Haemodynamic monitoring of critically ill patients with transoesophageal Doppler technology

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Abstract - Transoesophageal Doppler (TED) is a minimally invasive, quick and easy technique to assess descending aortic blood flow in critically ill patients. The frequency shift between emitted ultrasound and ultrasound scattered back to the probe by moving erythrocytes, enables flow velocity to be determined according to the Doppler principle. Using the velocity-time integral, flow velocity can be translated to the stroke volume of the descending aorta, from which the left ventricular stroke volume can be estimated. Moreover, TED technology measures additional haemodynamic parameters that may facilitate assessment of preload, afterload and myocardial contractility. Several validation studies have compared TED-derived cardiac output (CO) to reference methods and underline the usefulness of TED as a trend-monitoring device to follow changes of CO over time. Clinical use of TED monitoring in intensive care units (ICU), either as a substitute or supplement to other monitoring devices, has repeatedly been reported to yield useful data for the assessment and treatment of critically ill patients. Randomized controlled studies suggest improvements in outcome (less postoperative morbidity and shorter length of hospital stay) in the surgical patient population when TED is used to guide volume replacement intraoperatively or postoperatively on the ICU. However, data to support its usefulness in the non-surgical critically ill population are limited and also the usefulness of TED to guide vasoactive or inotropic therapy needs to be further determined. In this paper, we review current knowledge on technical and clinical aspects of the TED method and focus on its role in haemodynamic monitoring on the ICU.

Introduction

The monitoring of haemodynamic parameters plays a central role in the management of critically ill patients. Herein, determination of cardiac output (CO) can provide useful supplementary information to the standard pressure-derived parameters - which are routinely monitored in most critically ill patients. Traditionally, thermodilution techniques requiring a pulmonary artery catheter (PAC) are considered to be the gold standard of bedside CO measurement [1,2]. However, concerns about considerable risks [3], a reported lack of benefit on outcome [4-6] or even increased mortality [7] among patients monitored with PAC have limited its use in many intensive care units (ICU). Other established methods of CO monitoring, such as pulse contour analysis or transoesophageal echocardiography (TEE), are also either invasive or require a specially trained operator who may not be readily available. Ideally, a CO monitoring technique would be non-invasive, easy to learn so that it can be used without expert help, and quick to set up so that CO is displayed within minutes. In this context, transoesophageal Doppler (TED) ultrasonography of descending aortic blood flow may be a promising technique. The descending aorta conducts large portions of total systemic blood flow, therefore allowing conclusions on CO to be made. The technique is minimally invasive, it is quick and easy to learn and does not require a sterile environment. However, Doppler ultrasound cannot quantify blood flow itself but measures blood flow velocities. Translation of velocity into flow requires several assumptions, and a thorough understanding of the technology is necessary to allow valid interpretation of displayed data. We review the technical and clinical aspects of this method focusing on its role in the haemodynamic monitoring of critically ill patients.

Technical aspects of probe placement and blood flow velocity measurement

Transoesophageal assessment of descending aortic blood flow by Doppler ultrasound was first described in 1971 by Side and Gosling [8]. Previously, attempts had been made to direct an ultrasound beam towards the aorta from the suprasternal notch or an intercostal space [9,10]. However, technical difficulties with fixing the transducer in place limited the clinical usefulness of this approach, especially because continuous measurements were hardly ever possible. In contrast, oesophageal placement allows the probe to be maintained in close proximity to the descending aorta, because the oesophagus serves as a natural guide rail running parallel and adjacent to the aorta near the fifth to sixth thoracic vertebra [11-13].

Several TED devices have been developed for commercial use, however, currently there is only one product on the market in the Netherlands (CardioQ, Deltex Medical Ltd., Chichester, UK, distributed by Medical Technology Transfer MTT, Steenderen, NL). The CardioQ device uses 4 MHz Continuous Wave Doppler with a transducer mounted to the central axis of the probe at an angle of 45º. The flexible disposable probes can be easily inserted via the oral or nasal route to the mid-thoracic level, corresponding to an insertion depth of 35-45 cm [14]. After insertion, the probe is rotated towards the descending aorta (figure 1). A typical aortic waveform and a characteristic pulsatile sound pattern confirm alignment of the ultrasound beam with the aorta. Insertion is
quick and easy and training is only needed in about 12 patients to achieve adequate probe positioning [12, 15, 16]. Further, the time required for insertion is about one third of the time needed to insert a PAC [17].

