Intraoperative hemodynamic monitoring during organ transplantation: what is new?
Giorgio Della Rocca, Anita Brondani and Maria Gabriella Costa

Introduction
A consensus on hemodynamic monitoring during organ transplantation is still lacking, even though this is of crucial importance for the intraoperative management of these interventions. The anesthesiologists in case of markedly severe hemodynamic instability occurring intraoperatively need a reliable monitoring tool as a guidance for fluid, drug, and general management [1,2]. The efforts to reach a wide consensus are limited by local practices, healthcare expenditure limits, and the relatively low number of transplantations that are conducted in small volume centers.

This paper will review the recent developments in research on intraoperative hemodynamic monitoring during liver and lung transplantation.

Intraoperative hemodynamic monitoring during liver transplantation: what is new?
The cardiovascular system in patients with cirrhosis and portal hypertension is abnormal. The circulation becomes hyperdynamic, characterized by increased cardiac output (CO) and decreased peripheral vascular resistance (SVR) and arterial pressure [3,4]. Moreover, despite the increased CO at rest, under stressful situations such as hemorrhage, surgery, or vasoactive drug administration, the ventricular response is blunted, a condition known as cirrhotic cardiomyopathy [3–5]. In addition, liver disease may increase the risk of coronary complications in patients with nonocclusive disease: the coexistence of chronic inflammation, increased blood flow, and high metabolic demand occurring during liver transplantation (LTx) increases the risk of plaque rupture [6,7].

The patients with cirrhosis have a substantially reduced total blood volume index as shown by Henriksen et al. [8], who reported that central blood volume was significantly smaller in patients with cirrhosis than in controls. Because of this relative hypovolemia, adequate volume management during LTx is a cornerstone; moreover, tissue hypoperfusion during surgery has been shown to be a cause of poor outcome [9].

Currently, the pulmonary artery catheter (PAC) represents the most commonly used hemodynamic tool during...
LTx, but transesophageal echocardiography (TEE) is reaching always more diffusion. This is true to the point that both these monitoring systems are, to the state of the art, considered the essential foundation of intraoperative hemodynamic monitoring during LTx [1*,2*]. There is a third emerging monitoring tool in this field: this is represented by the hemodynamic volumetric monitoring through the transpulmonary thermodilution technique [10*,11*] (Table 1: [12–17,18**,19,20*]).

Since the first liver transplant procedure, an extended monitoring including a PAC has been used as a guide for hemodynamic management during anesthesia. It is still widely accepted that the PAC acts as a main character for monitoring the hemodynamic variations occurring during LTx, even though in the last years there has been a tendency toward its reduced use [21]. The lack of evidence of improved outcome with the PAC, the delayed recognition of rapid modifications of CO, the costs of the advanced PACs and the fear for development of complications during insertion, may be all responsible for the decreased implementation of PAC as a standard monitoring [1*,2*,11**,22,23].

The intraoperative estimate of preload is required to guide fluid administration [2*,10*,11**]. Central venous pressure (CVP) and pulmonary arterial occlusion pressure (PAOP), together with end diastolic ventricular volumes are most commonly used to measure right and left loads, respectively. To date, we do not have the evidence that a single monitoring improves the outcome, nor that a single variable should be preferred to some other. What we certainly know is that if we meet a situation of low values, we need something more useful than the common static measures of preload (CVP and PAOP), such as ventricular volumes or areas to lead immediate fluid resuscitation supported by careful monitoring [23].

Even if the superiority of right ventricular end diastolic volume index (RVEDVI) on filling pressures has been demonstrated, the debate on the weight of its limitations on its usefulness is not ceasing [17,18**,24–28]. The geometrical complexity of the right heart is such that the assessment of right ventricular volume remains today a very difficult task. De Simone et al. [19] demonstrated that RVEDVI as determined by thermodilution is larger than the one obtained through echocardiography. Nonetheless, the presence of significant agreement in measuring right ventricular ejection fraction (RVEF) confirmed that these two methods can be reliably used for serial measuring of RVEDVI and right ventricular function during surgery [19]. Other problems burden the clinical applicability of RVEDVI and RVEF: the advanced PAC catheter shows a delayed reactivity to rapid changes in intravascular volume, data might be inaccurate if there occurs poor positioning of the catheter in respect to the tricuspid valve or of the thermistor in relation to the pulmonary valve. Finally, the RVESVI is calculated from stroke volume index (SVI), which, in turn, is derived from cardiac index (CI) measurements: this has raised a lot of concern on mathematical coupling as potential limitation to the use of RVEDVI as a preload index. But the studies...

