Review Article

Monitoring during paediatric cardiac anaesthesia

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Monitoring of paediatric anaesthesia has become increasingly more complex in recent years and this is particulary true of cardiac anaesthesia. The purpose of this review is to give a comprehensive update of published material related to both routine and specialized cardiac monitoring. Routine monitoring can be particularly affected by the alterations of cardiac rhythm, blood flow, cardiac output and oxygenation which result from the congenital heart abnormalities themselves, the type of surgery undertaken and the effects of cardiopulmonary bypass. The use of specialized monitoring is becoming more widespread, particularly in the areas of cerebral function, mixed venous oxygenation, cardiac output measurement and coagulation. In the last five years, with the development of smaller probes, a great deal has been published on transoesophageal echocardiography. The use of the current monitors of cerebral function still remains controversial despite the need for a monitor of adequate brain perfusion, reflecting the need for a great deal of further research in this area. This review will concentrate on particular areas which have seen the most profound changes and on monitoring that may form the standards of tomorrow. Finally, amongst all the technology, it should not be forgotten that the most important clinical monitor is the bedside clinical monitoring of the physicians themselves.

Depuis quelques années, le monitorage de l'anesthésie pédiatrique devient de plus en plus complexe et tout particulièrement en anesthésie cardiaque. L'objectif de ce travail consiste à passer en revue la littérature actuelle qui traite du monitorage usuel et spécialisé. Le monitorage usuel peut être influencé par les modifications de la fréquence cardiaque, du courant sanguin, du débit cardiaque et de l'oxygénation provoqués par les anomalies cardiaques congénitales, du type de chirurgie et des retentissements de la circulation extracorporelle. L'utilisation du monitorage spécialisé est de plus en plus répandu et concerne particulièrement la circulation cérébrale, l'oxygénation du sang veineux mêlé, la mesure du débit cardiaque et la coagulation. Au cours des cinq dernières années, le développement de sondes plus petites a généré de nombreuses publications sur l'échocardiographie transoesophagienne. L'utilisation des moniteurs actuels de la fonction cérébrale demeure sujet à controverse bien qu'un moniteur de perfusion cérébrale adéquat demeure toujours aussi essentiel, confirmant ainsi le besoin de recherches supplémentaires sur ce sujet. Ce survol se portera spécialement sur les champs d'activités qui ont connu les changements les plus profonds et sur le monitorage qui établira les standards du futur. Finalement, au milieu de cette technologie, il ne faut jamais oublier que le moniteur clinique le plus important se trouve au chevet du malade en la personne du médecin.

Key words

ANAESTHESIA: paediatric, cardiac;
MONITORING: blood pressure, carbon dioxide, cardiac output, coagulation, echocardiography, electrocardiography, electroencehalography, neuromuscular function, oxygen, temperature, venous pressure.

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Conclusions

There have been considerable advances in the monitoring of the paediatric patient in recent years. Changes in basic paediatric monitoring have been made and the Canadian Anaesthetists' Society standards require pulse oximetry, blood pressure measurement, electrocardiogram (ECG), capnography when the trachea is intubated, temperature measurement and a stethoscope (precordial, oesophageal or paratracheal). Specialized monitoring includes the monitoring of mixed venous oxygenation saturation ($S\bar{v}O_2$) which is being increasingly used within the critical care area. Transoesophageal echocardiography (TOE) has become accepted in adult cardiac surgery particularly in the fields of mitral valve repair and aortic root surgery, where it allows immediate assessment of the adequacy of repair. The place of TOE in congenital heart disease is now becoming more clearly defined. Cerebral function monitoring is an area of a great deal of research and several new monitoring methods are under review. The use of the thromboelastogram in monitoring coagulation has been found to decrease blood and fluid replacement during liver transplantation and its use during cardiac surgery is increasing. Other end organs that are affected by cardiopulmonary bypass (CPB) include the gut, liver and immune system, possibly leading to multi-organ failure in some cases, and interest is being shown in their monitoring.

The purpose of this review is to present the recent publications relating to specific areas of both standard and specialized monitoring and indicate areas where these monitors may prove particularly useful to the practitioner involved in the care of paediatric cardiac patients.

Routine monitoring

Electrocardiogram

The ECG displays the electrical activity of the heart. Abnormalities in the ECG can reflect alterations in rate or rhythm and changes in the ST segment may incidate underlying ischaemia. The normal ECG in childhood changes with age and shows several differences from the adult, particularly in the first few years of life where the right ventrical mass is dominant. There are several general changes that occur with increasing age (Table I). Heart rate (HR), frontal plane QRS vector (axis), PR interval, R wave heights and T waves are some of the factors that alter with age (Table II) and the reader is referred to a more specialized review for further information.[1,2]

TABLE I General changes of the ECG with increasing age

The heart rate decreases.
All the intervals and durations (PR interval, QRS duration, QT interval) increase.
The right ventricular dominance of the infant is replaced by the left ventricular dominance of the adult.
The T wave vector is anterior in the newborn. During childhood it is intermediate and by eight to ten years it starts to move anterior again.

