Optimal volaemic status and predicting fluid responsiveness

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Multiple studies have demonstrated the favourable outcome achieved by goal-directed fluid management during the intraoperative period. Maximizing stroke volume by optimal fluid loading during high-risk surgery decreases both the incidence of postoperative complications and length of stay in intensive care.[1]

Haemodynamic monitoring is essential if fluid therapy is to be accurately titrated. It is crucial that optimal volaemic status is achieved, thus preventing the deleterious effects of inadequate tissue blood flow and also the harmful effects of fluid overload. Administration of excess fluid can cause several problems including an increase in demand in cardiac function as a result of extreme shift of the right on the Starling myocardial performance curve. Fluid accumulation in the lungs predisposes to pneumonia and respiratory failure, while other sequelae include inhibition of gastric motility and poor wound healing.

Responders and non-responders

The expected haemodynamic response to volume expansion is an increase in stroke volume and therefore cardiac output. Because the subsequent increase in stroke volume also depends on ventricular function, only a proportion of critically ill patients show a response to volume expansion by a significant increase in stroke volume. When fluid challenges are repeated, a further response may not occur.[2] Accurate assessment of preload responsiveness is therefore an important goal, if the adverse effects of fluid overload are to be avoided.

From the Frank–Starling law of the heart (Fig. 1), an increase in preload will significantly increase stroke volume only if both ventricles are on the ascending portion of the curve. If one or both ventricles lie on the flat portion, then the patient will be regarded as a non-responder; that is, cardiac output will not increase significantly in response to volume expansion.[3]

Cardiopulmonary interactions

Respiratory mechanics are also seen to influence cardiac output. Spontaneous inspiration induces a negative change in intrathoracic pressure causing a decrease in right atrial pressure, so increasing the pressure gradient and encouraging venous return.

Intermittent positive pressure ventilation induces cyclical changes in the loading conditions of the ventricles. The inspiratory increase in pleural pressure reduces right ventricular (RV) preload because of a reduced venous return pressure gradient. There is also an increase in RV afterload related to the increase in transpulmonary pressure. Consequently, RV stroke volume decreases, reaching a minimum at the end of inspiration. The inspiratory reduction in RV ejection leads to a decrease in left ventricular (LV) filling, seen after a delay of two to three beats (the pulmonary transit time). The reduced LV preload results in a decrease in LV stroke volume, which is at its minimum during the expiratory phase.

Assessing volume status and fluid responsiveness in the mechanically ventilated patient

There are many techniques available to assess volaemic status and there is an abundance of literature supporting the use of a wide variety of monitoring modalities, with each modality potentially generating several parameters. In common, however, studies have demonstrated the higher value of dynamic parameters (analysing cardiopulmonary interactions) compared with classic static preload indicators in predicting fluid responsiveness.[2]

Static parameters

Preload measurement, by whatever technique, is still commonly used to guide fluid therapy but can fail to estimate the response to fluids in one half of patients, thus rendering them exposed to the hazards of unnecessary fluid therapy.

Key points

Haemodynamic monitoring is essential in titrating fluid therapy, in order to avoid the deleterious effects of over- and under-filling.

Not all patients will respond to a fluid challenge. Therefore, it is useful to predict fluid responsiveness to identify those patients in whom fluid therapy will be of benefit.

Studies have consistently demonstrated the benefits of using dynamic parameters of filling over static parameters in the mechanically ventilated patient.

No particular dynamic parameter appears to have a greater predicting power over the others, and most are readily available using continuous beat-to-beat cardiac output monitoring.

Predicting fluid responsiveness in the spontaneous breathing patient is more challenging.