Table 1 Hemodynamic–volumetric and volumetric parameters and their correlation with different indices, during the intraoperative hemodynamic monitoring

<table>
<thead>
<tr>
<th>Author Year Setting Patients</th>
<th>ITBVI vs. O2/QT</th>
<th>ITBVI vs. CI</th>
<th>ITBVI vs. SVI</th>
<th>COHCCO vs. COPAC (bolus)</th>
<th>COHCCO vs. COPAC (continuous)</th>
<th>RVEDVI vs. CI</th>
<th>RVEDVI vs. SVI</th>
<th>cRVEDVI vs. SVI</th>
<th>RVEF3D-Echo vs. RVEFPAC</th>
<th>RVEDV3D-Echo vs. RVEDVPAC</th>
<th>ΔLVEDAI vs. ΔCI</th>
<th>ΔcRVEDVI vs. ΔCI</th>
</tr>
</thead>
<tbody>
<tr>
<td>Krenn et al. [12] 2000 LTx</td>
<td>0.23</td>
<td>0.37a</td>
<td>0.47a</td>
<td>0.18/lmin (1.59/lmin)b</td>
<td>−0.07/lmin (1.46/lmin)</td>
<td>0.41a</td>
<td>0.68</td>
<td>0.30a</td>
<td>0.93</td>
<td>0.62</td>
<td>0.82a</td>
<td>0.80a</td>
</tr>
<tr>
<td>Della Rocca et al. [13] 2001 LTx</td>
<td>0.37</td>
<td>0.55a</td>
<td>0.55a</td>
<td>0.18/lmin (1.59/lmin)b</td>
<td>−0.07/lmin (1.46/lmin)</td>
<td>0.41a</td>
<td>0.68</td>
<td>0.30a</td>
<td>0.93</td>
<td>0.62</td>
<td>0.82a</td>
<td>0.80a</td>
</tr>
<tr>
<td>Della Rocca et al. [14] 2002 LTx</td>
<td>0.37</td>
<td>0.55a</td>
<td>0.55a</td>
<td>0.18/lmin (1.59/lmin)b</td>
<td>−0.07/lmin (1.46/lmin)</td>
<td>0.41a</td>
<td>0.68</td>
<td>0.30a</td>
<td>0.93</td>
<td>0.62</td>
<td>0.82a</td>
<td>0.80a</td>
</tr>
<tr>
<td>Della Rocca et al. [15] 2002 SLTx/DLTx</td>
<td>0.37</td>
<td>0.55a</td>
<td>0.55a</td>
<td>0.18/lmin (1.59/lmin)b</td>
<td>−0.07/lmin (1.46/lmin)</td>
<td>0.41a</td>
<td>0.68</td>
<td>0.30a</td>
<td>0.93</td>
<td>0.62</td>
<td>0.82a</td>
<td>0.80a</td>
</tr>
<tr>
<td>Della Rocca et al. [16] 2003 SLTx/DLTx</td>
<td>0.37</td>
<td>0.55a</td>
<td>0.55a</td>
<td>0.18/lmin (1.59/lmin)b</td>
<td>−0.07/lmin (1.46/lmin)</td>
<td>0.41a</td>
<td>0.68</td>
<td>0.30a</td>
<td>0.93</td>
<td>0.62</td>
<td>0.82a</td>
<td>0.80a</td>
</tr>
<tr>
<td>De Wolf et al. [17] 1993 LTx</td>
<td>0.41a</td>
<td>0.68</td>
<td>0.85a</td>
<td>0.41a</td>
<td>0.68</td>
<td>0.85</td>
<td>0.30a</td>
<td>0.93</td>
<td>0.62</td>
<td>0.82</td>
<td>0.80a</td>
<td>0.80a</td>
</tr>
<tr>
<td>Della Rocca et al. [18**] 2008 LTx</td>
<td>244</td>
<td>0.41</td>
<td>0.68</td>
<td>0.41a</td>
<td>0.68</td>
<td>0.85</td>
<td>0.30a</td>
<td>0.93</td>
<td>0.62</td>
<td>0.82</td>
<td>0.80a</td>
<td>0.80a</td>
</tr>
<tr>
<td>De Simone et al. [19] 2005 CABG</td>
<td>25</td>
<td>0.68</td>
<td>0.85</td>
<td>0.68</td>
<td>0.85</td>
<td>0.30a</td>
<td>0.93</td>
<td>0.62</td>
<td>0.82</td>
<td>0.80</td>
<td>0.80a</td>
<td>0.80a</td>
</tr>
<tr>
<td>Della Rocca et al. [20*] 2009 LTx</td>
<td>20</td>
<td>0.85</td>
<td>0.85</td>
<td>0.85</td>
<td>0.85</td>
<td>0.30a</td>
<td>0.93</td>
<td>0.62</td>
<td>0.82</td>
<td>0.80</td>
<td>0.80a</td>
<td>0.80a</td>
</tr>
</tbody>
</table>