In order to accomplish optimal focusing of the ultrasound beam, slight manipulation of the probe is needed until the largest and sharpest possible waveform has been found. In this context we want to emphasize that continuously measured TED parameters may become inaccurate over time due to slight inadvertent axial rotation of the probe and loss of optimal focus. Therefore, occasional refocusing, especially whenever data is required clinically, is necessary to obtain valid results [15].

When the probe has been placed and focused (figure 1), blood flow velocity can be calculated based on the Doppler principle. Emitted ultrasound is scattered by erythrocytes travelling in the descending aorta and partially reflected back to the probe [18]. When ultrasound is reflected by a moving object such as erythrocytes, the frequency of reflected ultrasound is higher than the emitted frequency when erythrocytes move towards the probe and lower when they move away from the probe [19]. Erythrocyte velocity is directly proportional to the Doppler frequency shift (Δf), i.e. the discrepancy between transmitted frequency (fT) and received frequency. This relationship is described by the Doppler equation [20]:

\[ v = \frac{\Delta f \cdot c}{2f_T \cdot \cos \theta} \]

Blood flow velocity (v) can now be calculated from the frequency shift, because other factors that determine velocity are basically known and constant (c is the velocity of ultrasound waves in body tissue, fT the transmitted frequency and θ is the angle between ultrasound beam and blood flow). The angle θ is not precisely known, however, it closely approximates the angle with which the ultrasound transducer is mounted to the central axis of the probe (i.e. 45° with the CardioQ device), because the oesophagus and aorta run nearly parallel at mid-thoracic level.

**Translating velocity into hemodynamic parameters**

Measurement of blood flow velocity over time allows the plotting of a velocity-time curve, which is typically triangular in its systolic phase while during diastole flow is negligible in the descending aorta (figure 2). The base of the triangle represents systolic ejection time, often also referred to as flow time. Flow time (FT) depends on heart rate and can be corrected to one cardiac cycle per second (FTc) by the same principle used for correcting the QT interval of an electrocardiogram (QTc) for heart rate [19]. The upslope of the velocity time curve depicts acceleration of blood in the aorta, allowing calculations of mean acceleration. The graph peaks at the maximum blood flow velocity observed during systolic ejection, followed by a downslope, which corresponds to deceleration of blood during later systole [19].

In transoesophageal echocardiography (TEE), one of the established methods to calculate stroke volume (SV) is to multiply the velocity-time-integral (VTI) of transvalvular blood flow with the corresponding valve area [21]. The term VTI is commonly used with TEE is usually referred to as “stroke distance” with TED [19]. It corresponds to the distance the column of blood travels...
in the descending aorta during systole because the integral of velocity (cm s⁻¹) and time (s) is distance (cm). In analogy to TEE, descending aortic blood flow can be calculated as the product of descending aortic stroke distance and descending aortic cross sectional area. Subsequently, total left ventricular SV can be estimated assuming a constant distribution of blood flow between the descending aorta (~70%) and coronary and brachiocephalic circulation (~30%). While velocity and time are measured by the TED device, the third determinant necessary to calculate SV, i.e. aortic cross sectional area, is basically unknown. Some TED devices that are no longer marketed in the Netherlands, such as the Hemosonic 100 device (Arrow International, Reading, PA, USA), used to measure the aortic diameter via an integrated M-mode ultrasound probe. However, in clinical practice accurate determination of aortic diameter proved difficult. The CardioQ device does not directly measure aortic diameter but uses a nomogram based on the patient’s age, height and weight to translate velocity to flow [22].