In adult cardiac surgery there has been investigation of perioperative myocardial ischaemia, its prognosis, and the best way of detecting it.[3,4] In children, however, there has been little work looking at the ST segment. Bell *et al.*[5] reported three cases of ST changes in neonates consistent with myocardial ischaemia. The first case involved a child of 26 wk who developed ST changes during awake laryngoscopy and lung retraction that were presumed to be related to myocardial hypoxia, although pulse oximetry readings were not mentioned. In the second case, ST changes improved on starting trinitroglycerine, isoproterenol and dopamine and in the third were related to echocardiographic changes. Cherian and Rao[6] associate the ST segment with the adequacy of coronary blood flow during the arterial switch operation for transposition. Observing leads I and V_5 for the left coronary and lead II for the right, greater than 1 mm elevation for more than five minutes after cross-clamp release was said to indicate ischaemia. In one of their six patients persistent ST elevation in lead II was reversed by revising the right coronary anastomosis.

Perioperative arrhythmias have also been investigated. In one study, analyses of atrial ECGs obtained from temporary bipolar atrial epicardial electrodes were compared with single-lead ECGs interpreted by five paediatric cardiologists in 20 children after post-cardiac surgery.[7] Sinus rhythm was correctly interpreted in all, whereas atrioventricular conduction disturbances and narrow QRS tachycardias were identified correctly only 77% and 14% of the time, respectively. More of a concern was that those rhythms incorrectly interpreted, 89% received active therapeutic intervention (DC cardioversion or antiarrhythmic drug) indicating that where intervention is considered, single-lead surface ECG is inadequate.

The Fontan operation, where the right atrium is connected to the main pulmonary artery, leads to an increase in systemic venous pressure, and predisposes to supraventricular arrhythmias. These may lead to severe hypotension by causing an increase in pulmonary venous atrial pressure in a circulation which lacks a right-sided ventricle. The consequence of these arrhythmias and their predisposing factors have been analysed retrospectively by Gewillig *et al.*[8] Eleven patients (10.6%) developed peri-

TABLE II Summary of changes in the normal ECG with age

	*Heart rate**	*Axis in degrees†*	*PR interval (sec)‡*	*QRS duration (sec)§*	*Precordial leads (V_{1-6})*	*T waves*
Newborn	110–160	+30– +180 (+125)	0.07–0.14 (0.11)	0.05 (0.065)	Dominant Right ventricle. Tall R $V_{1,2}$. Deep S $V_{5,6}$. Pure R V_1<10 mm suggests RVH. Often reversal of adult RS progression	Low voltage. Inverted in $V_{1,2}$. V_1 can be upright for 3 days; after this suggests RVH
1 wk–1 mo	105–180	+65–+165 (+110)	0.07–0.14 (0.10)	0.05 (0.065)	Still dominant R in $V_{1,2}$. In V_6 S may >R	Increased voltage. inverted $V_{1,2}$
1–6 mo	105–185	+10–+110 (+70)	0.07–0.15 (0.10)	0.05 (0.07)	R wave still dominant V_1 but not V_2	Still inverted $V_{1,2}$
6 mo–3 yr	90–165	+5–+105 (+55)	0.07–0.16 (0.11)	0.055 (0.07)	R/S ratio V_1 can be <1. R dominant V_6	Still inverted $V_{1,2}$
3–8 yr	65–140	+5–+130 (+60)	0.09–0.16 (0.12)	0.07 (0.08)	Adult R/S progression is the rule	Still inverted V_1
8–16 hr	60–120	0–+90 (+60)	0.09–0.18 (0.14)	0.07 (0.09)	Adult QRS shape and R/S progression	Upright V_1. However, V_{1-4} can be inverted
Adult	60–100	0–+100 (+50)	0.12–0.2 (0.16)	0.08 (0.10)	Left ventricle dominant with adult R/S progression	Usually upright including V_1

*Range in beats · min^{-1}. †Range (mean). ‡PR interval varies with heart rate. §Average (upper limit).

operative tachycardias which, despite intensive medical treatment, were fatal in ten. Eight of these patients developed atrial flutter which was associated with preoperative raised mean pulmonary artery pressure and low aortic saturation, perhaps indicating that in those patients with severe lung hypoperfusion alternative strategies (e.g., shunts) should be considered. Three patients developed His bundle tachycardia but no predisposing factors could be found.

Pulse oximetry

This monitor measures the pulse rate and the level of oxygenated to deoxygenated haemoglobin in the blood in the form of a percentage using plethysmography and spectrophotometric analysis. Light at two different wavelengths (red and near infrared) are used to differentiate oxygenated and deoxygenated haemoglobin by shining them through peripheral arterial beds. As the arterial haemoglobin saturation changes, the ratio of the two wavelengths of light transmitted to a photodetector will change relative to each other. The ratio of oxyhaemoglobin to reduced haemoglobin plus oxyhaemoglobin is then calculated and displayed as the arterial haemoglobin oxygen saturation (SpO_2). The pulse oximeter utilizes a plethysmographic waveform to differentiate the pulsatile "arterial" saturation from the non-pulsatile "venous" saturation. The amplitude of the detected light is altered by the pulsatile waveform and the absence of pulsatile flow limits the ability to calculate the SpO_2.

