Replacing the pulmonary artery catheter by less invasive monitoring. Are we ready yet?

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Abstract - The goal of hemodynamic monitoring is to identify cardiovascular pathology, monitor resuscitation and determine when recovery has been achieved. The pulmonary artery catheter (PAC) has been used for over 40 years to accomplish those goals. PAC specific measures include cardiac output, intrathoracic vascular pressures and mixed venous O2 saturation (SvO2). Although newer less invasive devices are now available to monitor specific components of the profile given by the PAC, none can accurately estimate SvO2 or pulmonary arterial or venous pressures (as pulmonary artery occlusion pressure). However, cardiac output can be easily measured by many other devices including arterial wave form monitors and esophageal Doppler catheters and transthoracic echocardiography. To the extent that data useful for diagnosis and/or management can be made by these less invasive means, then the PAC should not be used. But in those settings where accurate measures of SvO2 and pulmonary vascular pressures are needed, the PAC is the only device that can do the job.

Keywords - Hemodynamic monitoring, clinical utility, minimally invasive monitoring, mixed venous oxygen saturation

Introduction
The pulmonary artery catheter (PAC) has been a fundamental hemodynamic monitoring tool in the daily practice of the intensive care units for almost 40 years [1]. During these years, the PAC has been widely used in critically ill patients for diagnostic and therapeutic guidance, and the benefit derived from its use was just assumed. It was difficult to argue that the PAC was not needed when prospective studies documented that bedside estimates of ventricular filling pressures were poor using bedside diagnostic clues [2]. Furthermore, several specific cardiovascular management approaches were developed to use these measured values. However, during the last years, the usefulness of the PAC has been under constant debate [3-5]. Moreover, when outcomes were assessed relative to PAC use, several studies consistently showed that the presence of a PAC did not improve survival of the patients [6-15]. In some of these studies, the presence of a PAC was actually associated with increased mortality [6-9]. In addition, recent technological advances have provided less invasive tools for cardiovascular monitoring, reinforcing the idea that the routine use of the PAC in critically ill patients has passed. However, we have also stressed that the PAC gives uniquely useful hemodynamic data, such as the mixed venous oxygen saturation (SvO2) [16], and when used for this strength may prove useful in guiding resuscitation [17,18]. Nevertheless, the data on the opposite side is quite strong, but is it strong enough to support the disappearance of the PAC?

Rationale for hemodynamic monitoring
If one is discussing whether the PAC is useful or not, one must first understand the meaning and purpose of hemodynamic monitoring. In the critically ill patient, despite the origin of his disease, maintenance of oxygen supply to the tissues is of utmost importance, while a definitive or specific treatment is provided. Circulatory shock can be arbitrarily divided into four broad categories of hypovolemic, cardiogenic, obstructive and distributive shock. Each is treated different and each has a characteristically different set of hemodynamic values, collectively referred to as the hemodynamic profile [19]. This is one of the fundamental principles for diagnosis and management of acutely unstable patients as treated in the critical care or emergency departments. In this regard the PAC seems ideally suited to monitor shock because it measures cardiac output, SvO2 and pulmonary artery occlusion pressure (Ppao), the three defining variables in most shock states.

The fundamental concept of hemodynamic monitoring-derived resuscitation is that the rapid reversal of tissue hypoxia by the correct treatment of the underlying process will improve outcome. In our daily acute care practice, we assume that hemodynamic monitoring is a natural extension of physical examination by quantifying the various aspects of the physical assessment. The type and degree of monitoring should depend on multiple aspects of the patient, such as severity, time-point of disease, and location. Essentially, monitoring is used to identify tissue hypoxia and to determine when tissue wellness has been restored. Critical illness results in a rise in metabolic demand, owing to increased catecholamine release, and the ability of the cardiovascular system to meet this demand and avoid tissue hypoxia correlates with survival [20]. Therefore, based on these arguments: the need to define the etiology of cardiovascular insufficiency and monitoring the response to therapy, the PAC has become a cornerstone monitoring device in the management of the patient in the intensive care unit (ICU).

Hemodynamic monitoring should be helpful in three specific ways:
1. Diagnostic tool: Recognition of specific hemodynamic profiles seen in disease processes.
2. Assessing and monitoring treatment, specifically fluid-responsiveness and vasoactive drug titration.
3. Hemodynamic goals: The goal-directed therapy, based on physiological end-points.