Clinical validation of TED-derived CO values
A total of 44 Medline-indexed studies evaluated the validity of TED in various populations of critically ill as well as perioperative patients by comparing TED-derived CO with reference methods, usually thermodilution techniques [reviewed in 14]. Those studies reporting Bland-Altman analyses demonstrate that TED does not grossly underestimate or overestimate CO in a systematic manner. However, they also suggest that individual CO values estimated with TED can considerably differ from values obtained with reference methods. During ICU treatment, exact absolute values are rarely needed, but it is important to know whether a patient has a low, normal or high CO and whether certain events or therapeutic interventions cause relevant changes in CO. Studies reporting correlation coefficients show a good correlation (median correlation coefficient 0.8) between TED-CO and reference-CO, demonstrating a strong linear relationship between measurement techniques [14]. This suggests that a high CO value measured with the reference technique is likely reflected by a high reading with TED and vice versa, and that the direction of changes of CO can be tracked by TED. Several studies specifically addressed CO changes and report that TED reliably follows CO changes over time. Thus, in summary, the validation studies demonstrate that TED is useful for estimating the dimension of CO and for subsequent trend monitoring of CO changes in critically ill patients [2,14].

Principles of haemodynamic monitoring with TED
Clinical assessment of CO may often be insufficient and misleading [23-25]. Here, TED can play a role in identifying patients with pathological low or high CO and provide additional parameters that facilitate assessment of preload, afterload and contractility. However, it should be noted that no single parameter is specific by itself, and that changes of one parameter are accompanied by compensatory changes of other parameters in vivo. Moreover, reference values of some of the parameters

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Figure 3. Velocity time plot of hemodynamic conditions associated with a reduced stroke volume (as indicated by a reduced velocity-time integral) and restoration of a physiologic waveform by adequate treatment. SD: stroke distance, FTC: flow time corrected for heart rate, PV: peak velocity, MA: mean acceleration. ↓ indicates that the parameter is decreased compared to the physiologic state.
have to date only been poorly established. Therefore, rather than observing the absolute value of a single parameter, the combination of different parameters and the pattern of how they respond to therapeutic interventions should be used to assess the haemodynamic situation in combination with all other available clinical information.

TED derived haemodynamic parameters and waveforms have been previously reviewed in detail [14,22,26]. Briefly, the FTc is directly related to preload and inversely related to afterload, therefore a low FTc can indicate hypovolaemia as well as a abnormally increased total peripheral resistance that is preload-independent, for example, due to vasopressors or hypothermia. An FTc in the range of 330-360 ms is generally considered normal because the systole takes about one third of the entire cardiac cycle, however, values of about 300 ms may be normal in younger adults. Peak velocity is directly related to contractility and indirectly related to afterload, so that a reduced peak velocity can indicate left ventricular heart failure as well as increased total peripheral resistance. Normal values for peak velocity depend on age and decrease from about 110-130 cm s⁻¹ in childhood and adolescence to 60-70 cm s⁻¹ at the age of 70 years. Mean acceleration is directly related to contractility, however, reference values for TED are lacking in the literature.

Taking all parameters together, a reduced FTc with a rather normal peak velocity suggests hypovolaemia, while marked reductions in FTc and peak velocity indicate a pathologically increased afterload (figure 3). A fluid challenge can help to clarify the situation in equivocal cases. The normal, not hypervolaemic heart operates on the ascending limb of the Starling curve (figure 4), therefore a fluid bolus will result in an adequate increase in SV. In this context, an increase is generally considered adequate if it exceeds 10% following a colloid bolus of 3 ml kg⁻¹ bodyweight [14]. Absence of such an increase suggests that the heart operates on the flat portion of the Starling curve and should alert the intensivist to suspect a pathologically increased afterload rather than to continue volume load. However, one should keep in mind that absence of an adequate response to volume therapy can sometimes also be caused by pathological states which compromise left ventricular filling such as cardiac tamponade, tension pneumothorax, lung embolism, severe mitral stenosis or ongoing haemorrhage. In these cases, other appropriate diagnostic techniques such as TEE may be necessary to confirm the suspected diagnosis. The Starling principle can also be used to guide volume therapy in hypovolaemic patients to optimize CO while avoiding hypervolaemia. In practice, repetitive fluid bolii can be applied until no further adequate fluid responsiveness has been observed, suggesting an optimal fluid load (figure 4).