The SpO_2 measured by the pulse oximeter is different from the arterial saturation detected by a laboratory co-oximeter (SaO_2). The co-oximeter uses multiple wavelengths of light to detect other types of haemoglobin, e.g., carboxy- and methaemoglobin. Foetal and methaemoglobin cause little variation in the accuracy of pulse oximetry compared with a co-oximeter. However, carboxyhaemoglobin from carbon monoxide is measured as oxyhaemoglobin and a co-oximeter measurement is essential.[9] It should also be remembered that pulse oximeters are calibrated from normal adults breathing hypoxic mixtures and not children and that at readings <70% they become increasingly inaccurate.[9]

In a large study of children the sensitivity of detecting desaturation episodes was greater with pulse oximetry than by clinical acumen particularly in infants.[10] Important considerations for the cardiac anaesthetist include the cold vasoconstriction and small pulse pressure seen after CPB which often precludes accurate estimations of arterial saturation (SpO_2).[11] In two studies the Biox 3700 was examined. When ten paediatric patients were cooled to 25°C, the SpO_2 was overestimated between 30° and 36°C and underestimated below 30°C compared with si-

multaneous co-oximeter readings.[12] However, a separate group found a correlation coefficient of 0.88 between simultaneous measurements of SpO_2 and co-oximeter readings which was not affected by low core temperature and when the pulse oximeter and ECG heart rate coincided, the SpO_2 reading was within $\pm 5\%$ ($P < 0.05$).[13]

Centrally placed monitors on the tongue and cheek have been shown to increase the accuracy of SpO_2 to SaO_2 during cooling[14,15] and also to detect desaturation and resaturation earlier than those placed peripherally.[16]

In cyanotic congenital heart disease where saturation can be $<80\%$, pulse oximetry overestimates the value by $5.8\% \pm 4.8\%$ (bias $\pm$ precision) compared with the co-oximeter.[17] A further study also revealed overestimation of SpO_2 to SaO_2 in children with a variety of severe congenital heart conditions, $88\% \pm 10\%$ compared with $84\% \pm 10\%$ respectively.[18]

Another potential area of inaccuracy is the influence of severe tricuspid regurgitation which tended to decrease the SpO_2 value from $+2\%$ to -11% compared with the SaO_2.[19] The reason for this discrepancy was postulated to be due to the pulse oximeter interpreting venous pulsations as arterial.

It should not be forgotten that a decreased vascular volume can lead to intermittent and eventual loss of SpO_2 readings. This can be particularly useful in neonates and small children, when a sudden change in SpO_2 may give an early sign of hypovolaemia before a decrease in blood pressure.[20] A further study in 50 neonates revealed that loss of the oximeter wave form on the extremity where a blood pressure cuff was gradually inflated gave a far better correlation with invasive systolic BP ($r^2 = 0.95$) than the Dinamap (Critikon, Tampa, FL) ($r^2 = 0.55$).[21]

One important complication of a burn to a foot suffered by a neonate due to a faulty probe should be mentioned.[22] As a precaution, if there is lack of correlation between the ECG and pulse oximeter HR the application site should be checked.

Other causes of unreliability include probe position, motion artifact, ambient light, electrocautery, skin pigmentation and nail polish.[23]

A particular use of the pulse oximeter is during pulmonary artery banding when desaturation of the pulse oximeter can be used as a guide to the tightness of the band and give early warning if it is too tight.[24]

Capnography

The partial pressure of carbon dioxide (CO_2) in the expired gases is measured by infrared light absorbance, Raman spectrography, mass spectrography, or rarely by photoacoustic spectrography. The details of these processes are described elsewhere.[25] Briefly, in the most popular method of infrared light absorbance, CO_2 specifically absorbs infrared light of certain wavelengths and the amount of light absorbed is proportional to the amount of CO_2. The expired gases can be sampled and the absorbance of the infrared light by CO_2 can be plotted as a wave form or capnogram. Raman spectrography relies on Raman scattering signals obtained from molecules of gas which have been subjected to an argon laser and has the advantage that all gases and vapours, including inhalational agents, can be measured. Mass spectrography uses a magnetic field to separate ions by charge and photoacoustic spectrography uses infrared absorbance but then measures it by an acoustic method which is claimed to increase accuracy.

The relationship between the partial pressure of end-tidal carbon dioxide ($PETCO_2$) and the partial pressure of carbon dioxide in arterial blood ($PaCO_2$) is dependent on several factors including pulmonary blood flow, cardiac output and particularly the ventilation to perfusion match within the lungs. Therefore during cardiac surgery, there are many situations which may cause inaccuracy due to changes in these factors as well as alterations in temperature, and the effects of CPB.[26] A recent study of congenital heart disease revealed that cyanotic heart disease caused considerable unreliability.[27] Unlike other occasions in paediatric anaesthesia, where $PETCO_2$ gives a good guide to $PaCO_2$,[25] in patients with congenital heart disease (particularly cyanotic) and during cardiac surgery the $PETCO_2$ can only be used as an indication of $PaCO_2$ and to recognize gross changes such as disconnection of the breathing circuit or air embolus. Pulmonary artery banding and systemic-to-pulmonary shunts also cause decreases in $PETCO_2$.[28] Arterial blood gases are drawn frequently during cardiac surgery and the difference between $PaCO_2$ and $PETCO_2$ can be regularly assessed. Ongoing studies to design miniaturized intraarterial fibreoptic sensors (at the moment only capable of going through a 20-gauge catheter) which will give continuous real-time monitoring of pH, $PaCO_2$, and PaO_2 are particularly interesting.[29,30]

The principle of capnography can also be used to measure nitrous oxide and the other anaesthetic gases by the measurement of the absorbance of infrared light at other specific wavelengths.

