Invasive and noninvasive cardiovascular monitoring options for cardiac surgery
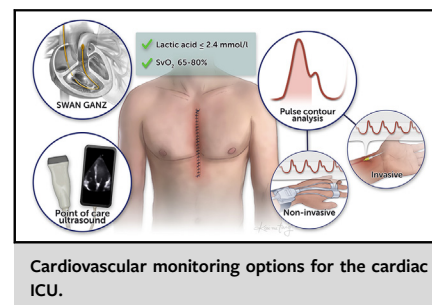
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Cardiovascular monitoring options for the cardiac ICU.

CENTRAL MESSAGE

Pulmonary artery catheters can be used selectively. Novel technology providing minimally or noninvasive monitoring offers alternatives and may enhance recovery after cardiac surgery.

Heart disease is the most common cause of death in the United States, with more than 655,000 deaths in the 2018 Centers for Disease Control and Prevention report. Surgical treatment of heart disease is common, expensive, and greater risk than many other surgical endeavors. Cardiovascular monitoring is an important process within this complex clinical setting that requires careful consideration of the patient and the clinical team, as well as the institutional resources to optimize a precise and personalized approach. A comprehensive evaluation of monitoring must consider patient anatomy and cardiopulmonary physiology, hemodynamic and physiologic goals, the phases of care, direct and indirect costs, and operational considerations such as duration of monitoring, therapeutic protocols, and team expertise. Invasive monitoring is a universally accepted component of cardiac surgical perioperative care, but there remain unresolved controversies as to the optimal monitoring strategies to optimize efficacy and efficiency. One of the long-standing controversies is the use of a pulmonary artery catheter (PAC) versus other monitoring alternatives (Figure 1).

PULMONARY ARTERIAL CATHETERS

PACs, introduced in 1970 by Swan and Ganz,[1] transformed the bedside assessment of hemodynamic monitoring in critically ill and postoperative patients by providing real-time estimation of cardiac output (CO). This is performed by thermodilution or with continuous measurement of mixed venous oxygen saturation. The PAC also enables accurate measurement of the central venous, right ventricular (RV), pulmonary artery, and pulmonary arterial wedge pressures, as well as indirect derivation of several other parameters such as systemic and pulmonary vascular resistance.

PAC use remains common in cardiac surgery, with 68% of respondents in a 2015 survey reporting its use in greater than 75% of cases.[2] However, several studies have failed to demonstrate a survival benefit. In a meta-analysis of 13 randomized clinical trials including 5051 subjects comparing use of a PAC versus nonuse in critically ill patients that included cardiac patients, the use of a PAC did not reduce overall mortality or days in hospital.[3] Other studies of patients undergoing cardiac surgery showed no reduction in morbidity, as well as an increase in mortality, duration of mechanical ventilation, and length of stay (LOS) in the intensive care unit (ICU).[4,5] Hospitalization costs were greater. However, patients receiving PAC were older and more likely to have pulmonary hypertension, chronic obstructive pulmonary disease, obesity, and chronic renal failure.[5] Two recent large observational studies compared patients undergoing cardiac surgery with PAC, matched by propensity score, also showed no impact on mortality or outcomes. A recent publication by Brown and colleagues[6] matched 3519 balanced pairs in a total of 11,820 patients undergoing coronary artery bypass grafting

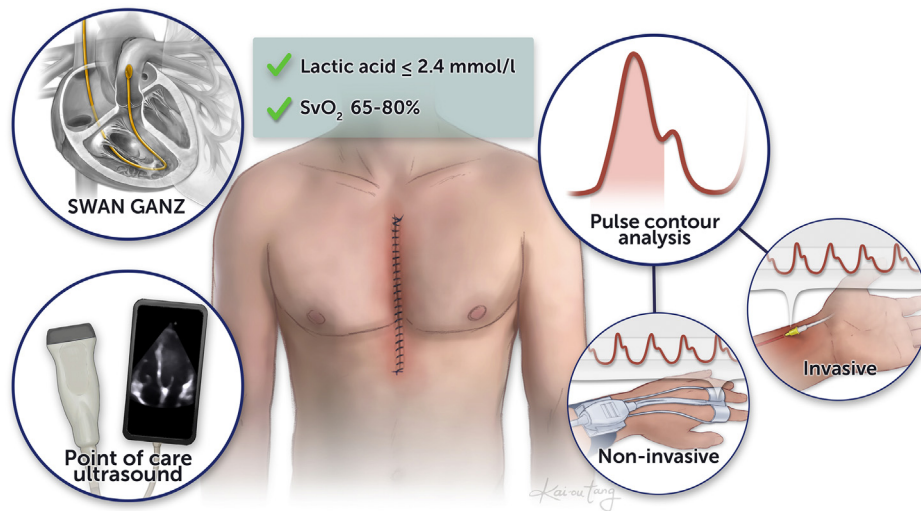https://doi.org/10.1016/j.xjon.2022.02.028