A reduced peak velocity associated with reduced mean acceleration and rather normal FTc indicates left ventricular failure. In patients with heart failure, the apex of the flow-velocity curve may also appear rounded as opposed to the rather pointed peak that is usually observed with adequate left ventricular function.

**Clinical use of TED on the ICU**

While, as described earlier, numerous validation studies confirmed in principle the ability of TED to estimate and track CO changes in critically ill patients, the question still arises as to whether it is useful in clinical practice as a diagnostic aid and to guide therapeutic decisions. In this context, Stawicki et al. report their experience in 19 ICU patients and 5 organ donors treated on the ICU [17]. Indications for TED placement were resuscitation of surgical and non-surgical patients, differentiation between types of shock, and inability to place or obtain reliable data from a PAC. The authors describe that TED data were useful in 23 out of the 24 cases, allowing successful event specific and goal directed treatment. Two other manuscripts also suggest that successful organ procurement can be facilitated by TED in haemodynamically labile organ donor patients [27,28], and TED monitoring of septic patients has been described in one case report [29]. Singer et al. describe the usefulness of TED to monitor circulatory effects of positive end expiratory pressure (PEEP) on the ICU, which led to the optimization of PEEP to obtain maximal oxygen delivery to the tissues [30]. Poeze et al. found that TED was a useful tool for detecting occult haemodynamic deterioration in cardiac surgery patients who were treated postoperatively on the ICU [31].
measured by TED was highly predictive for the development of subsequent complications, while other routinely monitored variables were less specific and sensitive.

Several studies addressed whether TED could adequately indicate volume demand in critically ill patients. In this context, Madan et al. suggest that FTc is a better indicator than pulmonary capillary wedge pressures to assess preload [32]. However, the FTc is not specific for preload because it is also inversely related to afterload and its use as a single marker to assess preload is discouraged [33]. Recently, novel dynamic parameters have been derived from standard TED parameters to assess variations of aortic blood flow during the respiratory cycle [34] or to assess variations in the stroke output index (i.e., the ratio of stroke volume index and corrected flow time) secondary to a volume challenge [35]. These parameters have been found to reliably predict fluid responsiveness in critically ill patients, however, a general consensus as to which parameter is most useful in clinical practice has yet to be established.

Especially because PAC monitoring failed to demonstrate improvements in patient outcome, the question arises whether TED guided volume replacement could have beneficial effects on outcome in critically ill patients. Chytra et al. studied 162 mechanically ventilated multiple-trauma patients admitted to an interdisciplinary ICU [36]. All patients were clinically managed to maintain oxygen saturation, mean arterial pressure, heart rate, urinary output, temperature and haemoglobin within predefined limits. Patients randomly allocated to the TED group (n = 80) additionally received colloid fluid challenges based on FTc and SV during the first 12 hours of ICU stay. TED guided patients had significantly lower lactate levels, less infection complications and a reduced length of ICU and hospital stay. A similar study was performed by McKendry et al. in cardiac surgery patients postoperatively admitted to the ICU [37]. Patients were randomized to a control group and a protocol group, and treatment was performed according to the allocated protocol during the first 4 hours postoperatively. Control patients (n = 85) received conventional management primarily based on monitoring of arterial and central venous pressures in combination with markers of tissue perfusion such as urinary output and arterial base deficit. CO was only monitored in this group if clinically indicated. In the protocol group (n = 89), therapeutic decisions were based on TED derived stroke volume index (SVI). The algorithm primarily included fluid challenges but also wherever necessary glyceryl trinitrate or adrenaline administration to increase SVI above 35 ml m⁻². Here, the median length of hospital stay was significantly reduced from nine to seven days in the TED guided group. The authors also observed a distinct trend towards a reduction in postoperative complications (17 complications in the protocol group vs. 26 complications in the control group, p < 0.08). While these are the only studies assessing the effect of TED guided therapy on outcome in the ICU, a total of eight studies performed intraoperatively in various surgical specialties including cardiac, abdominal, urologic, gynaecologic and orthopaedic surgery, also suggest beneficial effects [38-45]. In these studies, TED guided volume replacement was compared to conventional volume management guided by clinical assessment and/or central venous pressure. These investigations, in a total of 646 patients, suggest a reduced postoperative morbidity, reduced need for ICU admission and a reduced length of ICU and hospital stay in TED guided patients.