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doi:10.1093/bjaceaccp/mkq002 Advance Access publication 25 February, 2010
Continuing Education in Anaesthesia, Critical Care & Pain | Volume 10 Number 2 2010

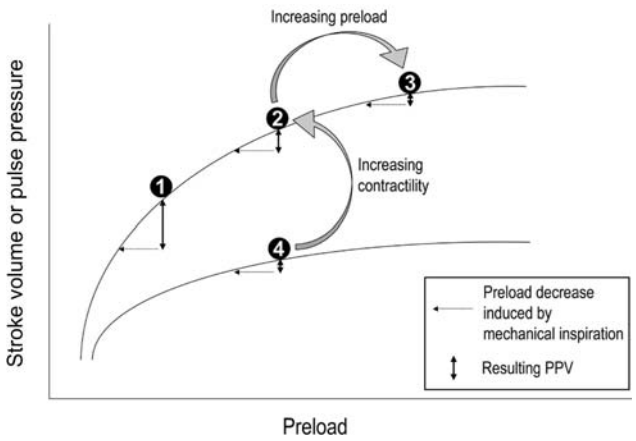

Fig 1 Determinants of PPV and SVV. These variables are markers of the position on the Frank–Starling curve, not indicators of blood volume or markers of cardiac preload. Increasing preload induces a decrease in PPV (from 2 to 3). PPV is minimal when the heart is operating on the plateau of the Frank–Starling curve (3 and 4). Decreasing preload induces an increase in PPV (from 2 to 1), also increasing contractility (from 4 to 2). © Biomed Central. Michard and colleagues. *Crit Care* 2007; **11**: 131, doi:10.1186/cc5905. Image can be downloaded from http://ccforum.com/content/download/figures/cc5905-1.TIFF. Permission to reproduce granted under BioMed Central's general terms.

Central venous pressure and pulmonary artery occlusion pressure

Central venous pressure (CVP) has been traditionally used to guide fluid administration within the operating theatre, but neither CVP nor pulmonary artery occlusion pressure (PAOP) have been shown to be accurate markers of RV and LV end-diastolic volumes, respectively. Similarly, in patients receiving a fluid challenge, changes in CVP and PAOP do not reflect changes in ventricular end-diastolic volumes.[4] This probably reflects non-linear ventricular diastolic compliance and an incomplete knowledge regarding transmural filling pressures. CVP and PAOP cannot therefore define the degree of ventricular filling or the potential response to a fluid challenge. Although pulmonary artery catheters have been much less widely used for this purpose in recent times, CVP remains in widespread use as a marker of preload; indeed, CVP measurement remains a component of the Surviving Sepsis Campaign guidelines. Both these parameters are likely only to be useful in predicting preload responsiveness at the extremes of filling.

RV end-diastolic volume and LV end-diastolic area

RV end-diastolic volume (RVEDV) can be measured by fast-response thermistor pulmonary artery catheter or by cardiac scintigraphy. A response to fluid is likely with an RVEDV index of <90 ml m^{-2} and unlikely with an index of >138 ml m^{-2}, respectively.[5] Static measurement of LV end-diastolic area (LVEDA), measured by transoesophageal echo (TOE), correlates well with LVEDV, and as such has been examined as a parameter of LV preload. Although LVEDA performs well in determining an endpoint for fluid administration, it is less useful in predicting those patients who would benefit from volume expansion. LVEDA correlates better with stroke volume than PAOP does, but neither correlates strongly. Estimation of the LVEDA may not accurately represent LV end-diastolic volume, which in turn relates little to diastolic chamber compliance. LVEDA is limited by underlying cardiac conditions, which may cause dilatation or poor LV systolic function, and there is considerable overlap in baseline LVEDA values in patients who do respond to a fluid challenge and patients who do not.

Global end-diastolic volume and intrathoracic blood volume

Transpulmonary thermodilution using a commercially available device (PiCCO, Pulsion Medical Systems) can be used to assess the global end-diastolic volume (GEDV), the largest volume of blood contained within the four heart chambers, and intrathoracic blood volume (ITBV), which comprises GEDV and pulmonary blood volume. Both parameters are readily available using the PiCCO system and GEDV has been validated as an indicator of cardiac preload. GEDV may also be useful in predicting preload response, but there are insufficient data to support this.