FIGURE 1. Common invasive and noninvasive hemodynamic monitoring options for management in the cardiac intensive care unit. Footnote: Arterial lactic acid is shown in mmol/L. *Right panel*, Invasive and noninvasive pulse contour analysis technology. *Left upper panel*, Swan-Ganz Catheter (Edwards LifeSciences). *Left lower panel*, Handheld point-of-care ultrasound. SvO_2, Central/mixed venous oxygen saturation from centrally placed upper extremity venous access or Swan-Ganz.

(CABG), aortic valve replacement, mitral valve replacement or repair, and a combination of CABG and aortic or mitral surgery. The cohort included urgent and emergent cases, and the study failed to demonstrate a survival benefit or improved outcomes. In addition, patients had prolonged ICU stay (48 vs 39 hours; $P < .001$) and increased transfusions (40.4% vs 35.5%; $P < .001$). A second prospective observational study composed of 5065 patients undergoing CABG in 1273 propensity-matched pairs demonstrated increased risk of all-cause mortality (adjusted odds ratio [AOR], 2.08), severe end-organ complications (cardiac AOR, 1.58; renal AOR, 2.47; cerebral AOR, 2.02), prolonged ICU stay (AOR, 1.55), longer time to extubation ($P < .00001$), and larger positive fluid balance ($P = .003$) with the use of a PAC.[7] Conversely, Shaw and colleagues[8] showed decreased LOS (9.39 days vs 8.56 days; $P < .001$) and cardiopulmonary morbidity ($P < .001$) with a PAC, but no difference in 30-day mortality ($P = .516$).

The current opinion is to use PACs more selectively (Table 1), such as in the evaluation and management of patients in shock; in those undergoing high-risk surgery; or in patients with pulmonary artery hypertension. PAC has been recommended in patients presenting with refractory cardiogenic shock or in patients undergoing acute mechanical circulatory support to monitor effectiveness of therapy, optimize device settings, assess the need for escalation, and guide timing and rate of weaning.[9] Other considerations include patients with a history of RV failure and those undergoing advanced heart failure surgery.[10]

PAC measurement requires familiarity with the device, as frequent inaccuracies can be observed. When compared with the direct Fick method, the PAC may be associated with a percentage error of >50%.[11] In addition, complications include arrhythmia, valvular damage, pulmonary infarction, infection, and thromboembolism. Pulmonary artery perforation is rare but carries a 70% risk of mortality.

TABLE 1. Clinical situations associated with usefulness of PAC in the cardiac ICU

Condition	CVP	RVP	PAP	PVR(I)	PCWP	SVR(I)	CO/CI
Acute cardiogenic shock	↑	↑	↑	↔/↑	↑	↑	↓
Acute vasoplegic (distributive) shock	↔/↓	↔/↓	↔/↓	↔	↓	↓	↔/↑
Acute tamponade (obstructive shock)	↑	↑	↔/↑	↔	↑	↔/↑	↓
Acute hemorrhage (hypovolemic shock)	↓	↓	↓	↔	↓	↔/↑	↓
Acute pulmonary hypertension	↑	↑	↑	↑	↔	↔	↓
Acute ventricular septal defect (VSD)	↑	↑	↑	↔	↔	↑	↓
Right ventricular failure	↑	↑	↔/↓	↔	↔	↔/↑	↓

CVP, Central venous pressure; *RVP*, right ventricular pressure; *PAP*, pulmonary artery pressure; *PVR*, pulmonary vascular resistance; *I*, indexed; *PCWP*, pulmonary capillary wedge pressure; *SVR*, systemic vascular resistance; *CO*, cardiac output; *CI*, cardiac index.

