Review

Which cardiac surgical patients can benefit from placement of a pulmonary artery catheter?

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Abstract

The use of pulmonary artery catheters (PACs) during cardiac surgery varies considerably depending on local policy, ranging from use in 5–10% of the patient population to routine application. However, as in other clinical fields, recent years have witnessed a progressive decline in PAC use. One of the reasons for this is probably the increasing use of transoesophageal echocardiography, even though careful analysis of the information provided by PAC and transoesophageal echocardiography indicates that the two tools should be considered subsidiary rather than alternatives. The principal categories of cardiac patients who can benefit from PAC monitoring are those with present and those with possible haemodynamic instability. On this basis we can identify five groups: patients with impaired left ventricular systolic function; those with impaired right ventricular systolic function; those with left ventricular diastolic dysfunction; those with an acute ventricular septal defect; and those with a left ventricular assist device. This review highlights the specific role of PAC-derived haemodynamic data for each category.

Introduction

Placement of a pulmonary artery catheter (PAC) is an intraoperative right heart catheterization procedure. It therefore provides clinical information on heart chamber pressures, blood flows and vascular resistances – similar to the information obtained during a catheterization laboratory investigation before the operation. Unsurprisingly, since the inception of the PAC cardiac pathology has been its natural ‘battlefield’ [1], and cardiac surgery is the natural setting in which is it applied.

By definition, the cardiac surgical patient always has underlying cardiac pathology; such pathology can affect intracardiac pressures and/or myocardial ability to sustain adequate cardiac output. As a consequence of the underlying pathology and/or use of specific drugs, the patient can exhibit changes in systemic and pulmonary resistive state. Moreover, the cardiac surgery itself may result in sudden changes in systolic and diastolic right or left ventricular function, and cardiopulmonary bypass (CPB) may induce release of vasoactive mediators that change flow resistances at the level of the systemic or pulmonary circulation. Finally, the common intraoperative and postoperative use of drugs that act potently on myocardial contractility, and that induce systemic or pulmonary vasodilatation or vasoconstriction permits control of the patient’s haemodynamic profile both during and after the operation.

In spite of this, and for several reasons, PACs are not routinely used in all cardiac surgical institutions or in all cardiac surgical patients. The present review addresses the present situation regarding use of PACs in cardiac surgery, and defines those categories of cardiac surgical patients that may truly benefit from PAC placement.

Use of pulmonary artery catheters in cardiac surgery: the evidence-based approach

In 1997 a consensus conference PACs [2] was convened to address the issue of PAC use in different clinical scenarios. In the setting of cardiac surgery it was agreed that clinical management with PACs does not improve outcome in low-risk cardiac surgical patients (grade C), plays an uncertain role in high-risk patients (grade C), plays an uncertain role in low-risk patients undergoing aortic surgery (grade B), and improves outcomes in high-risk patients undergoing aortic surgery (grade E). These assertions highlight a clinical scenario that has probably changed since the findings of the consensus conference were reported. They nevertheless offer a good starting point; they do not advocate ‘routine’ use of PACs in cardiac surgery but attempt to define the optimal patient selection.

However, the findings of two studies published immediately before [3] and after [4] the consensus conference was held

CABG = coronary artery bypass grafting; CPB = cardiopulmonary bypass; DO2 = oxygen consumption; EF = ejection fraction; LVAD = left ventricular assist device; PAC = pulmonary artery catheter; PAP = pulmonary artery pressure; PCWP = pulmonary capillary wedge pressure; RVEDV = right ventricular end-diastolic volume; \( \text{SvO}_2 \) = mixed venous oxygen saturation; TEE = transoesophageal echocardiography; VSD = ventricular septal defect.
resulted in a different interpretation, based on use of the PAC to assess oxygen-derived haemodynamic variables and to guide goal-directed therapy. In the first of the two studies, Polonen and coworkers [3] demonstrated that prolonged intensive care unit stay following cardiac surgery was associated with an increase in whole body oxygen extraction, reflecting a mismatch between the whole body oxygen demand and supply. In the second study the same authors [4] demonstrated that therapy targeted at optimizing oxygen delivery (DO2) immediately after cardiac surgery reduced the lengths of the stay in the intensive care unit and hospital. Both studies included an unselected patient population, raising doubt that even low-risk cardiac surgical patients could benefit from PAC use.

