Dynamic filling index: a novel parameter to monitor circulatory filling during minimized extracorporeal bypass

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Abstract

Objective: To evaluate the dynamic filling index, a novel parameter to monitor changes in venous return and drainable volume, in circulatory assisted patients. Minimized extracorporeal bypass systems lack volume buffering capacity, demanding tight control of drainable volume to maintain bypass flow. Therefore, with patients on minimized bypass quantitative assessment of venous drainable volume is crucial. Methods: In seven patients undergoing coronary artery bypass grafting using minimized extracorporeal bypass we utilized luxation of the heart to induce a reduction in venous return. The speed of the centrifugal pump was transiently and periodically reduced to monitor resultant changes in bypass flow. The dynamic filling index, a measure of drainable volume, was calculated as \( \frac{D_{\text{flow}}}{D_{\text{speed}}} \). Results: With luxation, the dynamic filling index was significantly reduced (from 2.4 ± 0.2 to 2.0 ± 0.2 ml/rotation, \( p = 0.001 \); 95% confidence interval of mean difference: 0.23—0.46 ml/rotation), whereas routinely recorded parameters, like bypass flow, pump inlet and arterial line pressure, did not change significantly. The intra-measurement reproducibility for the dynamic filling index was 0.5 ml/rotation (20% of the mean), suggesting good potential for this parameter to monitor on-pump venous return in patients. Conclusion: The dynamic filling index can detect small changes in venous return and drainable volume which remain unrevealed by routinely recorded parameters. This index could be a valuable tool to monitor and control circulatory filling in individual patients supported by minimized extracorporeal bypass.

Keywords: Minimized extracorporeal bypass; Cardiopulmonary bypass; Blood volume; Venous drainage; Venous return; Centrifugal pump

1. Introduction

Minimized extracorporeal bypass circuits (MEC) can be used for circulatory support in (postcardiotomy) heart failure, during percutaneous interventions, and in respiratory failure [1–4]. MEC are also used for full cardiopulmonary bypass during heart surgery [5], have been reported to reduce preoperative hemodilution and transfusion requirements, and show a lower incidence of postoperative complications [6–9]. Despite the advantages and applications MEC offer, venous return remains a matter of concern. These small circuits lack the buffering capacity of a venous reservoir. As a result, the patient’s venous vascular system functions as reservoir, and bypass flow directly depends on venous return and resultant drainable volume (DV). DV, however, varies with changes in vascular resistance and conditions leading to reduced venous return, like internal hemorrhage, loss of vascular tone, and capillary leakage.

In previous laboratory studies, we found that the relationship between bypass flow and pump speed in a minimized perfusion setup is modulated by venous return and DV [10,11]. \( \text{Fig. 1}\) illustrates the pump flow-pump speed relationship. Bypass flow increases linearly with pump speed if DV is sufficient, but the slope of the curve reduces with decreasing DV. The slope can be characterized by the dynamic filling index (DFI, expressed in ml/rotation) which acts as a marker of circulatory filling.

In the present study, we tested our method to monitor DV using the DFI in patients to obtain proof of principle in actual clinical context. We assessed the reproducibility of the
measurement and its sensitivity to detect changes in venous return in individual patients.

2. Materials and methods

Informed consent was obtained from all patients included. The study was approved by the medical ethical committee of the Maastricht University Medical Center.

2.1. Patients

We used per-operative data of seven patients undergoing MEC-supported coronary artery bypass grafting (CABG). Patient group age, weight, and length were 64 ± 8 years (mean ± SD), 82 ± 14 kg, and 1.73 ± 0.07 m, respectively.

2.2. Methods

During the surgical procedure, the arrested heart is tilted to expose targeted coronary arteries on the posterior aspect of the heart (luxation). It is known that with gross luxation DV is often reduced, as reflected by a decline in bypass flow. After repositioning the heart, bypass flow is normally restored. Heart luxation and repositioning were utilized to induce changes in DV. Care was taken not to obstruct the venous cannula inlet. Fig. 2 illustrates the changes in DV with luxation in venograms obtained by transesophageal echocardiography.

During MEC support, pump speed manipulations are used routinely by the perfusionist to assure proper drainage of bypass flow. To quantify the instantaneous slope of the flow-speed relationship by the DFI (Fig. 1), pump speed was periodically and manually manipulated to create sequences consisting of three consecutive transient speed reductions (−100 rpm), each lasting 10 s, superimposed on the steady state pump speed. Consequently, each DFI measurement sequence took 50 s to perform.