Following the 1996 publication by the SUPPORT (Study to Understand Prognosis on Preferences for Outcomes and Risk of Treatments) investigators that showed an increased 30-day mortality and ICU stay with PAC,* there has been a surge of alternative hemodynamic monitoring devices to replace the PAC with less-invasive methods while capturing the same important physiologic parameters and eliminating PAC-related complications. Pulse contour analysis, ultrasonography, partial carbon dioxide rebreathing, bioimpedance, and pulse-wave transit time (PWTT) are some of the methods that estimate CO (Table 2).[12,13] When evaluating these innovative devices, one must consider that they provide mathematical estimations and extrapolations of hemodynamic values, given their minimally invasive nature. The percentage error (ie, accuracy), derived by the Bland–Altman analysis, is the difference in the measured value (usually CO) from the reference method. A value up to 30% is considered clinically acceptable.[14] The concordance rate (ie, precision) is a surrogate for a device's trending ability with changes in a patient's hemodynamic status compared with the reference method.

ALTERNATIVE TECHNOLOGIES

Pulse Contour Analysis

Pulse contour analysis is by far the most-used and -studied technology for minimally invasive estimation of CO and is derived from the arterial waveform pressure signal using proprietary algorithms to each device. The CO may be derived by pulse contour analysis alone or in conjunction with transpulmonary thermodilution or indicator dilution. Most of these technologies are uncalibrated such that they do not require intermittent alignment, and many are noninvasive. Volume clamp methods typically involving finger cuffs and radial artery applanation tonometry and allow for real-time hemodynamic monitoring without the use of arterial lines. The noninvasive nature of these devices is appealing for monitoring in the era of enhanced recovery after cardiac surgery protocols (Enhanced Recovery After Surgery Cardiac). Numerous small, randomized clinical trials have been published comparing CO measured by bolus thermodilution with commercially available technologies. Invasive pulse contour technologies that use an arterial line have demonstrated percentage errors ranging from 23% to 74% and concordance rates from 84% to 93% compared with thermodilution.[15-21] Noninvasive pulse contour technologies using radial artery applanation tonometry have demonstrated percentage errors ranging from 23% to 58% and concordance rates from 84% to 100% compared with thermodilution.[22-25] In a meta-analysis, not exclusively in cardiac surgery patients, 24 studies compared pulse contour analysis with a reference method and showed a mean percentage error of 41% and precision of 1.22 L/min.[26]

The overall accuracy of pulse contour analysis is clinically significant and devices that integrate this technology may play a role in routine postcardiac surgery care, especially when compared with other minimally invasive hemodynamic monitoring modalities. Their high concordance rate suggests accurate trending ability and can be used at the bedside for titrating medications and measuring acute changes in hemodynamic status. In addition, the recent development of algorithms founded on machine-learning from large intraoperative datasets can assist in detection of sub-optimal hemodynamic parameters prior to the development of hypotension.[27,28] Limitations of arterial pulse contour analysis include aortic regurgitation, arrhythmias, intra-aortic balloon counter-pulsation, hemodynamic instability, and extracorporeal circulation.[16,17] However, newer algorithms have begun to address some of these limitations.

Ultrasonography

Ultrasonography has evolved since the 1970s including 2-dimensional, 3-dimensional/4-dimensional echocardiography, esophageal Doppler, and the ultrasonic cardiac output monitor (USCOM). Esophageal Doppler ultrasonography can estimate CO but can also provide estimates of left ventricular (LV) function, preload, and contractility. A few small observational studies and clinical trials have shown a percentage error of 43%, a high degree of bias, and poor correlation when compared with PAC thermodilution in CABG and/or valve surgery patients.[19,29-31] Given this, and the invasive nature of intubating the esophagus in the ICU, the utility of esophageal Doppler to assess hemodynamic parameters in the postoperative period is limited.

