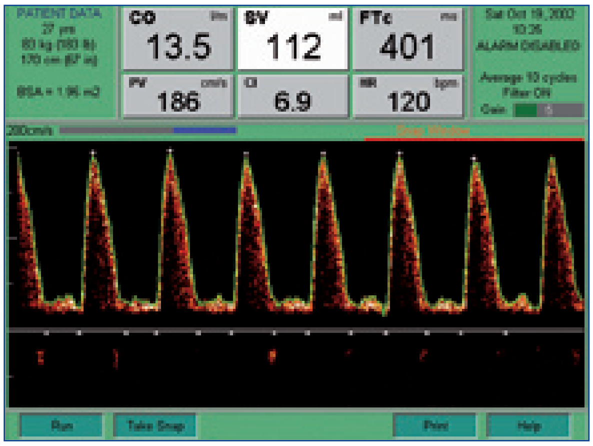
Corrected flow time

The base of the waveform is known as the flow time and corresponds to the period of systolic contraction. When compensated for heart rate this is called the corrected flow time (FTc) which is inversely related to systemic vascular resistance. FTc is shortened with a vasoconstricted circulation, most commonly seen with hypovolaemia but may also be seen as a response to vasopressor therapy or hypothermia (*Figure 6*).

Figure 6. Hypovolaemia.



CO 4.5
SV 45
FTc 227
PV 62.8
MD 636
HR 99



CO 13.5
SV 112
FTc 401
PV 186
CI 6.9
HR 120

Figure 7. Sepsis.

Conversely, FTc is widened in the vasodilated circulation (*Figure 7*), such as that seen with sepsis or following adequate fluid administration (Singer et al, 1991).

Peak velocity and mean acceleration

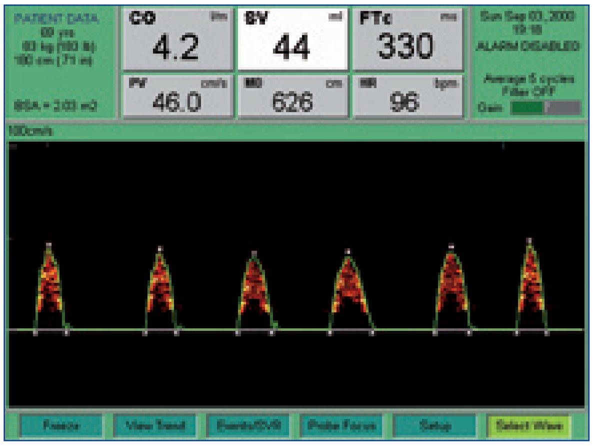
The fastest observed velocity of the blood in the thoracic aorta reached during systole represents the peak velocity, while the mean acceleration is the average acceleration of blood flow in systole represented by the up slope on the velocity–time graph.

Both peak velocity and mean acceleration are markers of left ventricular contractility and afterload. There is strong correlation between changes in mean acceleration and peak velocity with ventricular contraction in dogs. Close correlation has been shown between these changes in peak velocity and mean acceleration when comparing electromagnetic flowmetry and Doppler (Wallmeyer et al, 1986).

In humans, peak velocity and mean acceleration values are inversely related to severity of ischaemic heart disease and directly related to the left ventricular ejection fraction (Bennett et al, 1974) (*Figure 8*).

Increases in peak velocity and mean acceleration occur following fluid administration or inotrope stimulation, and conversely reduce when there is volume depletion or

Figure 8. Left ventricular failure.



CO 4.2
SV 44
FTc 330
PV 46.0
MD 626
HR 96

myocardial depression (Bennett et al, 1984; Wallmeyer et al, 1986; Singer et al, 1991).

Validity of Doppler techniques in clinical medicine

A review addressing the validity of oesophageal Doppler monitor-generated data compared to pulmonary artery catheter has been published (Dark and Singer, 2004). This systematic review highlighted 198 original papers, with 11 validation papers reporting on 21 studies. As a monitor of absolute cardiac output there was limited clinical agreement with pulmonary artery catheter. This may in part reflect the limitation of statistical method when using a ‘gold standard’ which itself is subject to variation in its reproducibility. However, where changes in cardiac output occurred the reference pulmonary artery catheter and oesophageal Doppler monitor data were consistent in their disagreement, thus allowing accurate assessment of cardiac output, particularly where trends in measurement are monitored.

They concluded that high validity for monitoring changes in cardiac output with oesophageal Doppler monitoring in the critically ill exists, but there were insufficient number of studies to assess the validity of echo oesophageal Doppler in this setting. Thus with optimal waveform acquisition and careful waveform analysis, useful information regarding cardiac loading conditions and contractile function can be obtained. These data are most powerful when interpreted in the patient’s clinical context and when multiple readings are conducted to provide a trend in observation in response to appropriate therapy.

Doppler cardiac output monitoring in clinical practice

The physiological challenge of surgery and the emerging evidence suggesting morbidity benefits from perioperative haemodynamic optimization (Shoemaker et al, 1988; Mythen and Webb, 1995) has made DCOM a potentially attractive modality for use in the surgical setting. This is reflected in the great number of publications in this area, including randomized controlled trial data showing improved patient outcome following oesophageal Doppler monitor-guided interventions. In the high risk elderly orthopaedic population occult hypovolaemia may be associated with poor outcome. Improved morbidity and associated socioeconomic benefits from reduced hospital stay have been demonstrated by oesophageal Doppler monitor-guided fluid optimization during fractured neck of femur repair (Sinclair et al, 1997). Similar benefits are reported from studies in both cardiac and major general surgery (Mythen and Webb, 1995; Gan et al, 2002). Alternative algorithms exist for the oesophageal Doppler monitor. Sinclair et al (1997) described a simple algorithm for fluid optimization using hydroxyethyl starch and monitoring changes in stroke volume and corrected flow time (*Figure 9*). Mythen and Webb (1994) suggest giving intravenous colloid until there is no increase in stroke volume whereas McKendry et al (2004) include when to commence inotropes and vasodilators.