Thus, the indication and uses of hemodynamic monitoring are varied. Once one has identified the need for hemodynamic monitoring, the choice of monitoring tool now emerges. If we are to remove the PAC from our tool kit, we must inquire which might be the reasons for replacing or discarding a tool that has been used over the past years as a gold standard in critically ill patients. There are two potential reasons to discard PAC use: the data acquired from the PAC is not useful in treating the patient, or the same information can be acquired from a less invasive and safer device. We previously published a list of criteria for the use of any hemodynamic monitoring device, which is duplicated in Table 1 [21]. Let us consider these two issues separately.

1. Is the PAC a useless hemodynamic monitoring tool?

From a clinical point of view, it seems reasonable to assert that the PAC provides useful information about the physiological status of the monitored patient, and thus, it should be useful and helpful to achieve a diagnosis, and guide therapy [22]. However, the lack of data proving that the use of PAC improves outcome in critically ill patients has been central in the debate, even though no other monitoring tool has provided that improvement in survival [23,24]. Clearly, no monitoring tool will be capable to improve patient outcome, unless coupled to a treatment that does. Therefore, it is that treatment, and how the tool helps in guiding that treatment, what will be responsible of the benefits regarding patient’s survival [18], and not the tool itself. In fact, the PAC has been overused for many years, and this non-specific use might be responsible, at least in part, for the lack of efficacy pointed out in different studies [25,26].

Some studies have shown that PAC use in goal-directed therapies improves outcome. When resuscitation strategies were driven by PAC-measured hemodynamic variables, such as oxygen delivery (DO₂), cardiac index (CI), or SvO₂ [27-35], survival was increased and hospital length of stay decreased. In surgical patients, for instance, different per-operative and post-operative hemodynamic optimization protocols, driven according to a DO₂ target, have proved to diminish mortality and post-operative complications [27-29,30-34]. Consequently, it seems that the PAC is, in fact, a useful tool, even capable of improving survival when coupled to specific physiologic endpoints in a treatment algorithm. Therefore, the problem of prior association studies of PAC use and outcome might rely on how, when, where, and on which patients the PAC was used. In the recent FACTT study [15] comparing Ppao vs. central venous pressure (CVP) for fluid management strategies, one would not expect to see a beneficial effect of the PAC because neither Ppao nor CVP are reliable measurements of preload-responsiveness, and might be even harmful when used for that purpose [36]. Similarly, one cannot conclude that PAC-guided therapy has no impact on outcome when a considerable part of the treatment group does not achieve the DO₂ endpoint [37]. The PAC has also shown a lack of benefit when used to guide resuscitation in the late stages of medical conditions, once organ failure has already developed [38-41], or when used in populations with low expected mortality rates [41]. Clearly, once organ injury has developed the potential for rapid reversal of organ dysfunction by increasing DO₂ is minimal.

In addition to the debate regarding outcome, the potential complications derived from the catheter insertion were pointed out to strengthen the arguments against the PAC. These complications can be summarized as: insertion-related local complications (hematoma, arterial puncture, pneumothorax), arrhythmias, pulmonary artery rupture, catheter-related infections, and thrombo-embolic events. Various studies have shown that complications derived from PAC are due primarily from a central vascular access placement (42-44). However, PAC use is associated with increased risk of infections (0.7-1.3% incidence of bacteremia) [44-48] and thrombotic complications during prolonged retention (>48 hours), increased risk of arrhythmias during insertion (although with a low incidence of serious arrhythmias, and without influence on patient outcome) [44,47], and very rare pulmonary artery rupture complications. According to these data, PAC insertion should be performed only in those patients in whom the information derived will be used to diagnose and treat existing or potential cardiovascular insufficiency. And PAC insertion should not be avoided because of safety concerns in critically ill and high-risk surgery patients where precise cardiovascular monitoring is needed. Thus, the PAC is a useful tool for monitoring cardiovascular status, and should represent an acceptable risk of complications when used properly in these specific populations.

2. Are there newer less invasive monitoring devices available that can obtain the same data as the PAC?

The PAC provides information on three different variables: intrathoracic intravascular pressures, blood flow measurements (cardiac output), and a tissue perfusion marker (SvO₂). The PAC allows the accurate measurement of these variables, and can monitor them in a continuous fashion. Furthermore, from cardiac output, SvO₂ and pulse oximetry (SpO₂) measures one can readily calculate DO₂ and VO₂. What devices can replace cardiac output, Ppao and SvO₂ measures?