The extracorporeal perfusion circuit comprised a Rotaflow centrifugal pump and Quadrox oxygenator (Maquet MECC Circuit, Maquet Cardiopulmonary AG, Hirrlingen, Germany). A 29 F Opti-Flow cannula (Stöckert, Sorin Group Italia S.r.l., Mirandola Mo, Italy) was used for central venous cannulation. During bypass anesthesia was preserved by propofol (2—4 mg/kg/h, i.v.) and intermittent boluses of sufentanil (0.1 μg/kg, i.v.). Activated clotting time was monitored.
during the procedure and maintained above 480 s. Hemodynamic parameters, i.e. arterial line pressure ($p_{\text{arterial line}}$) and pump inlet pressure ($p_{\text{pump inlet}}$), were measured using the pressure sensors integrated in the pump console (Medtronic Inc., Minneapolis, MN, USA). $p_{\text{pump inlet}}$ was measured 10—20 cm upstream of the pump inlet. $p_{\text{arterial line}}$, which is directly linked to aortic blood pressure [12], was measured just upstream of the arterial line filter. Bypass flow was measured via the electromagnetic flow sensor of the Biomedicus pump console. Measured values for pump speed, bypass flow, $p_{\text{pump inlet}}$, and $p_{\text{arterial line}}$ were acquired continuously by the pump console, and transmitted via direct serial communication link to a PC at an update rate of 1 Hz.

2.3. Data processing and statistical analysis

For both bypass flow and pump speed three samples preceding each speed manipulation (down and up) were taken and averaged by taking the median value (Fig. 3, points A—F). From the averages per point, five DFI values were calculated by dividing the measured change in flow by the induced change in speed ($\Delta$flow/±100 rpm, in ml/rotation). An average DFI value per measurement sequence was calculated by taking the median of the five DFI realizations. Average $p_{\text{arterial line}}$ and $p_{\text{pump inlet}}$ were calculated from the corresponding samples taken at steady state pump speed (A, C, and E) during the DFI measurement sequence.

To obtain a measure for the within-sequence variability for the DFI and the other parameters, we calculated the intra-sequence reproducibility (ISR) over the group. ISR is defined as the standard deviation over all errors of the individual realizations with respect to the average values per sequence. The ISR was determined from 30 measurement sequences.

Depending on preoperative conditions like number of distal anastomoses, or hemodynamic instability during DFI measurement, the number of measurement sequences used to determine the DFI varied from 2 to 7, and was 4 on average for each subject for both positions of the heart (luxation and no luxation). All obtained DFI measurement sequences were included in the analyses.

Data are given as mean ± SD. Differences in hemodynamic and pump-related parameters and the DFI between the luxation and no luxation conditions were compared using a paired Student’s t-test, assuming equal variance (MS Excel 2003, Microsoft Corp., Redmond, WA). All p values below 0.05 were considered statistically significant.

3. Results

The effect of the pump speed manipulations on bypass flow is illustrated in Fig. 4. The figure shows pump speed, bypass flow, the calculated DFI, $p_{\text{pump inlet}}$, and $p_{\text{arterial line}}$, during luxation, no luxation and extreme luxation. During each phase, the DFI measurement sequences are visible as triplets of reduced speed with corresponding changes in bypass flow, $p_{\text{pump inlet}}$, and $p_{\text{arterial line}}$.

During luxation of the heart, the first DFI reads 2.1 ml/rotation with a standard deviation of 1.6 ml/rotation. The subsequent DFI measurement shows considerably lower intra-sequence variability, but a comparable average value.
In the next phase (no luxation) the changes in bypass flow in response to the induced changes in pump speed were larger, resulting in an increased average DFI (2.5 ± 0.4 ml/rotation). The observed difference in variability between no luxation (SD = 0.4 ml/rotation) and luxation (SD = 0.2 ml/rotation) indicates that the observed mean difference (2.5–2.0 = 0.5 ml/rotation) is statistically borderline detectable. The last phase in Fig. 4 (extreme luxation) shows a steeply declined DFI value, indicating significantly reduced drainable volume (p < 0.0001). This impediment of drainage by the MEC system is also evident from a clear reduction in bypass flow (from 4.5 to 2.6 l/min).