Despite such findings, many institutions continue to use PACs routinely in cardiac surgical patients. In a survey conducted in 1998 in 30 large cardiac surgical institutions in the USA, Schwann and coworkers [5] found that 67% of programmes included routine use of PACs in coronary artery bypass grafting (CABG). In Europe there is a greater tendency to select patients for PAC use; in our own survey (data available on request) we estimated that, in 2004, about 20% of Italian cardiac surgical institutions were routinely using PACs for cardiac operations, whereas the remaining 80% were following various forms of patient selection. A recent article [6] reported an impressive decrease in PAC use in cardiac surgery in Japan, from 100% in 1997 to less than 10% in 2001.

Therefore, at present one can conclude that the indications for PAC insertion in cardiac surgery vary greatly from country to country and from institution to institution. However, it seems reasonable to conclude that there is a general trend in cardiac surgery, which is reflected by a 9% fall in PAC sales all over the world [7]. This reduction is probably due to recent, highly publicized studies [8-11] that found either no benefit from or even worse outcomes associated with PAC use. Moreover, during the past decade the PAC has had to contend with a strong competitor in the cardiac surgical setting, namely transoesophageal echocardiography (TEE).

The perpetual debate: pulmonary artery catheter versus transoesophageal echocardiography

TEE is currently employed as a monitoring tool and is widely applied during and after cardiac surgery. Two-dimensional TEE provides valuable images of the heart and great vessels, and its roles in assessing valve function, right and left ventricular contractility, and left ventricular diastolic function are well established. By combining the two-dimensional view with a continuous or pulsatile Doppler study, TEE is theoretically able to provide information about cardiac chamber pressures, transvalvular pressure gradients and cardiac output. Table 1 summarizes haemodynamic data with respect to availability and reliability of measurement with PAC and TEE monitoring. Clearly, it is difficult to consider the two tools 'competitors'. Indeed, all data pertaining to pressures, resistances and flows are more reliably determined using a PAC. The only pressure that can be assessed reliably with TEE is the systolic pulmonary pressure (in the presence of tricuspid valve regurgitation). The left atrial pressure may be assessed in the presence of mitral valve regurgitation but with an unacceptable level of approximation. However, in a recent article Diwan and coworkers [12] reported a noninvasive way to determine left ventricular filling pressure in patients with mitral valve disease, using the isovolumetric relaxation time, and the time interval between the onset of early diastolic mitral inflow velocity and annular early diastolic velocity (assessed using tissue Doppler imaging). Furthermore, they demonstrated that the indices obtained with this approach are predictive of pulmonary capillary wedge pressure (PCWP). This very sophisticated technique clearly requires much expertise and technical equipment, and its application is difficult in an intraoperative setting.

In a recent article Oh [13] suggested that echocardiography is a potential ‘noninvasive Swan-Ganz catheter’, indicating that PAC is still the reference technique. One of the most important haemodynamic variables during and after a cardiac operation is the cardiac output. It is feasible to measure this parameter using TEE but it has limitations; the general consensus is that it is strongly operator dependent and less reliable than the thermodilution technique. It has been suggested that cardiac output, as measured using TEE, is better suited to monitoring trends than it is to providing absolute values [14-16].

The PAC is superior in the fields of pressures, flows and resistances, but it is well accepted that TEE provides a good profile of left ventricle size, ejection fraction (EF), fractional area changes and shortening fraction. It is not possible to measure these systolic function indices using a PAC. With respect to the right ventricle, some information is available using TEE and some from the modified volumetric PAC, with both techniques being relatively unreliable because of the peculiar shape of the right ventricle (for TEE) and the technical limitations of thermodilution-based determination of right ventricular EF [17].