ΔLVEDAI, variation of the left ventricular end diastolic volume area index; CABG, coronary artery bypass grafting; CI, cardiac index; COHCCO, cardiac index obtained with the single dye transpulmonary indicator technique; COPAC, cardiac output obtained with the pulmonary artery catheter; cRVEDVI, continuous right ventricular end diastolic volume index; DLTx, double lung transplantation; ITBVI, intrathoracic blood volume indexed; LTx, liver transplantation; O2/QT, shunt; RVEDV3D-Echo, right ventricular end diastolic volume obtained with the three-dimensional echocardiography; RVEDVPAC, right ventricular end diastolic volume; RVEFPAC, right ventricular ejection fraction obtained with the three-dimensional echocardiography; RVESVI, right ventricular ejection fraction obtained with the pulmonary artery catheter; SLTx, single lung transplantation; SVI, stroke volume index.

Note: Δ, bias and SD between the two techniques (Bland and Altman analysis).
We designed a study on a population of 20 liver transplanted patients to investigate the relation between SVI and different preload indexes (cRVEDVI, CVP, PAOP, and LVEDAI) [20*]. At multivariate analysis, only cRVEDVI retained statistical significance at the 0.05 level. On the contrary, at multivariate analysis, an increase of 1 cm/m² in LVEDAI leads to an increase of 1.47 ml/m² in SVI (P = 0.054). PAOP and CVP showed a regression coefficient of 0.96 (P = 0.052) and −0.29 (P = 0.51), respectively. The model showing the best fit to the data was the one including cRVEDVI (r² = 0.60) [20*] (Table 1).

Unfortunately, the majority of LTx anesthesiologists are not yet familiar with TEE; this is a matter of course mainly dependent on the high costs of machinery, but also on the fact that TEE equipment might be restricted to other operative rooms, and eventually to a major concern regarding training. We must be aware that training intensivists and anesthesiologist in ‘limited-scope’ TEE could be rapidly and safely managed and could yield information pertinent to management even in the early stages of skill acquisition [31]. However, the American Society of Echocardiography does not distinguish a ‘limited-scope’ training and recommends a training program involving 300 transthoracic echocardiographic examinations, 25 esophageal intubations, and 50 TEE examinations within a 6-month period [36]. These recommendations would restrict significantly the use of TEE during LTx [31].

To date, scientific evidence and common clinical practice state that hemodynamic monitoring during LTx is to be conducted both with PAC and TEE [1*,2*]. It is worth noting that other groups propose the introduction of an intraoperative fluid and drug management based on transpulmonary thermal dye dilution technique.

The hemodynamic status of cirrhotic patients has been analyzed with the hemodynamic–volumetric monitoring to evaluate intravascular blood volume before and after LTx [13]. Using transpulmonary thermodilution techniques, we demonstrated that intrathoracic blood volume indexed (ITBVI) and CI were correlated, whereas filling pressures failed to show any correlation. In that study, we demonstrated that in cirrhotic patients the hyperdynamic circulation coexisted with a hypovolemic status [13]. ITBVI was markedly reduced as the hepatic disease strongly increased the third space.

During the last 10 years, transpulmonary thermodilution monitoring has been playing the role of a unique instrument to measure circulating blood volumes [37] (Table 1). In the study of Krenn et al. [12], patients who underwent LTx were monitored with the double dye transpulmonary thermodilution technique. They observed that a
postreperfusion ITBVI increase influenced pulmonary function, as demonstrated by an increased $Q_{SB}/Q_{T}$ without alteration of extravascular lung water index (EVLWI) or oxygenation impairment [12]. We used the single indicator thermodilution technique to compare the values of each preload variable with the single TPID technique during anesthesia for LTx [14]. In terms of preload data, the main finding of this study showed a good correlation between ITBVI and SVI and CI, whereas no consistent correlation could be established between PAOP and SVI or CI. Significant correlations confirmed ITBVI as a preload index during phases characterized by major hemodynamic changes due to the clamping of the inferior vena cava, unclamping of the anastomoses, and graft reperfusion, bleeding, and surgical manipulations [14].

In recent years, a growing attention has been given to the validation of less invasive monitoring tools in hyperdynamic patients. Yet these monitoring devices do not find a possible field of application for intraoperative monitoring, but testing their quality in such clinical condition is a further step toward their diffusion in high-risk surgical patients or as a first step in monitoring critical illness. We obtained good results with the lithium dilution technique compared with the PAC [38*]. In contrast, needless calibration algorithm of the Vigileo monitor is accurate at low and normal CO, but does not fit the hyperdynamic cirrhotic patients [39*,40,41].