Temperature monitoring

There is no ideal site for temperature monitoring of the paediatric patient.[31] (Figure 1). During cardiac surgery accurate central temperature monitoring is essential when brain protection is provided by cooling during CPB. Hypothermia reduces the metabolic rate of the brain exponentially and is the most effective means of protecting the brain from CPB or total circulatory arrest-induced injury.[32] Peripheral (extremity) temperature monitoring is

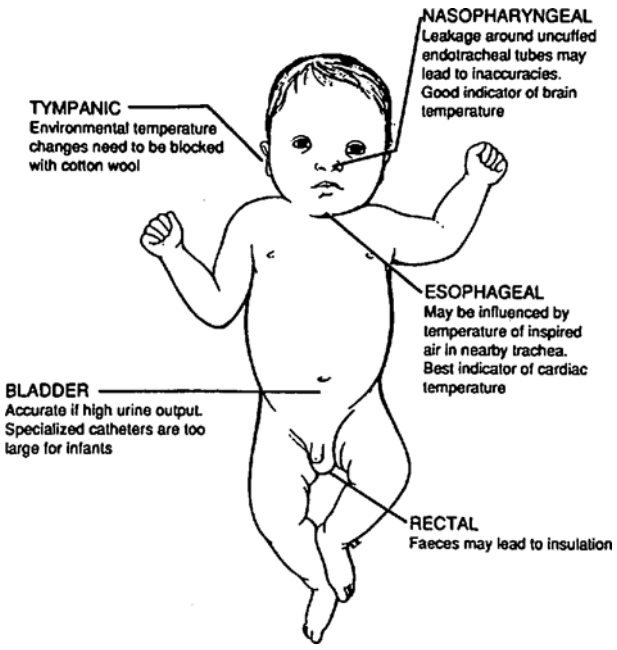

FIGURE 1 Sites for central temperature monitoring.

also measured occasionally as a guide to post-bypass perfusion.

Reports vary as to the incidence of temporary and permanent neuropsychiatric complications following hypothermic CPB with or without circulatory arrest although some studies put it as high as 25%.[33] Inadequate cerebral cooling has been proposed as a cause and recently attempts at measuring jugular venous bulb saturation (SjO_2) as an indicator of cerebral oxygen uptake and therefore of cerebral metabolism ($CMRO_2$) have been performed. If cerebral cooling is inadequate cerebral oxygen extraction will be increased leading to a low SjO_2. Kern *et al.*[34] found SjO_2 levels in six of 17 patients less than one year old had a lower level (87.1% ± 6.3% versus 98.1% ± 0.9%) at a tympanic membrane temperature of 15°C. These six patients also had a SaO_2 to SjO_2 difference of 11.4% ± 6.9%, compared with 0.3% ± 0.4% in the other 11 patients, and were said to show desaturation. These patients could not be predicted by continuous measurement of on-line tympanic and rectal temperature or mixed venous oxygen saturation during periods of stable haemodynamic, $PETCO_2$, SaO_2, CPB and anaesthetic levels. These results suggest that these patients had higher $CMRO_2$ and that a low SjO_2 may indicate inadequate brain cooling. None of these patients had gross neurological deficits and formalized neuropsychiatric tests were not performed. Support for the concept of inadequate cerebral cooling comes from Foster *et al.*[35] who measured jugular venous bulb temperatures (Jvt) as an indicator of the temperature of blood perfusing the brain and found that at normal pump flows the Jvt paralleled arterial, nasopharyngeal and tympanic temperatures. However, at low flows (<50 ml · kg^{-1} · min^{-1}), whilst arterial and nasopharyngeal temperatures remained constant, the Jvt continued to increase indicating that currently used methods of assessing temperature may not adequately reflect the brain temperature. Kern *et al.*[36] have also shown that the rate and method of cooling during CPB may alter the efficiency of brain cooling and decrease in $CMRO_2$. In their study a group of children who were rapidly cooled to 15°C by setting the water temperature of the heat exchanger to 4–5°C were compared with a group cooled to a temperature of 18°C over 20 min and they had SjO_2's of 86.2% ± 12% and 98% ± 0.9% ($P < 0.01$) respectively. Prolonged cooling for 20 min led to complete $CMRO_2$ suppression but there was still delayed recovery of $CMRO_2$ on reversal of cirulatory arrest, indicating that further protective measures are needed.[37] (For further information see jugular venous saturation in Monitoring of the Brain.) Further aspects of the physiology of thermoregulation and the effects of anaesthesia in the paediatric patient are discussed elsewhere.[38]

Stethoscopes

Precordial and oesophageal stethoscopes are still extremely useful monitors. The heart sounds may become distant with the decreased cardiac output of hypovolaemia or deep anaesthesia. Intramyocardial air can be detected by the characteristic "machinery" heart murmur. Combined oesophageal stethoscopes with temperature probes are particularly useful in paediatric cardiac surgery. An ECG electrode has also been combined with an oesophageal stethoscope to aid in the diagnosis of dysrhythmias. During surgery, stethoscopes can become an essential monitor when other more sophisticated monitors become displaced.

Urine output

Urine output is measured routinely during CPB. The production of 0.5 ml · kg^{-1} · hr^{-1} of urine is used as a simple way of monitoring adequate renal perfusion. However, urine output can also be influenced by glycosuria and drugs such as diuretics and mannitol. Large amounts of dilute urine are produced in "high output" renal failure. In oliguria, the specific gravity and concentration of urea and electrolytes in urine can help differentiate pre-renal from renal and obstructive causes, providing diuretics have not been given.