Diastolic dysfunction can be diagnosed and graded only using TEE. Fluid responsiveness is better defined by TEE-derived variables (left ventricular end-diastolic area, peak blood velocity variation) [18-21], but some information can be derived from the PAC as well (PCWP and peak pulmonary pressure variation) [22].

Finally, unlike TEE, the PAC allows measurement of mixed venous oxygen saturation (SvO2), and consequently the derived oxygen delivery and consumption variables. These variables...
have a well defined role in assessment of haemodynamic status in patients undergoing cardiac surgery [3,4].

TEE is a valuable monitoring technique both during and after cardiac surgery. However, its limitations are that it is a semiquantitative method and it does not permit continuous monitoring.

At present, cardiac anaesthesiologists’ choice of PAC or TEE monitoring is strongly influenced by their expertise with and availability of TEE. In 2002 a large survey conducted in Canada [23] revealed that use of the PAC remained the preferred monitoring technique among cardiovascular anaesthesiologists.

In conclusion, PAC and TEE are not competitors. Rather, they are subsidiary tools. High-risk patients may benefit from the use of both. My personal feeling is that the more I use TEE, the more I use the PAC.

### Table 1
Haemodynamic data availability and reliability with PAC and TEE

| Parameter                  | PAC  | TEE  |
|----------------------------|------|------|
| SvO₂                      | Yes  | +++  | No  |
| CVP                       | Yes  | +++  | No  |
| PAP                       | Yes  | +++  | Possible if TR ++ |
| LAP (wp)                  | Yes  | ++   | Possible if MR + |
| CO                        | Yes  | +++  | Yes  |
| SV                        | Yes  | +++  | Yes  |
| Systemic resistance       | Yes  | +++  | Yes  |
| Pulmonary resistance      | Yes  | +++  | Yes  |
| RVEDV                     | Yes  | +    | Yes  |
| Right ventricular EF      | Yes  | +    | Yes  |
| LVEDV                     | No   |     | Yes  |
| Left ventricular EF       | No   |     | Yes  |
| Left ventricular FAC      | No   |     | Yes  |
| Left ventricular SF       | No   |     | Yes  |
| Delta SV                  | No   |     | Yes  |
| Delta peak pressure       | Yes (pulmonary) | +++ | No |
| Peak velocity changes     | No   |     | Yes  |
| Valve function            | No   |     | Yes  |
| Fluid responsiveness      | Yes  | +    | Yes  |
| Diastolic function        | No   |     | Yes  |

CO, cardiac output; CVP, central venous pressure; EF, ejection fraction; PAC, fractional area change; LAP, left atrial pressure; LVEDV, left ventricular end-diastolic volume; MR, mitral regurgitation; PAC, pulmonary artery catheter; PAP, pulmonary artery pressure; RVEDV, right ventricular end-diastolic volume; SF, shortening fraction; SV, stroke volume; SvO₂, mixed venous oxygen saturation; TEE, transoesophageal echocardiography; TR, tricuspid regurgitation; wp, wedge pressure.

### Selecting cardiac surgical patients for pulmonary artery catheter placement

If we accept that the PAC should not routinely be used in cardiac surgery (although this is debatable), then selection of patients should be guided by their risk profile. In this regard, the available scoring systems appear to unsuitable. A patient could belong to a high-risk group because of various noncardiac pathologies (diabetes, lung disease, peripheral arteriopathy, neurological dysfunction, and others); these comorbidities do not necessarily represent a good reason to use a PAC. It is preferable that decisions be guided by haemodynamic status, as indicated by conditions such as left ventricular systolic and/or diastolic dysfunction, low output state, need for left ventricular reshaping, right ventricular dysfunction, pulmonary hypertension, need for mechanical circulatory support and mechanical complications of acute myocardial infarction (MI).