Transthoracic Doppler ultrasonography uses similar technology in a noninvasive manner with probe placement at the supraclavicular, suprasternal or parasternal positions. A meta-analysis of 6 studies found a mean percentage error of 43% compared with thermodilution[32]; however, not all publications included cardiac surgical patients. The USCOM monitor is safe, noninvasive, rapid, and cost-effective. However, operator dependency and poorly estimated valve area are sources of error. Among cardiac surgical patients, USCOM estimations of height-derived aortic and pulmonary valve area showed poor correlation with echocardiographic measurements, and failure to obtain Doppler readings occurred in nearly 25% of patients.[33]

Transesophageal echocardiography (TEE) is the standard of care for intraoperative imaging of valvular repairs and for evaluation of ventricular function, and is often used to evaluate the unstable patient in the ICU who has limited acoustic windows. Continuous monitoring has been made possible with miniature TEE probes (ie, transoral miniaturized hemodynamic TEE) and intensive care providers can be trained to interpret TEE, allowing continuous direct visualization of biventricular function and preload. Anatomic detail, however, requires a formal evaluation by a certified

TABLE 2. Summary of cardiovascular monitoring options

Technology	CO determination	PE and CR, %	Advantages	Limitations	Estimated pricing (USD)
Pulse contour analysis Minimally invasive: pressure recording analytical method (PRAM)*	CO derived from arterial waveform pressure signal.	PE: 23-74 (41) CR: 84-93	• Minimally or noninvasive • Estimates several hemodynamic variables: CO, SV, SVV, SVR • Ease of use	• Unreliable in certain clinical situations • Requires recalibration after acute hemodynamic changes.	Device: $18,000-$20,000 Set up: $290 Service: daily cost $25
Noninvasive pulse contour analysis • Continuous noninvasive cardiac output (CNCO†) • Multibeat analysis (MBA‡) • Radial artery applanation tonometry (RAAT§)		PE: 23-58 (41) CR: 84-100			
Esophageal Doppler‖	CO estimated from shift in Doppler frequency, blood flow velocity in aorta, and nomogram-based patient cross-sectional area.	PE: 43 CR: not reported	• Provide corrected flow time and SVV • Continuous monitoring	• Intubation of the esophagus • Positioning error • Learning curve • Inaccurate in aortic diseases • Population variation (nomogram)	Device: $20,000-$27,000 Individual set up: $190 Service: daily cost $5
Transthoracic Doppler¶	CO derived from SV from blood velocity through the aortic or pulmonary valve, and nomogram-based patient cross-sectional area.	PE: 56-62 CR: not reported	• Noninvasive • Rapid • Cost-effective • Short learning curve	• Operator dependent • Difficult to achieve continuous monitoring • Population variation (nomogram)	Device: $27,000 Setup and service contract not disclosed
TEE#	CO calculated using LVOT diameter and velocity	PE: not reported CR: not reported	• Provides information about preload, afterload, and contractility • Diagnosis of acute conditions • Miniaturized probes for continuous monitoring	• Invasive • Intubation of the esophagus • Expertise (operator)	Device: $70,000 Setup $1250 Service: daily cost not disclosed
Point-of-care TTE**		PE: 25-40 CR: 94	• Training opportunities • Diagnosis • Availability of portable devices.	• Limited data on TTE-derived CO in cardiac surgical patient • Expertise (operator)	Device: $2000-$7000; Set-up $1000 Service: daily cost $0 - $5
Partial CO_2 Rebreathing††	Uses Fick equation to calculate CO from the change in ratio of CO_2	PE: 45 CR: not reported	• Noninvasive • No calibration	• Underestimation of CO under certain mechanical ventilatory settings	Device: $18,500 Setup $215

(Continued)

TABLE 2. Continued

Technology	CO determination	PE and CR, %	Advantages	Limitations	Estimated pricing (USD)
	production and $ETCO_2$ in response to intermittent partial rebreathing.		• Utility in mechanically ventilated patients	• Inaccurate for patients with primary pulmonary pathophysiology • Inability to assess volume and fluid responsiveness • Expertise	Service contract—daily cost $5
Bioimpedance‡‡	Impedance changes from variations in blood resistance to induced current over volume fluctuations of the cardiac cycle. Sensors on endotracheal tube. CO determined by SV and HR	PE: 40-53 CR: 87-99		Requires intubation, invasive	
Bioimpedance/ bioreactance§§	Phase shift between applied current and measure of returning voltage between 4 sensors. Correlated with blood flow. CO determined by SV and HR	PE: 43 CR: not reported	• Noninvasive • Averages signal over 1 minute (arrhythmias) • Predictive of fluid responsiveness • Ease of use • Versatile in different settings	• Influenced by mode of ventilation, fluid, cardiothoracic procedures and conditions, low CO, and electrocautery. • Sensitive to location of electrodes, body size, temperature, and humidity	Device: $20,000 Setup $500; Service: daily cost not disclosed
PWTT‖‖	Time for pulse pressure waveform to propagate between two arterial sites. CO derived from inverse correlation between PWTT and SV.	PE: 41-64 CR: 76	• Uses basic instruments in the ICU: ECG and pulse oximetry • Intuitive • Inexpensive	Decreased concordance with mechanical ventilation	