Over the last years, a number of new techniques have developed in the area of cardiovascular monitoring, and the major advances have arrived from the arterial pressure pulse contour analysis.

<table>
<thead>
<tr>
<th>Table 1. Tests for documentation of effectiveness of invasive monitoring</th>
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<tr>
<td>1. Information received from invasive monitoring can not be acquired from less invasive and less risky monitoring systems.</td>
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<td>2. Information received from invasive monitoring allows for improving the accuracy of diagnosis, prognosis, and/or treatment based on known physiological principals.</td>
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<td>3. The changes in diagnosis and/or treatment result in an improved patient outcome (morbidity and mortality).</td>
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<td>4. The changes in diagnosis and/or treatment result in a more effective use of health care resources.</td>
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Several devices use different algorithms to derive continuous flow measurements (CO) from this analysis [48-50]. Currently, the widely available devices are the LIDCO®, the PICCO®, and the FloTrac-Vigileo®. Either, the LIDCO® and the PICCO® require a venous central line, an arterial line and initial calibration (according to the thermodilution principle), whereas the FloTrac-Vigileo® only requires an arterial line to derive the CO, and no initial calibration. Nevertheless, one device, the FloTrac-Vigileo® system, has poor reliability in unstable conditions [51]. In addition to pulse contour analysis, esophageal Doppler monitoring of aortic blood flow has been proposed as a reliable technique to CO [52,53]. And recently, a new device based on chest bioreactance has demonstrated its reliability for measuring CO non-invasively in post-surgical patients [54]. This is a promising technology, although there is a lack of data regarding its reliability in unstable critically ill patients yet. Therefore, today there exist reasonable less invasive to non-invasive alternatives to the PAC in monitoring cardiac output.

2.2. Intrathoracic intravascular pressures measurement.

The properly positioned PAC provides pressures from three different locations: the right atrium (CVP), the pulmonary artery (Ppa), and the pulmonary veins - the so called “wedge”, or occlusion, pressure (Ppao). Since the CVP can be also monitored with a central venous access, we will focus on the pulmonary artery pressure (PAP) and Ppao. Originally, the PAC was developed to allow the measurement of the Ppao, which estimates the pulmonary venous pressure downstream from the alveolar capillary bed. And still today, Ppao remains as the best estimate of the pulmonary venous pressure at the bedside, a useful measurement that has no practical alternative. The main clinical applications of the Ppao are summarized in table 2.

Some of the applications shown in table 2, such as diagnosis of structural cardiac disorders or preload-responsiveness assessment, can be achieved with alternative tools (echocardiography and pulse-contour analysis, respectively). In fact, Ppao displays remarkably poor accuracy in the evaluation of fluid-responsiveness [24]. We do not recommend that one use Ppao values to predict response to fluid resuscitation. Here, variables obtained from the arterial waveform analysis (such as pulse pressure variation) have shown more reliability in predicting preload-responsiveness [36]. However, the Ppao is still the best aid in the diagnosis of the origin of pulmonary hypertension, and the differentiation between cardiogenic and non-cardiogenic pulmonary edema. Measures of Ppao are commonly used to determine the cause of pulmonary edema. It has been stated that Ppao values below 18-20 mm Hg suggest a non-hydrostatic cause, whereas values above 18-20 mm Hg suggest a hydrostatic cause [55]. Nevertheless, these are not hard values, and one can find low values in patients with hydrostatic pulmonary edema if either the Ppao increase had been transient, or if pulmonary capillary pressure exceeds Ppao [56]. Furthermore, increased pleural pressure (hyperinflation, i.e.) can lead to artificially elevated Ppao values in a patient without hydrostatic pulmonary edema, since the Ppao is measured relative to atmospheric pressure [57]. Regarding the application in the differential diagnosis of pulmonary edema, the utility of the PAC is not limited to its diagnostic aid, being also a useful variable in its management. Therefore, the Ppao is a physiological variable not measurable by any other means and useful in the limited cases described above. Thus, to the extent that the accurate diagnosis of pulmonary edema or the management of pulmonary hypertension requires close titration, there is no substitute for the PAC.