Neuromuscular function

Neuromuscular function is often poorly monitored during

cardiac surgery. This is because large doses of opioids are used in combination with ED_{95} doses of muscle relaxants and patients are usually transferred to the ICU with their lungs ventilated. However, closer monitoring of neuromuscular function is needed for those patients whose neuromuscular blockade will be reversed and their tracheas extubated at the end of surgery. These operations would include closed heart operations, and in some centres patients after uneventful atrial secundum defect repairs. Close monitoring of the onset of muscle relaxation, prior to intubation of the trachea, is desirable to avoid undue laryngeal stimulation which could precipitate ischaemia, dysrhythmias, or a pulmonary hypertensive crisis. No specific type of neuromuscular monitor is required for cardiac surgery.

Arterial pressure

This can be measured invasively or noninvasively. The commonest noninvasive methods are by use of the Doppler method or by oscillometry. The Doppler method relies on a probe (see Cardiac Output for more detail) being placed over an artery to record flow and its cessation due to inflating a proximal blood pressure (BP) cuff. This method can be performed manually or by an automated machine. The oscillometric method is an automatic blood pressure cuff, for example the Dinamap (Critikon, Tampa, FL), which relies on two pressure indicators, one for cuff pressure and one for the amplitude of pulsations. The accuracy of both methods relies on the correct size cuff (occupying two-thirds of the upper arm) being used. A study by Gravlee *et al.*[39] found a mean and standard deviation differences of −6 and 8 mmHg compared with direct mean brachial arterial pressure. Unfortunately the Dinamap fails to detect the BP when there is low BP, low cardiac output or tachycardias making it unreliable in unstable patients.

INVASIVE MONITORING

In the case of open heart surgery, where continuous BP monitoring and multiple blood samples are required, an artery is cannulated and a pressure transducer converts the pressure signal generated to an electrical waveform. Special care is needed during assembly to avoid the introduction of microorganisms (which could lead to sepsis) or air bubbles which would lead to inaccuracies in measurement (damping).

Dangers of invasive monitoring include: vascular compromise and thrombosis (which in its severest form can lead to amputation),[40] disconnection, accidental injection, infection and damage to nearby nerves.[41] Therefore, noninvasive measurements by the methods just described are often used in closed heart operations in children. The radial artery is routinely used for cannulation. Some authors state that the radial arteries should be assessed and a modified Allen's test performed for adequacy of ulnar circulation.[42] However, the need to perform the test has been challenged in recent years by a lack of ischaemia in arteries cannulated, despite a negative test.[43,44]

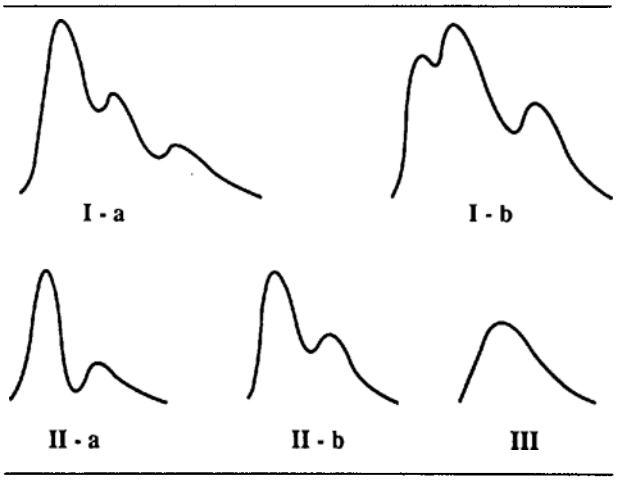

FIGURE 2 Classification of radial artery pressure wave contours. (Reproduced with permission from *Nomoto et al.*: Hemodynamic assessment of radial-arterial pressure-wave contours in children. Thorac Cardiovasc Surg 1991; 39: 349–52.)

A system of classification of the radial artery pressure-wave contours has been analyzed in 45 children undergoing open heart surgery.[45] Stroke volume and systemic vascular resistance (SVR) were calculated from the cardiac output (CO) obtained by thermodilution. The radial artery pressure-wave contours were classified into types I, II and III with each wave having three, two and one shoulder respectively (Figure 2). Type I had a higher CO with a lower HR and larger stroke volume (SV) than type II. Type III occurred with low cardiac output. The second waves of types I (the percussion wave) and II (the dicrotic notch) can also be used to indicate the SVR: higher SVR caused the second wave of type I to be greater than the first (Type I-b) and the dicrotic notch of type II to be greater than half of the first wave (Type II-b). Therefore, a decrease in SV resulted in Type I becoming Type II and a decrease in SVR resulted in a change from "b" to "a" and vice versa. The authors claim that, in combination with thermodilution, a continuous assessment could be made of SVR and SV and alert clinicians to haemodynamic changes at an early stage. It should also not be forgotten that an aortic-to-radial pressure gradient may develop and the radial pressure, although usually within 5 mmHg of aortic, may be considerably decreased.[46]

Finally, in coarctation of the aorta the left arm should not be used for blood pressure monitoring, including radial artery cannulation, as the left subclavian artery may

be involved in the coarctation or in its subsequent repair.