Dynamic parameters

In patients undergoing positive pressure ventilation, heart–lung interactions can be used to reliably identify fluid responsiveness. Most dynamic parameters can be measured using widely available devices for continuous beat-to-beat cardiac output monitoring (Fig. 2).

Stroke volume variation

Stroke volume variation (SVV) is the change in stroke volume during the respiratory cycle, and is calculated by the formula SVV (%) $= (SV_{max} - SV_{min})/SV_{mean}$. SVV can be assessed continuously by any beat-to-beat cardiac output monitor. Many studies have shown this to be a reliable predictor of fluid responsiveness.[6] Despite the clinical importance of threshold values, little information is available in the literature. One study has cited an SVV of 9.5% or more will predict an increase in stroke volume of at least 5% in response to a 100 ml volume load, with a sensitivity of 79% and a specificity of 93%.[7]

Pulse pressure variation

Pulse pressure (difference between systolic and diastolic pressure) is directly proportional to LV stroke volume and inversely related to arterial compliance. The respiratory changes seen in LV stroke volume determine changes in the peripheral pulse pressure during the respiratory cycle.[3]

Pulse pressure variation (PPV) can be expressed as a percentage using the equation PPV (%) $= (PP_{max} - PP_{min})/PP_{mean}$. Measurement of PPV can be used to predict preload non-responders in those with a PPV $<13\%$. Also, high baseline PPV values correlate well with subsequent increase in cardiac index. In addition, the decrease in

LiDCO, Vigileo: Stroke volume variation, systolic pressure variation, pulse pressure variation

PiCCO: Stroke volume variation, global end-diastolic volume, intrathoracic blood volume

Transoesophageal echocardiography: SVC collapsibility index, aortic blood velocity

Transthoracic echocardiography: IVC collapsibility index

Oesophageal Doppler: Stroke volume variation, aortic blood velocity

Fig 2 Examples of dynamic parameters obtainable with various cardiac monitoring modalities.

PPV after fluid therapy correlates well with the resulting increase in cardiac index.[8] As PPV is also subject to arterial compliance, in theory patients with reduced arterial compliance (e.g. elderly patients with peripheral vascular disease), there may be a big change in pulse pressure for only a small change in LV stroke volume.

Systolic pressure variation and Δdown

Systolic pressure variation (SPV) induced by intermittent positive pressure ventilation results from changes in aortic transmural pressure secondary to changes in LV stroke volume, and changes in extramural pressure caused by changes in pleural pressure. For this reason, SPV is a less specific indicator of LV stroke volume and less useful in predicting fluid responsiveness. SPV is the difference between the maximal and minimal values of systolic pressure over a single respiratory cycle and can be divided into two components: Δup and Δdown. These require a reference systolic pressure taken during an end-expiratory pause.

Δdown is the difference between the reference systolic pressure and the minimal value of systolic pressure over a single respiratory cycle. It reflects the expiratory decrease in LV preload and stroke volume related to the inspiratory decrease in RV stroke volume. Δdown appears to be the major component of SPV, and during haemorrhage, its value increases. It predicts fluid responsiveness well because the higher the Δdown value before fluid infusion, the greater the increase in cardiac index post-infusion.[9]

Aortic blood velocity (ΔV_{peak})

Changes in aortic blood velocity have also been proposed to assess fluid responsiveness, as changes in aortic blood flow should reflect changes in LV stroke volume assuming that aortic annulus diameter remains constant over the respiratory cycle. Aortic blood flow can be measured by a pulsed-wave Doppler echocardiography at the level of the aortic valve and ΔV_{peak} is calculated as the difference between the maximal and minimal peak velocity of aortic blood flow over a single respiratory cycle divided by the mean of the two values and expressed as a percentage. A ΔV_{peak} threshold value of 12% discriminates between responders and non-responders.[3] Similarly, ΔV_{peak} is readily measured in the descending aorta using transoesophageal Doppler.