Intraoperative hemodynamic monitoring during lung transplantation

Lung transplantation is a hard scenario: this intervention is often characterized by marked hemodynamic instability during the induction of anesthesia through the pulmonary artery clamping and after the pulmonary reperfusion and ventilation of the newly implanted graft [42,43]. The hemodynamic monitoring plays a cornerstone role. Continuous knowledge of the mean and transpulmonary pressures, pulmonary vascular resistances, preload and afterload indexes, and right and left ventricle functions is mandatory to better manage the cardiorespiratory status [15]. Similarly to what has been previously discussed for LTx, to the present date, a guideline for intraoperative monitoring does not exist, and the single centers act mainly on the basis of local resources and protocols. Together with invasive arterial pressure monitoring, PAC and TEE are widely accepted as essential monitoring tools [42]. Some centers anyway use the advanced PAC technology to get data on right ventricular ejection fraction and right end diastolic volume, the transpulmonary thermodilution technique is implemented too [43,44].

We demonstrated that the ITBVI measured with the single dye thermodilution technique showed a fairly good correlation pressure during intraoperative monitoring of 56 patients undergoing single or double lung transplantation [15] (Table 1). Hemodynamic data were collected in fixed phases: induction of anesthesia, during one lung ventilation and perfusion, after restoring of double lung ventilation and perfusion and at the end of surgery. Throughout the study, no correlation has been found between PAOP and SVI [15]. The transpulmonary monitoring device has also implemented an algorithm for pulse contour analysis to monitor continuously CO. These CO values have been validated by the author in a study on a population of 58 patients who underwent both single and double lung transplantations: even if rapid hemodynamic changes occur, continuous CO data are reliable [16].

Another parameter derived by transpulmonary monitoring is the EVLW. It has been recently demonstrated to be a valuable guide for management of lung donor [45]. In a study designed to evaluate nonhemodynamic management of 60 postbrainstem death cadaveric donors, EVLWI had indeed been used as a therapeutic goal for treatment. EVLWI is a validated index of pulmonary edema and may be elevated before changes in gas exchange, clinical status, or chest roentgenogram [45]. On a univariate analysis, a normal EVLWI, and on a multivariate analysis, a lower variation of EVLWI and a higher baseline PaO2/FiO2 predicted the eventual suitability of lungs for transplantation [45–47].

To date, no studies evaluating RVEF or RVEDV during lung transplantation have been conducted. Moreover, the information given by the CVP and PAOP are burdened by severe limitations such as mechanical ventilation, open chest surgery, and altered heart and thoracic compliance [15]. On the contrary, TEE offers the possibility to directly visualize the heart structures, either left or mainly right function, wall motion abnormalities, right ventricle decompression, and it may be extremely useful in determining the urgent need for cardiopulmonary bypass [43,48].

Conclusion

Intraoperative hemodynamic monitoring during both liver and lung transplantation is mainly based on PAC. The new development in PAC technology gives the opportunity to monitor right heart pressures and preload with variables (namely RVEF and RVEDV) that seem to reflect, better than the ‘historical’ filling pressures, the preload status. As of now, this advanced monitoring has been studied only on LTx population of patients and further studies are needed to validate the applicability of such parameters during lung transplantation.

TEE is receiving a growing attention, given its ability to permit direct visualization of heart structures, shape, and function.
Transpulmonary thermodilution offers the possibility to measure the intrathoracic blood volume as a preload index and EVLW as a lung function status. This monitoring tool is becoming part of the common monitoring setting, even if further studies are needed in larger populations of transplanted patients.

References and recommended reading

Papers of particular interest, published within the annual period of review, have been highlighted as:

• of special interest
•• of outstanding interest

Additional references related to this topic can also be found in the Current Literature section in this issue (p. 318).

1 De Wolf AM. Pulmonary artery catheter: rest in peace? Not just quite yet. . . .
2 De Wolf AM, Aggarwal S. Monitoring preload during liver transplantation.
3 Liu H, Gaskari SA, Lee SS. Cardiac and vascular changes in cirrhosis: RVEDV.

Intraoperative hemodynamic monitoring Della Rocca et al. 295

This study demonstrates on a population of 23 patients undergoing LTx that intermittent and continuous values of CO determined with the lithium dilution technique show a good agreement with intermittent and continuous pulmonary artery thermodilution.


Study on 18 patients after LTx that demonstrates that arterial pulse wave CO measurement has clinically acceptable bias and precision. At higher levels of CO, it underestimates PAC measurement and is not reliable as thermodilution in hyperdynamic patients.