Alternative sites for arterial cannulation include femoral, brachial, axillary, umbilical and dorsalis pedis. Complications of these sites are again of ischaemia, infection and thrombosis.[47,48] The femoral artery can be easier than the radial to cannulate but may cause problems in the event of femoral bypass. In the study of Glenski *et al.*,[49] femoral artery cannulation had no increase in sepsis and perfusion-related complications compared with radial cannulation in infants and children. However, in neonates, the perfusion-related complications were considerably higher and may have exceeded those from cannulation of the radial artery. A study of axillary artery monitoring in 16 patients found no complications.[50] The artery was cannulated by palpating the artery with the arm flexed to 90° and the palm under the head and then use of the Seldinger technique. An umbilical artery catheter may be inserted shortly after birth and provide excellent monitoring and assess in the neonatal period. Athough the dorsalis pedis artery is absent in about 5% of children cannulation appears to be reasonably safe but may overestimate aortic pressure by 5 mmHg on average.[51]

Central venous pressure

A central venous line is often required not only for measuring central venous pressure (CVP) but also for the rapid administration of fluids and drugs and for the infusion of irritant inotropic drugs. Central venous pressure can be used as a monitor of right heart filling pressure and blood volume status. The classical wave form of the CVP with prominent "a" and "v" waves when related to the ECG can also be used to diagnose cardiac abnormalities, especially when timed with an ECG tracing. The normal CVP tracing has three waves and two descents (Figure 3). The "a" wave is caused by atrial contraction, and the "x" descent is caused initially by right atrial relaxation and then by the descent of the floor of the right atrium during ventricular systole. The relatively small "c" wave is generated within the right atrium as right ventricular isovolumetric contraction displaces the tricuspid valve leaflets upwards. The "v" wave was designated as it starts during ventricular systole and is generated by passive filling of the right atrium against a closed tricuspid valve. The "y" descent represents the ending of the "v" wave by the sudden opening of the tricuspid valve, following right ventricular relaxation and the right atrial pressure decreases. The "a" wave is absent in atrial fibrillation or nodal rhythms, and has increased prominence in conditions where the atrium is contracting against increased pressure such as tricuspid stenosis, pulmonary stenosis or acute or chronic pulmonary hypertension (Figure 4). The "v" wave is prominent in tricuspid regurgitation,

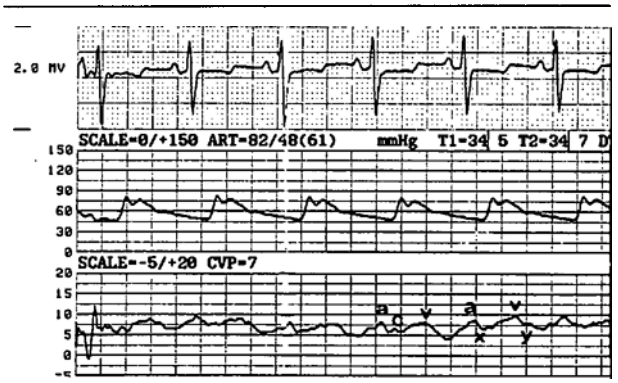

FIGURE 3 Recordings of simultaneous ECG, radial artery pressure and CVP at 25 mm · sec^{-1}. Example of a normal CVP tracing with "a," "c" and "v" waves, and "x" and "y" descents.

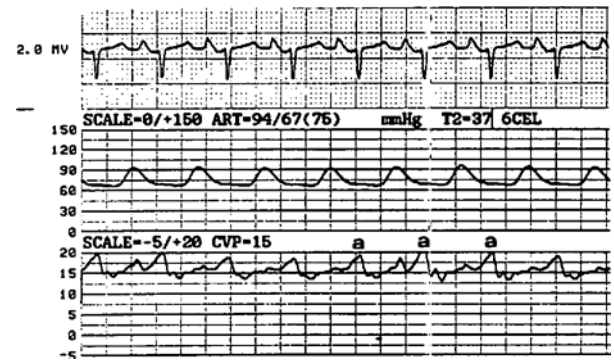

FIGURE 4 Prominent "a" waves in a patient with pulmonary hypertension.

constrictive pericarditis or cardiac tamponade. Differentiation of the "a" and "v" waves can be made clinically by timing them with the carotid pulse when the "v" waves should coincide, whilst the "a" waves are just before the carotid pulse. More accurately they can be differentiated by a simultaneous ECG recording when "a" waves occur just after the P wave and "v" just after the QRS complex.[52] The waveform can also be useful in helping to differentiate nodal from sinus tachycardia by looking at the "a" wave position (Figures 5 and 6). If a sinus beat can be captured with a pacemaker and the waveform changes then the rhythm cannot be sinus.

INTERNAL JUGULAR VEIN

In most centres measurement of the CVP is usually achieved by cannulating the internal jugular vein. This is because of its high success rate of up to 97%.[53-55] The right side is usually preferred, as it runs a straighter course to the superior vena cava, and the left may be connected to a left superior vena cava which could be tied off during surgery.

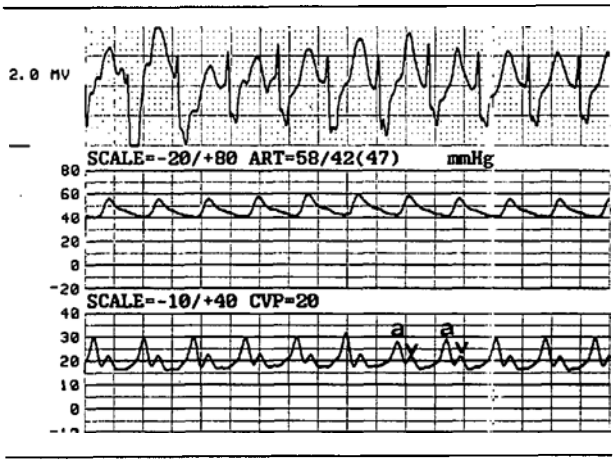

FIGURE 5 Tachycardia and hypotension in the same patient as Figure 4. The regular "a" and "v" waves confirm this as a sinus tachycardia which was confirmed on an oesophageal ECG and corrected with volume replacement.