In a recent survey Jacka and coworkers [24] investigated the appropriateness of PAC use in cardiac surgery according to
Canadian cardiac anaesthesiologists. Left ventricular impairment was considered an appropriate indication by 74% of the anaesthesiologists, unstable angina by 55%, and the presence of both the previous factors was considered an appropriate indication by 87% of the anaesthesiologists. In the same year, Schwann and coworkers [5] identified six independent predictors for use of PACs in CABG surgery: EF, STS risk score, intra-aortic balloon pump, congestive heart failure, redo surgery and New York Heart Association functional class IV.

It therefore appears generally accepted that a condition involving haemodynamic risk is the best indicator for use of a PAC during cardiac surgery. On this basis, and according to my personal experience, I have identified five categories of patients who may benefit from the intraoperative placement of a PAC.

**Patients with severely depressed left ventricular systolic function**
From a clinical perspective, these patients belong to the group that is identified in many risk scoring systems as ‘preoperative EF <0.30’. This group is becoming larger as the clinical condition of cardiac surgical patients deteriorates. Moreover, in recent years there has been a growing tendency to conduct surgical reshaping of the post-ischaemic dilated left ventricle, which means conducting surgery in patients with an EF of even less than 0.2 [25,26].

Patients with severely depressed left ventricular systolic function usually enter the operating room receiving a cocktail of drugs including diuretics and vasodilators. They often maintain an acceptable perfusion pressure as a result of compensatory peripheral vasconstriction. Once anaesthesia is induced, this delicate balance between myocardial contractility, intravascular filling and peripheral resistance may be disturbed, leading to hypotension. Conversely, the presence of a normal blood pressure does not guarantee adequate cardiac output. In this scenario, the PAC may offer a great deal of clinically relevant information.

**Before establishing cardiopulmonary bypass**
Before CPB is established, data from the PAC may be used to determine the cardiac output of the patient, and to control left ventricular filling pressures (PCWP). PAC data may also be used to control the pulmonary artery pressure (PAP) in order to identify the presence of pre-capillary or post-capillary pulmonary hypertension; if pre-capillary hypertension is excluded, PAP may be used as a continuous indicator of LV filling. The PAC can be used to assess systemic vascular resistance. Finally, it can be used to measure the SvO2 in order to verify the adequacy of DO2 with respect to oxygen consumption.

All this information should be integrated to derive a goal-orientated therapeutic strategy, aimed at maintaining ‘normal’ cardiovascular physiology (i.e. cardiac index >2.4) through use of intravascular fluid filling, inotropes and vasodilators. From this perspective, some indices should be considered the clinical ‘target’ and others should be considered markers of the physiological reserve and of the physiological response to treatment.

**Immediately after cardiopulmonary bypass and during the early postoperative course**
During this period almost invariably these patients need inotropic/vasoactive support and strict control of left ventricular preload. The use of an intra-aortic balloon pump is common, and sometimes a ventricular assist device is needed to wean the patient from CPB. Therefore, all of the considerations during the pre-CPB to ensure that the patient’s haemodynamic profile is optimal remain valid subsequently. In my opinion, particular attention should be directed at intravascular filling; patients with depressed left ventricular systolic function are to the right of the Starling diagram, where the preload-generating force is almost exhausted and where inadequate left ventricular filling may result in low cardiac output or, conversely, excessive filling may provoke pulmonary vascular congestion. Therefore, the fluid responsiveness of the patient should be carefully assessed. Indeed, PCWP has been replaced by echo-derived indices of preload (i.e. left ventricular end-diastolic area) [21], by Doppler-derived indices [18] and certainly by dynamic indices such as peak pressure variation and aortic blood velocity variation [27,28]. However, almost all authors agree that a ‘fluid responder’ is a patient who reacts to a fluid change with a certain increase in stroke volume. It is therefore clear that the best and most reliable marker of fluid responsiveness is a PAC-derived parameter; moreover, despite its relatively low specificity and sensitivity, careful monitoring of PCWP during fluid administration may help in avoiding pulmonary circulation overload.