CO, Cardiac output; *PE*, percentage error expressed as range and (mean) (%); *CR*, concordance rate, expressed as range (%); *USD*, US dollars; *SV*, stroke volume; *SVV*, stroke volume variation; *SVR*, systemic vascular resistance; *LVOT*, left ventricular outflow tract; *CO₂*, carbon dioxide; *ETCO₂*, end-tidal carbon dioxide; *HR*, heart rate; *ICU*, intensive care unit; *ECG*, electrocardiogram. *Examples of devices include FloTrac/Vigileo (Edwards Lifesciences); LiDCOrapid and PulseCO (LiDCO Group Plc); MostCare (Vygon Health); ProAQT/Pulsioflex (Getinge). †Examples of devices include CNAP system (CNSystems Medizintechnik GmbH); ClearSight (Edwards Lifesciences). ‡An example of a device includes Argos (Retia Medical). §An example of a device includes T-line 200 pro (Tensys Medical Inc). ‖Examples of device include CardioQ (Deltex Medical); HemoSonic (Arrow International). ¶An example of device includes: USCOM (USCOM Ltd). #*TEE*, Transesophageal echocardiography. An example of a miniaturized device includes the hTEE probe (ImaCor Inc). **TTE*, Transthoracic echocardiography. Examples of devices include the Butterfly iQ (Butterfly Network Inc); Lumify (Philips); and Vscan (GE Healthcare). ††An example of a device includes NICO monitor (Novametrix Medical Systems). ‡‡An example of a device includes ECOM (ECOM Medical Inc). §§An example of a device includes NICOM (Cheetah Medical). ‖‖*PWTT*, pulse-wave transit time. An example of a device includes esCCO (Nihon Kohden).

echocardiographer and this mode of monitoring is invasive, and is better suited for complex patients requiring mechanical ventilation postoperatively.[34]

In medical ICUs, transthoracic echocardiography (TTE) has shown great utility in the diagnosis of structural heart defects, evaluation of postoperative hypotension, or in the investigation of strokes. TTE estimation of CO in surgical patients, but not after cardiac surgery, was found to have a percentage error of 40% compared with PAC.[35] Accuracy is limited by the inability to measure the LV outflow tract diameter. In mechanically ventilated patients in the ICU, TTE had a lower percentage error: 25%, and a concordance rate of 94% when compared with thermodilution-estimated CO,[36] but serial examinations are labor intensive and impractical. However, with the advent point of care or handheld ultrasound, clinicians can evaluate an acute problem in a time sensitive fashion at the bedside. This is particularly helpful in the context of heart failure, shock, cardiac arrest, and tamponade and to evaluate biventricular function and volume status in the context of respiratory failure and sepsis. Newer technology uses mobile application-based technology. Furthermore, artificial intelligence and telerobotic addition to point-of-care technology may optimize acquisition and interpretation of data. Further studies are needed to evaluate the benefits and accuracy of handheld ultrasound in monitoring of cardiac surgical patients.

Less-Common Alternatives

Partial carbon dioxide rebreathing technique studies were mostly performed in the early 2000s. Noninvasive cardiac output monitor was used for determination of CO in sedated, mechanically ventilated subjects following elective cardiac surgery with excellent accuracy (bias of 0.050 L/min) when compared with other studies involving simulation of pulmonary pathophysiology.[37] The mean percentage error from thermodilution-estimated CO of the method is 45%.[26] However, noninvasive cardiac output monitor requires specialized equipment and familiarity with the system, and low tidal volumes, low minute ventilation, and spontaneous breathing are limiting factors.[38,39]

Bioimpedance systems are based on the principle that the electrical resistance of blood changes with movement and fluctuations in volume. In patients undergoing elective cardiac surgery, the endotracheal cardiac output monitor system has shown percentage errors of 40% to 53% and concordance rates of 87% to 100% when compared with thermodilution reference methods.[23,40,41] In a meta-analysis, 13 studies conducted with postsurgical and critically ill subjects resulted in a mean percentage error of 43% for transthoracic electrical bioimpedance devices.[26] This system is influenced by mode of ventilation, thoracic fluid content, movement, arrhythmias, low flow states, and electrocautery.

