Review

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

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Published: 27 November 2006

This article is online at http://ccforum.com/content/10/S3/S6

Critical Care 2006, **10(Suppl 3):**S6 (doi:10.1186/cc4833)

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 echocardiograpy, even though careful analysis of the information provided by PAC and trans-oesophageal echocardiograpy 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; DO_2 = 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; 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 (DO_2) 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 (SvO_2), and consequently the derived oxygen delivery and consumption variables. These variables

Table 1

Haemodynamic data availability and reliability with PAC and TEE

	PAC		TEE	
Parameter	Feasibility	Reliability	Feasibility	Reliability
Sv_{O_2}	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; FAC, 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; Sv_{O_2}, mixed venous oxygen saturation; TEE, transoesophageal echocardiography; TR, tricuspid regurgitation; wp, wedge pressure.

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.

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

345 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 vasoconstriction. 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 $Sv{O_2}$ in order to verify the adequacy of $D{O_2}$ 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 $D{O_2}$ 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 $D{O_2}$, 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 $Sv{O_2}$ 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 Svo_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 Svo_2 allows to quantify its adequacyto 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. Svo_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

Table 2

Clinical meanings and usefulness of various PAC-derived haemodynamic variables in different clinical conditions

Clinical scenario	Useful PAC-derived indices	Clinical meaning/uses
Impaired left ventricular systolic function	CI	Clinical target (i.e. >2.4 l/min per m^2) Monitor effects of inotropic therapy Monitor fluid responsiveness
	PCWP	Left ventricular filling pressure Monitor fluid responsiveness Monitor effects of inotropic/vasodilating therapy
	PAP	Check for the presence of pre-capillary or post-capillary pulmonary hypertension Possible use as continuous index of left ventricular preload
	SVR	Check for the presence of a peripheral vasoconstrictive status
	Svo_2	Monitor the effects of vasodilating therapies Clinical target (i.e. >75%) Check matching of Do_2 to Vo_2 Monitor adequacy of CI Monitor the effects of drug and fluid administration
Impaired right ventricular function	CI	As above
	Svo_2	As above
	PCWP	As above
	CVP	RV preload and venous system filling status Monitor fluid responsiveness
	PVR	Check for the presence of pulmonary hypertension Guide inhaled nitric oxide therapy and ventilator settings
	Right ventricular EF	RV contractility index
	RV EDV	RV preload
Left ventricular diastolic dysfunction	CI	As above
	Svo_2	As above
	PCWP	As above, with particular respect to fluid responsiveness and fluid administration Follow changes from pseudo-normalization to restrictive pattern
Acute ventricular septal defect	CI	Suggestive for VSD reopening after correction if increased
	Svo_2	Diagnostic for VSD reopening after correction if increased
LVAD	CVP	Right ventricular preload and general filling status of the patient
	PVR	Presence of pre-capillary pulmonary hypertension Need for iNO therapy and monitor the effects
	Right ventricular EF	Right ventricular contractility and preload
	RVEDV	
	Svo_2	Adequacy of LVAD flow to the metabolic needs

CI, cardiac index; CVP, central venous pressure; Do_2, oxygen delivery; EF, ejection fraction; LVAD, left ventricular assist device; PAC, pulmonary artery catheter; PAP, pulmonary artery pressure; PCWP, pulmonary capillary wedge pressure; PVR, pulmonary vascular resistances; RVEDV; right ventricle end-diastolic volume; Svo_2, mixed venous oxygen saturation; SVR, systemic vascular resistances; Vo_2, oxygen consumption.

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.

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