Finally, one of the most important goals in treating these patients is to optimize their haemodynamics, aiming to match DO2 to oxygen consumption and so avoid lactic acidosis. High levels of blood lactate have been observed during and after cardiac surgery [29,30], and this has been associated with various adverse outcomes. Conversely, a goal-orientated approach, aimed at maintaining high levels of DO2, was associated with a better outcome [4]. Therefore, it may be concluded that, throughout the intraoperative and postoperative course of high-risk cardiac surgery, patients should be afforded constant (possibly continuous with the new generation of PACs) monitoring of SvO2 because it is a useful marker of cardiac output adequacy.

**Patients with impaired right ventricular function**
The PAC is a right-sided heart catheter, and unsurprisingly it offers much clinical information on the right ventricle and pulmonary vascular status. Implemented with a specific algorithm (additionally requiring the heart rate), the
thermodilution principle permits measurement of the right ventricular EF and its derivative right ventricular end-diastolic volume (RVEDV). This ‘volumetric PAC’ is presently available for continuous monitoring. However, this measurement is reliable only in the absence of tricuspid regurgitation [17], and its role and clinical importance are still debated [31-33].

Right ventricular dysfunction is quite common in patients before and after cardiac surgery. Basically, the right ventricle may be affected by previous ischaemic damage or it may develop an acute right ventricular myocardial infarction during or after cardiac surgery. Also, because it is a volumetric pump, the function of the right ventricle may be severely impaired by pulmonary hypertension. Pulmonary hypertension and right ventricular dysfunction following CPB can result in failure to wean from CPB, and acute right ventricular failure can be life threatening [34]. The discrimination between right ventricular failure with and that without pulmonary hypertension is of paramount importance therapeutically; in a recent consensus conference [35] a group of European experts recommended the use of inhaled nitric oxide only in presence of pulmonary hypertension.

In the presence of a low output state resulting from right ventricular failure, during or after cardiac surgery, the most reliable diagnostic tool is of course TEE. However, the PAC is able to quantify the degree of the low cardiac output state and define the pathophysiological scenario (i.e. it can be used to assess PAP and PCWP). Most importantly, however, is that it allows one to follow changes in haemodynamic pattern and to use this information to guide fluid administration and inotropic therapy, and to identify changes in pulmonary pressures resulting from inhaled nitric oxide therapy and/or mechanical ventilatory support.

The most important data obtained from the PAC in this setting are as follows: cardiac output and \( S_{\text{Vo}_2} \), PAP and PCWP, central venous pressure, and right ventricular EF and RVEDV. Cardiac output helps in grading the severity of the patients clinical condition, and \( S_{\text{Vo}_2} \) allows to quantify its adequacy to metabolic needs. PAP and PCWP may be used to identify the presence of pre-capillary or post-capillary pulmonary hypertension and follow the effects of pulmonary vasodilatory therapy. Central venous pressure is an index of right ventricular preload and global venous filling. Finally, right ventricular EF and RVEDV (with the previously mentioned limitations) may be used as indices of right ventricular contractility and preload.

Patients with left ventricular diastolic dysfunction

The diagnosis and grading of diastolic dysfunction are typically within the domain of TEE. However, some valuable and clinically relevant information may be obtained with the use of a PAC. Diastolic dysfunction may be graded based on a combination of Doppler-derived data [36]. The first degree of diastolic dysfunction (impaired relaxation) is usually seen after weaning the patient from CPB, and is often reversible. The second degree (pseudo-normalization) is a more severe condition, which sometimes is an intermediate step toward the third degree (restrictive pattern). In the latter condition the Doppler study is characterized by an increased ratio (>2) between E and A waves of mitral flow, and by a blunted systolic waveform of the pulmonary vein flow. Both of these conditions result from increased left atrial pressure. It has been demonstrated that both mitral flow and pulmonary vein flow indices are correlated with the PCWP. Therefore, measurement of PCWP may be of value in assessing the time course of diastolic dysfunction and the effect of therapeutic manoeuvres.