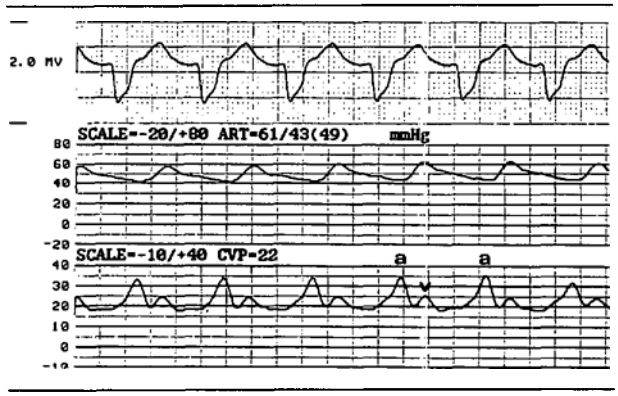

FIGURE 6 Recording of Figure 5 at 50 mm · sec^{-1} showing the timing of waveforms more clearly.

There are several complications of internal jugular vein cannulation (Table III).

In children there seems to be a far higher chance of puncturing the carotid artery (11–15%)[55,56] than in adults and therefore, particularly in cyanosed patients, transduction of the pressure prior to dilatation is recommended. Recent methods to try to decrease these complications include pre-insertion ultrasound. Ultrasound guidance of the anatomy of the internal jugular vein reduced time and decreased the number of needle passes and complications in a trial of 40 infants and neonates.[64] Ultrasound also revealed that in 59% of patients the internal jugular vein lay directly anterior to the common carotid artery, leading to persistent failure to cannulate the vessel when approaching from lateral to the artery.[65] A recent report examined the factors influencing successful cannulation of the internal jugular vein in infants

TABLE III Complications of internal vein cannulation

Haematoma[55,56]
Puncture and cannulation of carotid artery[55,56]
Pneumothorax[56]
Haemothorax[56]
Thoracic duct injury (on left)
Venous[57] and arterial[58] air embolism
Horner's syndrome[59] or phrenic nerve damage[60]
Thrombosis[61]
Sepsis[62]
Cardiac tamponade[63]

using the high approach favoured by most institutions.[55] The overall success rate was 97.2% but this decreased to 78.6% with children <4 kg.

Cardiac tamponade is a complication with a mortality of 65 to 78%, particularly when a poorly positioned catheter erodes through the right atrium (RA).[63] McGee *et al.*[63] have not only reviewed the causes of cardiac tamponade but also describe an elegant method to help position the catheter tip in the superior vena cava (SVC) above the right atrium using an Arrow-Johans right atrial ECG adapter (Arrow), which is attached to the saline-filled distal lumen of the CVP catheter. The patient had a standard three lead ECG attached and then the left chest (negative) lead was attached to the adapter. As the CVP catheter was advanced, the upright P wave became higher as it approached the sinoatrial (SA) node in the RA. When the height of the P wave reached that of the R wave the SA node had been reached and the catheter was withdrawn 3 cm (to the SVC) and fixed in position. Advancing the catheter past the SA node caused the P wave to become biphasic. This was an adult study and awaits paediatric verification. However, correct positioning of the CVP is even more difficult to achieve in children and the venous cannula used for CPB often obstructs CVP readings when the tip of the CVP is positioned incorrectly.

Finally, it must be remembered that the internal jugular vein should not be used in patients having a Glen or Fontan operation as the SVC is involved in the surgery: the femoral vein is preferred.

OTHER VESSELS

Other approaches to measuring the CVP with fewer complications have been looked for. In a recent study external jugular cannulation was compared with the internal jugular approach, although the external jugular was only used if it was easily visible. Despite the finding of no carotid artery punctures in the external jugular group, the high probability of positioning other than in the right atrium or superior vena cava (16%) meant that this approach should not be used for monitoring during

paediatric cardiac surgery but only for vasoactive drug infusions.[56]

Subclavian vein cannulation has a higher incidence of pneumothorax (approximately 1%; bilateral attempts are not recommended) and if the subclavian artery is punctured there is difficulty in controlling bleeding which may be catastrophic in the anticoagulated patient. Also, sternal retraction can compress the vein leading to erroneous measurements. Therefore, this site is used less often.

An alternative approach for central venous catheterisation is via the axillary vein. This approach was assessed in 52 children (median wt. 7 kg) with a success rate of 79%.[66] Children were placed in the Trendelenberg position with the arm abducted from 100 to 130°, the vein was entered parallel and inferior to the artery. The CVP was monitored successfully in five of five patients and complications of 2% pneumothorax and 2% haematoma are comparable to other routes.

Femoral vein cannulation, although regularly used in neonates, is reported in long-term use to have complications of thrombosis (16%) and sepsis (3%).[67] However, there have been no recently published data. It has been thought that measurement of the central venous pressure from the abdominal inferior vena cava was inaccurate but in a paper by Lloyd *et al.*,[68] 20 infants and children had simultaneous right atrial pressures and inferior vena cava pressures monitored, and at end expiration the mean pressures were within 1 mmHg of each other. This indicates that in situations where there is no inferior vena cava obstruction (including tense ascites), the safer femoral route may be considered. In conclusion, it should be remembered that all approaches have a higher success rate (and lower complication rate) when performed by an experienced anaesthetist.