<table>
<thead>
<tr>
<th>Table 1</th>
<th>Hemodynamic parameters and DFI during luxation and after repositioning.</th>
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<tbody>
<tr>
<td></td>
<td>No luxation</td>
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<tr>
<td>Bypass flow (l/min)</td>
<td>Mean ± SD</td>
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<tr>
<td>Pump speed (rpm)</td>
<td>3071 ± 142</td>
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<tr>
<td>DFI (ml/rotation)</td>
<td>2.4 ± 0.2</td>
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<tr>
<td>$p_{\text{pump inlet}}$ (mmHg)</td>
<td>–50 ± 11</td>
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<tr>
<td>$p_{\text{ arterial line}}$ (mmHg)</td>
<td>161 ± 14</td>
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</table>

Values represent mean ± SD over seven patients and intra-sequence reproducibility (ISR) averaged over the group. DFI, dynamic filling index; $p_{\text{pump inlet}}$, pump inlet pressure; $p_{\text{ arterial line}}$, Arterial line pressure. *Luxation compared to no luxation; paired Student’s t-test.

In the present study, we demonstrated that pump speed manipulations can be used to obtain an index (DFI) for drainable volume (DV) in MEC-supported patients. The DFI appears to be more sensitive to changes in DV than the direct hemodynamic and pump-related parameters.

In our patients, the DFI revealed a significant reduction in DV during luxation of the heart (Table 1). The severe reduction in the DFI we recorded in one of our subjects (Fig. 4) was the result of substantial cannula obstruction and/or caval vein occlusion with extreme luxation. In a previous study, we showed that such a decrease in the DFI is indicative of insufficient volume available for drainage [11]. The present study demonstrates that even small changes in DV can be detected by DFI measurement. In contrast, bypass flow, $p_{\text{pump inlet}}$, and $p_{\text{ arterial line}}$ did not reveal a change in DV (Table 1).

The measurement of DFI requires manipulations of pump speed of sufficient magnitude and at well-defined time intervals. Theoretically, measurement of the incremental flow-speed ratio ($\Delta q/\Delta \text{speed}$) would enable a comprehensive reconstruction of the flow-speed curve. As our data indicate, however, a certain minimum drop in pump speed is required to induce a detectable change in pump flow. The 100 rpm reduction in pump speed we employed proved to be sufficient to measure DFI in our patient group. Moreover, our sampling method and median averaging effectively suppressed noise in the DFI due to ‘normal’ variability in the measured flow. The DFI measurement currently utilizes 10 s intervals of reduced speed. In our study, bypass flow reached a steady state within the speed manipulation interval. The safety and sensitivity of DFI measurement, as determined by the amplitude and timing parameters, remain to be established in a wider range of clinical MEC applications.

DFI measurement specifically utilizes the direct modulation of drainage flow by pump speed. In any circuit containing a venous reservoir, drainage flow and pump speed are decoupled, rendering DFI measurement unsuitable.

To evaluate the potential of the DFI to monitor changes in DV in individual patients, the variability in single DFI measurements should be smaller than the difference in DFI observed with subsequent measurements. Our results (Table 1) indicate that, in the present setup, DFI cannot discriminate differences smaller than 0.5 ml/rotation (ISR) within individuals. In order to detect changes in DV in an individual patient, those changes need to be at least greater than the ISR as determined in our patients.

We employed manipulations of the heart during coronary bypass surgery in order to modulate DV. Although the effect of luxating the heart created reproducible changes in DFI, we did not obtain in our patients alternative evidence for the absolute changes in DV. In previous studies performed under well-controlled conditions we have demonstrated that the DFI responds straightforwardly to caval vein constriction and changes in transmural pressure at the drainage site [11]. The DFI may also be affected by a change in arterial line pressure. In the present study, however, arterial line pressure did not change significantly. Luxation of the heart may result in cannula obstruction, leading to the obvious reduction in bypass flow. In our experiments we made sure that with luxation the cannula tip was not obstructed. Moreover, a previous study on cannula performance revealed high resistance against inlet obstruction for the cannula used in this study [10]. Therefore, the observed changes in DFI are likely to reflect changes in DV, as induced by limiting venous return.

Other investigators have reported both static and dynamic assessment methods to detect acute drainage impedance and pumping failure [13–18]. The approach in these studies was to characterize pumping conditions for device control purposes, whereas our focus was on patient condition and interaction with the support system. To the best of our knowledge, our study is the first to investigate quantitative assessment of venous return and volume available for drainage in patients supported with MEC. In future studies, we will apply DFI measurements in medium- to long-term MEC supported patients in the intensive care unit, and make a comparative evaluation between the DFI and routinely used methods to assess venous return and patient filling [19].

5. Conclusion

During MEC support venous return, as reflected by the volume that can be drained by the system, can be assessed by...
measuring the dynamic filling index. This parameter could be a valuable tool to monitor circulatory filling in patients supported by minimized extracorporeal circulatory support systems.

References