Among the various pathological features that lead to diastolic dysfunction, a rather interesting pattern is that represented by hypertrophic cardiomyopathy (whether idiopathic or resulting from aortic valve stenosis). In this setting the main problem is supplying the left ventricle with adequate preload; it is quite typical to find an echo-derived low preload (i.e. very low left ventricular end-diastolic area) with a concomitant PAC-derived sign of elevated filling pressures (i.e. high PCWP). Such patients need volume, but every fluid administration should be carefully guided by constant measurement of PCWP, in order to avoid an abrupt increase in pulmonary venous pressure with consequent congestive heart failure.

Acute ventricular septal defect

Acute ventricular septal defect (VSD) is a severe complication of myocardial infarction. When present, it is associated with high mortality rates. Opinions on the correct timing of the repair operation differ, but the only therapeutic option is closure of the VSD, either surgically or by applying specific closing devices in the catheterization laboratory. In both cases, the insertion of a PAC is mandatory; because the rate VSD reopening after both procedures is considerable, the PAC is a potent diagnostic tool. \( S_{\text{Vo}_2} \) is a valuable and rapid marker of left-to-right shunt, and in presence of abnormally high values an echo study may confirm the presence of the shunt.

Left ventricular assist device

A left ventricular assist device (LVAD) may be used in the setting of cardiac surgery, for treatment of refractory postoperative heart failure, or as a bridge to recovery or to transplantation. LVADs unload the left ventricle and decrease left atrial pressure; however, they simultaneously increase right ventricular preload. In this specific pathophysiological situation, LVAD flow is completely sustained by the right ventricle, which is responsible for effective filling of the device. Unfortunately, right ventricular dysfunction that is refractory to conventional pharmacologic therapy occurs in 20–40% of patients supported with a LVAD. The role played by pulmonary resistance is of great importance. If resistances are normal then the LVAD decreases the right ventricular afterload and aids right ventricular function; in the case of pulmonary
hypertension this effect is lost, and the dysfunctional right ventricle is unable to fill the LVAD adequately [35]. Right ventricular failure in patients with LVAD is a severe condition that leads to high rates of mortality [37,38].

I believe that patients with a LVAD may derive particular benefit from PAC monitoring. The most important information in this setting comes from right-sided pressures and volumes: central venous pressure, right ventricular EF and RVEDV are all markers of right ventricular function during left heart assistance; and PAPs are diagnostic of pulmonary vascular resistance status, and may guide the choice of a selective (inhaled nitric oxide) pulmonary vasodilator [35].

**Summary of pulmonary artery catheter derived haemodynamic data**

Table 2 summarizes the usefulness and clinical meaning of the various PAC-derived haemodynamic data in the five categories of patients. There probably are other clinical scenarios in which PAC placement may be considered.
appropriate. For example, many institutions consider PAC placement mandatory for intraoperative monitoring of patients undergoing off-pump CABG surgery. However, as indicated at the start of the present review, cardiac surgery represents a clinical field in which, depending on local policy, PAC use may range from 0–5% of the patient population up to 100%.

Conclusion
Cardiac surgery is probably a clinical field in which we should all agree with Pinsky and Vincent [7]: ‘Let us use the pulmonary artery catheter correctly and only when we need it.’ Of course, the definition of what represents correct use and a correct indication may vary depending on local policy, economic considerations, the patient population and, most of all, the specific expertise of the medical and nursing staff. With regard to the latter, adequate training as to the pathophysiological meaning of this monitoring and diagnostic tool should be given and periodically refreshed so that all of the potential benefits of the PAC can be realized while avoiding potential misuse.

Competing interests
MR has received fees for presenting PAC courses and has received reimbursements from Edwards Lifesciences for participation in meetings.