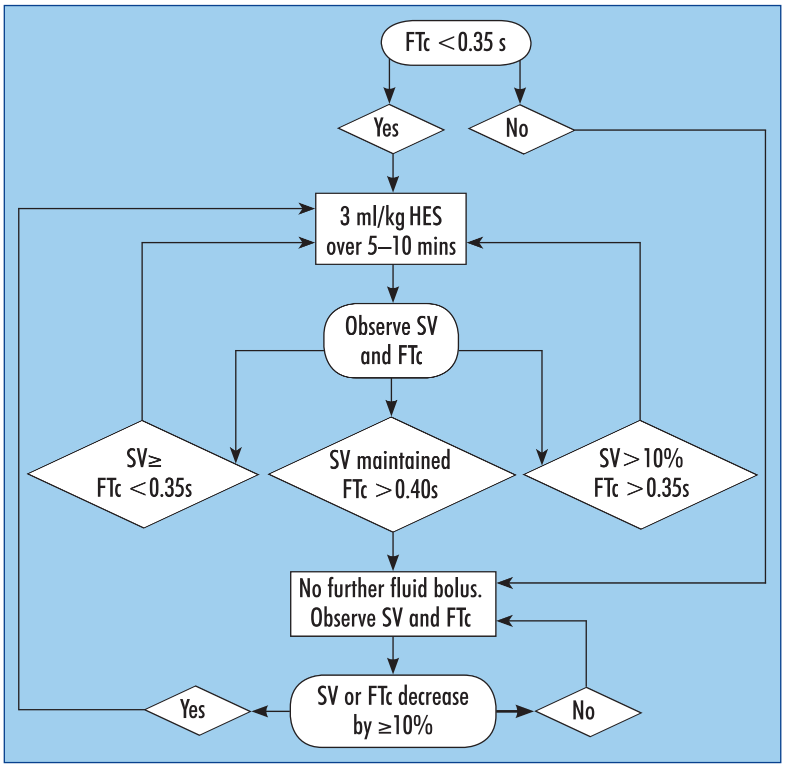
The scope of this technology has been widened following its success and is now available for use in critically ill children with useful estimation of cardiac output across all ages (Tibby et al, 2000). Similarly, unpublished data from the authors’ unit at University College London Hospitals gives reliable trends in changing haemodynamic status during laparoscopic surgery in children of all ages, although there is no validated paediatric nomogram yet developed.

Extending the reach of Doppler cardiac output monitoring

There is increasing evidence to support early and aggressive management of critically ill patients (Rivers et al, 2001). Outreach teams are now commonplace on many UK hospital wards, bringing the concept of intensive care to the patient rather than waiting for patients to decompensate and require critical care admission. This emerging philosophy lends itself well to DCOM: accurate haemodynamic parameters allow rapid determination of physiological disruption and correction without the need for critical care admission.

Similarly pre-optimization of patient physiology before surgery, with its potential benefits to the patient (Shoemaker et al, 1988) and for reduced hospital costs (Fenwick et al, 2002), could become a more practical proposition if it could be used in the ward environment.

Figure 9. Intraoperative fluid management algorithm. FTc = corrected flow time; HES = hydroxyethyl starch; SV = stroke volume.



Atlas and Mort (2001) reported the use of oesophageal Doppler monitor probes in non-sedated patients following application of local anaesthesia to the nasal airway and posterior oropharynx. Since then newer compliant probes, designed for improved tolerability and specifically for use in the awake patient, have been developed and there is increasing potential for extending monitoring in a wide range of clinical settings. The introduction of a new generation of completely non-invasive suprasternal probes with improved reproducibility of data brings the promise of low risk technologies to the patient's bedside. Both nursing and paramedical staff may operate these devices without direct physician supervision. McKendry et al (2004) report successful use of oesophageal Doppler monitoring to guide a nurse-delivered protocol for fluid optimization in early post-cardiac surgical patients and similarly there have been favourable early experiences with nurse-led oesophageal Doppler monitor patient assessment in the critical care outreach environment (Walker et al, 2004).

Conclusions

In order for such devices to become acceptable they need to be reliable, reproducible and accurate, as well as being cost effective relative to similar equipment. DCOM has been validated, and allows for optimization of treatment with possible early critical care and hospital discharge.

Reliable protocols are allowing treatments to be nurse directed while new improved technology provides estimation of cardiac output in awake, non-sedated patients away from critical care areas.

Such experiences highlight the exciting potential for such flow based technologies to offer early monitoring of the circulation and appropriate timely treatment interventions as part of a successful protocol not exclusively led by physicians. **BJHM**

The authors would like to thank Deltex Medical, Chichester, UK for kindly giving permission for the pictorial material reproduced for this review.

Conflict of interest: none.

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KEY POINTS

- Surrogate markers of cardiac output such as blood pressure and urine output are unreliable.
- Cardiac output is measured using the Doppler equation by monitoring a change in reflected sound wave frequency from erythrocytes in the aorta.
- Doppler technology is now becoming easier to use and progressively less invasive, allowing measurement in non-sedated patients on the ward.