PWTT integrates data from basic instruments (eg, electrocardiogram and pulse oximetry) to estimate continuous cardiac output with percentage error ranges between 41% and 64% and concordance rates of 76% when compared with thermodilution measured intra- and postoperatively after cardiac surgery.[42,43] PWTT systems are noninvasive, easily interpreted, and relatively inexpensive. However, different ventilatory settings and maneuvers tend to decrease concordance rates.[44]

Surrogates of CO

Assuring adequate end organ perfusion after cardiac surgery through maintenance of appropriate hemodynamic goals is essential for optimizing postoperative outcomes, and perfusion markers such as blood arterial lactate and central venous oxygen saturation may serve as important tools in the guidance of cardiothoracic critical care management. In a prospective randomized clinic trial of 502 patients,[45] arterial lactate levels >3 mmol/L at 6 hours after ICU admission were an independent risk factor for major complications including acute kidney injury, cardiogenic shock, acute respiratory lung disease, and mortality in adult patients after cardiac surgery. Lactate is also a strong predictor of mortality during extracorporeal life support after failure to wean from cardiopulmonary bypass following surgery[46] but is nonspecific: tissue hypoxia (eg, sepsis, compartment syndrome, hepatic insufficiency, mesenteric ischemia) as well as nonhypoxic causes (eg, hypothermia, drug therapy) can lead to lactate elevation. Central venous oxygen saturation is another commonly used marker of adequate cardiocirculatory function and both low (<60%) and "supranormal" (>80%) results are associated with increased in-hospital mortality, 3-year mortality, postoperative hemodialysis, and prolonged hospital LOS in the context of cardiac surgery.[47,48] Such variables to monitor hemodynamic parameters are best used in addition to other monitoring strategies and adjustments must be weighed against the confidence in which the clinician places in their understanding of the patient's pathophysiologic presentation.

SUMMARY

Until recently, PACs have been used routinely in cardiovascular critical care in a large proportion of centers surveyed[2] despite evidence demonstrating a lack of clinical benefit in routine cardiac surgery. This may be attributed to ICU models and staffing, and the perceived high reliability of the data. Overtreatment has been demonstrated in many studies using PACs, with negative impact on mechanical ventilation time, fluid balance, postoperative transfusions, ICU LOS, complications, and mortality. A majority of elective cardiac surgical procedures can be performed without a PAC, however; complex multivalve operations, heart failure surgery, heart transplantation, and emergent

presentation with shock may warrant invasive monitoring with a PAC.

Introducing new technologies or a change in practice requires a clinical champion and a commitment to staff education. Alternative noninvasive monitoring strategies described herein, in conjunction with biomarkers, provide excellent surrogates to clinicians. Recent interest in enhanced recovery after cardiac surgery and value-based care may shift the care paradigm. Selective PAC and reducing duration of invasive lines while maintaining monitoring capacity, may accelerate mobilization, prevent excessive fluid administration, transfusions, and accrued ICU postoperative morbidity. A shift to noninvasive miniaturized novel technology could allow patients to be monitored in more adapted ward setting to continue optimizing their recovery. In addition, predictive analytics, technological advancements in robotics, as well as and machine learning algorithms have improved image acquisition, and may further aid clinicians in the interpretation of data, as they get more sophisticated. Finally, improved communication systems and critical care staffing models with virtual support from experts evaluated during the coronavirus disease 2019 pandemic,[49,50] are examples of innovation in perioperative care systems and give us an opportunity to reconsider our relationship with technology.

Conflict of Interest Statement
The authors reported no conflicts of interest.

The *Journal* policy requires editors and reviewers to disclose conflicts of interest and to decline handling or reviewing manuscripts for which they may have a conflict of interest. The editors and reviewers of this article have no conflicts of interest.

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