References
1. Swan HJ, Ganz W, Forrester J, Marcus H, Diamond G, Chonette D: Catheterization of the heart in man with use of a flow-directed balloon-tipped catheter. N Engl J Med 1970, 283:447-451.
2. Anonymous: Pulmonary artery catheter consensus conference. Chicago, Illinois, December 6-8, 1986. New Horiz 1987, 5:175-206.
3. Polonen P, Hippelainen M, Takala R, Ruokonen E, Takala J: Neutrophil counts, cytokines, and the number and activity of tissue and blood monocytes in sepsis: a prospective study. Acta Anaesthesiol Scandinav 1997, 41:911-917.
4. Polonen P, Ruokonen E, Hippelainen M, Poyhonen M, Takala J: A prospective, randomized study of goal-oriented hemodynamic therapy in cardiac surgical patients. Anesth Analg 2000, 90:1052-1059.
5. Schwann TA, Zacharias A, Rioridan CJ, Durham SJ, Engoren M, Habib RH: Safe, highly selective use of pulmonary artery catheters in coronary artery bypass grafting: an objective patient selection method. Ann Thorac Surg 2002, 73:1394-1402.
6. Handa F, Kyo SE, Miyao H: Reduction in the use of pulmonary artery catheter for cardiovascular surgery [in Japanese]. Masui 2003, 52:420-423.
7. 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.
8. Sandham JD, Hull RD, Brant RF, Knox L, Pineo GF, Doig CJ, Laporta DP, Viner S, Passerini L, Devitt H, et al.; Canadian Critical Care Anaesthetic Clinical Trials Group: A randomized, controlled trial of the use of pulmonary-artery catheters in high-risk surgical patients. N Engl J Med 2003, 348:5-14.
9. Rich R, Warszawski J, Anguel N, Deye N, Combes J, Barnoud D, Boulain T, Lefort Y, Fartoukh M, Baud F, et al.; French Pulmonary Artery Catheter Study Group: Early use of the pulmonary artery catheter and outcomes in patients with shock and acute respiratory distress syndrome: a randomized controlled trial. JAMA 2003, 290:2713-2720.
10. Yu DT, Platt R, Lanken PN, Black E, Sands KE, Schwartz JS, Hliber PL, Graman FS, Kahn KL, Snyderman DR, et al.; AMCC Sepsis Project Working Group: Relationship of pulmonary artery catheter use to mortality and resource utilization in patients with severe sepsis. Crit Care Med 2003, 31:2734-2741.
11. Connors AF, Speroff T, Dawson NV, Thomas C, Harrel FE Jr, Wagner D, Desbiens N, Goldman L, Wu AW, Califf RM, et al.: The effectiveness of right heart catheterization in the initial care of critically ill patients. JAMA 1996, 276:889-897.
12. Dwam A, McCulloch M, Lawrie GM, Reardon MJ, Naghree SF: Doppler estimation of left ventricular filling pressures in patients with mitral valve disease. Circulation 2005, 111:3281-3289.
13. Oh JK: Echocardiography as a noninvasive Swan-Ganz catheter. Circulation 2005, 111:3192-3194.
14. Quijones MA, Otto CM, Stoddard M, Wagggoner A, Zoghbi WA: Recommendations for quantification of Doppler echocardiography: a report from the Doppler Quantification Task Force of the Nomenclature and Standards Committee of the American Society of Echocardiography. J Am Soc Echocardiogr 2002, 15:167-184.
15. Leple JL, Murphy GS: Transesophageal echocardiographic monitoring of hemodynamics. Int Anesthesiol Clin 2004, 42:59-81.
16. Costachescu T, Denault A, Guimond JG, Couture P, Carignan S, Sheridan P, Hellou G, Blar L, Normandin L, Babin D, et al.: The hemodynamically unstable patient in the intensive care unit: hemodynamic vs. transesophageal echocardiographic monitoring. Crit Care Med 2002, 30:1214-1223.
17. Spinale FG, Mukherjee R, Tanaka R, Zile MR: The effects of valvular regurgitation on thermodynamic ejection fraction measurements. Chest 1992, 101:723-731.