2.3. Mixed venous oxygen saturation.

Measurement of SvO2 has been advocated as a reflection of global tissue perfusion. In several diseases, low values of SvO2 have been related to poor prognosis [35,58,59]. Similarly, central venous oxygen saturation (ScvO2) has been proposed as a simple method to assess the adequacy of global tissue perfusion in different clinical scenarios [60,61]. However, whether the ScvO2 mirrors SvO2 has been under constant debate, especially in critically ill patients. Nevertheless, Rivers and coworkers, using ScvO2 to titrate resuscitation efforts in early septic shock, documented an improved outcome [62]. Despite the differences between SvO2 and ScvO2 during shock, various studies have shown that both measurements tend to change in a parallel manner, with higher values of ScvO2 when compared to SvO2 when blood flow distribution is unaltered. If flow to the lower body is reduced, then a proportionally higher flow will go to the upper body, which is sampled by ScvO2. In these settings ScvO2 may be very much higher than SvO2 and give the false impression of perfusion adequacy despite overt shock. Therefore, ScvO2 is a reasonable surrogate of SvO2 in many clinical settings, and during shock states, if used to define a low SvO2 not to determine whether resuscitation goals have been achieved [63,64].

Thus, there are less-invasive reliable alternatives to some of the features that PAC provides, mainly regarding blood flow and SvO2 measurements. However, there is no practical alternative to the Ppao measurement and applications. Therefore, unless specific Ppao values are needed to diagnose disease and guide therapy, the routine use of the PAC cannot be recommended. In these conditions, less invasive monitoring tools should be used. However, one major caveat exists here as well. With the exception of the LIDCO® device

Table 2. Clinical applications of the Ppao

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<thead>
<tr>
<th>1. Diagnosis of cardiovascular disorders</th>
<th>2. Diagnosis and management of pulmonary edema</th>
<th>3. Evaluation of preload and preload-responsiveness</th>
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<td>.by pressure analysis.</td>
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<td>.differentiate pulmonary HT due to increased vascular resistance from pulmonary venous HT (left heart)</td>
<td>.Acute Mitral valve regurgitation.</td>
<td>.Constrictive pericarditis and restrictive cardiomyopathy.</td>
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<td>.Inter-auricular and inter-ventricular communications.</td>
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as a post-operative resuscitation guide [65], none of these less invasive monitoring tools has been shown to improve outcome. The PAC may provide a better understanding of the etiology of disease and closer guide to its management in certain clinical situations where cardiac and intravascular pressures are important, such as cardiac surgery, severe heart failure, or ARDS. Although, its benefit is lost in the DO₂-optimization trials, which can be easily run using the less invasive monitoring tools.

In addition, to examine the ability of new technologies to provide variables obtained from the PAC, we should also consider the capability of these new systems to obtain additional variables, such as pulse pressure variation (PPV), stroke volume variation (SVV), extravascular lung water (EVLW), and intrathoracic blood volume (ITBV). These are extra assets available at the bedside that can be useful in the decision-making process. The value of PPV and SVV obtained from pulse-contour analysis systems to predict preload-responsiveness has been widely proven in several conditions [36], and their use has become essential in the fluid management of critical care patients. Moreover, intra-thoracic volume measurements (EVLW, ITBV) obtained from the thermal-dilution technique (PICCO®) might prove useful in selected clinical conditions, such as EVLW in the fluid management of patients with ARDS [66,67]. However, to date, no studies have documented the utility of EVLW and ITBV measures in the diagnosis or management of critically ill patients.

Conclusions
The fact that the use of the PAC has fallen over the last years [5] does not mean that the information it provides is useless. Although clinical practice needed supporting data from well-designed clinical trials, in the absence of such trials, reliance on physiological principles remains the most common rationale for monitoring and treatment. Not always will there be an algorithm showing the path the clinician has to follow to succeed in his patient management to improve patient outcome. That precise resuscitation algorithms benefit in selected patient groups cannot be extrapolated to the rest of the critically ill population. Often the bedside clinician has to deal with complex patients, and has to decide which degree of cardiovascular monitoring is the best for that particular situation. For those patients, the use of the PAC may be warranted if baseline and changing hemodynamic profile data are needed.

Thus, the PAC is a useful hemodynamic monitoring tool in the care of selected critically ill patients. Its use should be limited to those patients in whom a specific rationale for the information derived form the PAC can be given. There are reliable less-invasive alternatives to the PAC placement in many clinical scenarios. Finally, it is important that the clinician becomes familiar with different monitoring tools, and decides the specific monitoring system for a given patient.

References

17. - Pinsky MR, Vincent JL. Let us use the pulmonary artery catheter correctly and only when we need it. Crit Care Med 2005; 33: 1119-1122.
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