While a substantial body of evidence supports the use of TED in guiding volume therapy in surgical patients perioperatively and on the ICU, data concerning non-surgical patients are limited. In addition, studies specifically addressing the usefulness of TED to guide vasoactive and inotropic therapy in critically ill patients are lacking. Moreover, there are no randomized controlled studies that directly compare patients managed with TED to patients managed with PAC or other invasive techniques. Comparison in the outcome of the patient groups could help to determine whether TED can indeed replace other invasive techniques in certain patient populations. Of course, TED cannot measure pulmonary artery pressures as PAC does, nor can it be used to evaluate valvular function as TEE does. Therefore, TED will never be a substitute for all other techniques that measure CO, because each technique also specifically monitors other parameters, which may be of specific interest in certain patient populations. However, it may likely be a useful, simple and less invasive alternative in a variety of patients, or be used for advanced haemodynamic monitoring in patients not felt to warrant the risks of invasive monitoring - where CO would otherwise not be monitored at all. In contrast, if invasive monitoring is considered necessary, TED may still be useful as a supplement to other techniques as it provides unique additional haemodynamic data, which may aid the intensivist in gaining a detailed picture of the patient’s haemodynamic situation.

Contraindications and limitations

Contraindications derive from the necessity to insert a probe into the oesophagus and include any pathology which predisposes the patient to an increased risk of injury or bleeding at the insertion site or oesophagus. Such pathology includes severe bleeding disorders, oesophageal varices, malformations, strictures, tumours, oesophagitis or recent oesophageal or upper airway surgery [14].

Technical limitations derive from the blood flow velocity measurement itself as well as the assumptions needed to translate velocity into CO. The intensivist needs to be aware of these limitations, as there are conditions in which TED derived measurements may not necessarily be reliable. The measurement of blood flow velocity assumes that all erythrocytes travel in the same direction and at the same speed. Indeed, in healthy subjects, descending aortic blood flow is usually laminar with a relative uniform velocity profile over the aortic cross section [46]. However, skewed velocity profiles and rotational blood flow in the descending aorta has also been described [47]. Non-laminar flow is likely to occur in patients with pathology of the aorta or aortic valve. Another important aspect in velocity measurement is the angle with which ultrasound is insonated into the aorta, because the cosine of this angle makes part of the Doppler equation. As described earlier this angle is not precisely known.
**References**


Despite these limitations, trend monitoring should generally be possible if the basic conditions remain constant. However, it is important to realize that changes in the basic condition, e.g., sudden changes of aortic diameter and blood flow distribution due to acute hemorrhage, may lead to inconsistent or even misleading CO readings [59]. Thus, the intensivist needs to be aware of the technical limitations of TED to avoid misinterpretation of displayed data.

**Conclusions**

Transoesophageal Doppler measurements of descending aortic blood flow velocity is a minimally invasive, easy to learn and quick method for continuous trend monitoring of CO. Besides CO, TED measures additional haemodynamic parameters which may aid the intensivist in the assessment of preload, afterload and myocardial contractility. The usefulness of TED to guide volume therapy has been suggested by several studies, however, data supporting its usefulness in guiding vasoactive or inotropic therapy in critically ill patients is lacking. Likewise, the role of TED for replacing more invasive measurement techniques in the ICU still needs to be established. Nevertheless, the existing evidence suggests that TED may be a promising minimally invasive technique for advanced haemodynamic monitoring in critically ill patients and may help to provide safe and effective treatment. The intensivist needs to be aware of the technical limitations and pitfalls so that any misinterpretation of displayed data is avoided.

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