18. Lattik R, Couture P, Denault AY, Carrier M, Harel F, Taillefer J, Tardif JC: Mitral doppler indices are superior to two-dimensional echocardiographic and hemodynamic variables in predicting responsiveness of cardiac output to a rapid intravenous infusion of colloid. Anesthes Analg 2002, 94:1092-1099.
19. Diebel LN, Wilson RF, Tagett MG, Kline RA: End-diastolic volume: a better indicator of preload in the critically ill. Arch Surg 1992, 127:817-822.
20. DiCorte CJ, Latham P, Greilich PE, Cooley MV, Grayburn PA, Jessen ME: Esophageal doppler monitor determinations of cardiac output and preload during cardiac operations. Ann Thorac Surg 2000, 69:1782-1786.
21. Tousignant CP, Walsh F, Mazer CD: The use of transesophageal echocardiography for preload assessment in critically ill patients. Anesth Analg 2000, 90:351-355.
22. Burhe W, Buhre K, Kazmaier S, Sonntag H, Weyland A: Assessment of cardiac preload by indicator dilution and transesophageal echocardiography. Eur J Anaesthesiol 2001, 18:669-677.
23. Jacka MJ, Cohen MM, To T, Devitt JH, Byrick R: The appropriate- ness of the pulmonary artery catheter in cardiovascular surgery. Can J Anesth 2002, 49:276-282.
24. Dor V, Di Donato M: Ventricular remodeling in coronary artery disease. Curr Opin Cardiol 1997, 12:533-537.
25. Menicanti L, Di Donato M: The Dor procedure: what has changed after fifteen years of clinical practice? J Thorac Cardiovasc Surg 2002, 124:886-890.
26. Michard F, Teboul J-L: Using heart-lung interactions to assess fluid responsiveness during mechanical ventilation. Crit Care 2004, 4:282-289.
27. Michard F, Feissel M, Faller J-P, Teboul J-L, Mangin I, Ruyer O: Respiratory changes in aortic blood velocity as an indicator of fluid responsiveness in ventilated patients with septic shock. Chest 2001, 119:867-873.
28. Demers P, Elkouri S, Martineau R, Couture P, Carignan S: Outcome with high blood lactate levels during cardiopulmonary bypass in adult cardiac operation. Ann Thorac Surg 2000, 70:2082-2086.
29. Maillet JM, Le Besnerais P, Cantonni M, Natal P, Ruffenach A, Lessana A, Brodaty D: Frequency, risk factors, and outcome of hyperlactatemia after cardiac surgery. Chest 2003, 123:1361-1366.
with transesophageal echocardiography and fast-response thermodilution. J Cardiothorac Vasc Anesth 1995, 9:670-675.
32. Yu M, Takiguchi S, Takanishi D, Myers S, McNamara JJ: Evaluation of the clinical usefulness of thermodilution volumetric catheters. Crit Care Med 1995, 23:681-686.
33. Hofer CK, Furrer L, Matter-Ensner S, Maloigne M, Klaghofer R, Genoni M, Zollinger A: Volumetric preload measurement by thermodilution: a comparison with transoesophageal echocardiography. Br J Anaesth 2005, 94:748-755.
34. Riedel B: The pathophysiology and management of perioperative pulmonary hypertension with specific emphasis on the period following cardiac surgery. Int Anesthesiol Clin 1999, 37: 55-79.
35. Germann P, Braschi A, Della Rocca G, Dinh-Xuan AT, Falke K, Frostell C, Gustafsson LE, Hervé P, Jolliet P, Kaisers U, et al.: Inhaled nitric oxide therapy in adults: European expert recommendations. Intensive Care Med 2005, 31:1029-1041.
36. Appleton CP, Hatle LK, Popp RL: Relation of transmitral flow velocity patterns to left ventricular diastolic function: new insights from a combined hemodynamic and Doppler echocardiographic study. J Am Coll Cardiol 1988, 12:426-440.
37. Kavarana MN, Pessin-Minsley MS, Urtecho J, Catanese KA, Flannery M, Oz MC, Naka Y: Right ventricular dysfunction and organ failure in left ventricular assist device recipients: a continuing problem. Ann Thorac Surg 2002, 73:745-750.
38. Helman DN, Oz MC: Developing a comprehensive mechanical support program. J Card Surg 2001, 16:203-208.