Superior vena cava collapsibility index and inferior vena cava distensibilty index

During positive pressure ventilation, the variation in superior vena cava (SVC) diameter can be used to predict preload response. The SVC diameter can be measured using TOE and the SVC collapsibility index is calculated as (maximum diameter on expiration − minimum diameter on inspiration)/maximum diameter on expiration. In hypovolaemia, the increase in pleural pressure may be sufficient to completely collapse the vessel. An SVC collapsibility index >36% has been shown to predict fluid responsiveness with both excellent sensitivity and specificity. Clearly, this technique is dependent on the availability of the necessary equipment and echocardiography expertise.

Inferior vena cava (IVC) measurement can be obtained by transthoracic echocardiography using a subcostal approach. IVC diameter depends upon the relation between the surrounding pressure, that is, intra-abdominal pressure, and its luminal pressure, that is, right atrial pressure. During positive pressure ventilation, there is, during inflation, an increase in intrathoracic pressure which transmits to the right atrium while only minimally transmitting to the abdomen. The IVC transmural pressure therefore increases leading to an increase in vessel diameter. An IVC distensibilty index (maximal diameter at inflation−minimal diameter at expiration/maximal diameter) above 18% can predict fluid responsiveness.[10] The major limitation of the IVC distensibilty index is clearly intra-abdominal pressure, which is often raised in a number of surgical conditions.

Assessing fluid responsiveness in the spontaneous breathing patient

Most of the available literature, describing the superiority of dynamic parameters over static parameters, has been demonstrated on the sedated and mechanically ventilated patient. Spontaneous breathing is associated with variability in tidal volume, of which SVV and ΔPP are dependent. Also, spontaneous inspiratory effort increases intra-abdominal pressure which could exaggerate the preload response. Passive leg raising can be used in the spontaneous breathing patient, but requires the use of a fast response cardiac output measurement, such as transthoracic echo (measuring velocity time interval at the aortic valve as an index of aortic flow)

as changes in mean arterial pressure cannot be used to predict fluid response during the endogenous fluid challenge of the passive leg raise.

Summary

There are now numerous studies demonstrating the superiority of dynamic parameters over static parameters in predicting fluid responsiveness and the evidence indicates that these dynamic parameters should be utilized when fluid expansion is required in the critically ill. Limitations of these studies include the wide variety of definitions used for 'responder' and 'non-responder', the wide variety of fluid used, and also the speed at which the volume is infused, all of which may influence the perceived haemodynamic response.

The use of the pulmonary artery catheter continues to wane, partly due to its lack of proven mortality benefit and possible risk of serious harm (although many of the associated studies were considered flawed, the use of the PAC has remained much more selective), but there is an increasing demand to provide less invasive methods to determine, not only continuous but also dynamic, cardiac parameters. It may be very difficult to prove that fluid administration guided by these techniques leads to a mortality benefit.

Some of the equipment required to measure the dynamic parameters may not be widely available and some parameters require experience and skill in measurement and interpretation. One must also consider the financial cost of buying and using additional equipment. Monitors, for example, range from roughly £5000–18 000 to purchase, while the disposable components can range from £50–100 per episode. Much of the disposable cost is for calibration of cardiac output measurement. When one considers that the dynamic variables do not require a calibrated measurement to be calculated, the price of calibration disposables can be avoided. In our centre, for example, we use the LiDCO device uncalibrated to determine SVV and PPV and to monitor response in stroke volume when fluid challenges are administered.

Underlying patient pathology may affect the reliability of readings, and training in the use of new equipment must also be carefully implemented. In the absence of a single parameter that consistently and accurately predicts fluid responsiveness, the use of many of these parameters, together with clinical assessment and experience, will enable us to make the best judgements for our patients.

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Please see multiple choice questions 16–18