Specialized monitoring

Pulmonary artery pressure and mixed venous saturation

The placement of a catheter in the pulmonary artery can be achieved pre- or postoperatively by means of a balloon tipped catheter that is floated through the heart and positioned by *x*-ray imaging or observation of the transduced waveform. However, perhaps the easiest way for a catheter to be placed is by the surgeon at the end of surgery under direct vision.

The uses and information derived from the catheter depend upon the type of catheter introduced but include infusion of drugs, measurement of intracardiac pressures, sampling of intracardiac blood, thermodilution cardiac output, continuous measurement of mixed venous oxygen saturation by means of a fibreoptic catheter and atrial or ventricular pacing.

The wedging of a balloon tipped catheter in an end pulmonary artery gives an occlusion pressure (PAOP) which, in the absence of mitral valve disease, left atrial myxoma, elevated airway pressure (especially PEEP), pericardial tamponade and pulmonary hypertension, gives an accurate estimate of left ventricular end-diastolic pressure (LVEDP) which may reflect left ventricular filling and function. Pulmonary artery end diastolic pressure (PAEDP) gives an accurate estimate of PAOP, in the absence of increased pulmonary vascular resistance, e.g., mitral stenosis, and decreases the risk of pulmonary artery rupture. The PAOP and PAEDP are most accurately measured at end expiration to avoid elevated airway pressures[69] (making an expiratory pause useful on ventilators). It is also important that the PAOP is measured in an area of the lung where pulmonary venous pressure exceeds pulmonary alveolar pressure, i.e., a dependent part of the lung in a large pulmonary artery (West zone 3).[70] Marked respiratory variation of the tracing or a PAOP greater than PAEDP should lead to the suspicion of inaccurate positioning.[70]

TABLE IV Indications for insertion of a pulmonary artery catheter

Severe cardiac dysfunction (especially if there is disparity between ventricles)
Pulmonary hypertension
Conditions necessitating high ventilatory pressures
Mixed venous oxygen saturation ($S\bar{v}O_2$) measurement
Serial cardiac output measurements

The measurement of pulmonary artery pressures is still controversial during cardiac surgery.[71] In addition physicians often misunderstand the derived information.[72] Introduction of the pulmonary artery catheter has been slow in paediatric practice, initially due to the lack of small catheters and also by the ease of placing a catheter directly in the left atrium during surgery.

There are many indications for insertion of a pulmonary artery catheter[73] (Table IV).

There has been recent interest in the continuous online measurement of mixed venous oxygen saturation ($S\bar{v}O_2$)[74] with the development of small oximeter catheters that can be inserted into the pulmonary artery via the right ventricle by the surgeon at the end of surgery (Figure 7). The $S\bar{v}O_2$ from analysis of the Fick equation is directly related to CO, SaO_2, the haemoglobin concentration (Hb) and inversely proportional to the rate of oxygen consumption ($\dot{V}O_2$). Therefore:

$$S\bar{v}O_2 = SaO_2 - [\dot{V}O_2/(Hb \times 13.8) \times CO]$$

where $\dot{V}O_2$ is measured in $ml \cdot min^{-1}$, Hb in $g \cdot L^{-1}$, and CO in $l \cdot min^{-1}$

Therefore, changes in $S\bar{v}O_2$ allow monitoring of the over-

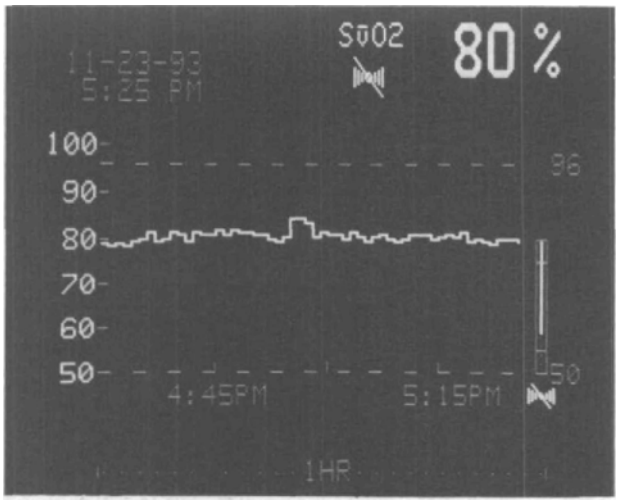

FIGURE 7 Example of mixed venous oxygen saturation ($S\bar{v}O_2$) recording. The increase prior to 5 pm was due to preoxygenation before endotracheal suction.

all balance of oxygen supply and demand within the body (Tables V and VI).

The normal $S\bar{v}O_2$ is 75%, and anaerobic respiration occurs when it is <30%, at normothermia.[75]

Most of the initial experience in $S\bar{v}O_2$ monitoring has been in adult patients[76,77] but there have been reports of its paediatric use.[78] The $S\bar{v}O_2$ was found to reflect the overall balance between oxygen supply and delivery continuously in a group of 16 infants after cardiac surgery.[78] Also, the rapid monitoring of changes in the above variables was found to be valuable for immediate recognition and treatment.[78] A further indication for $S\bar{v}O_2$ monitoring may be in predicting increased mortality from cardiac failure in postoperative congenital heart patients at risk for pulmonary hypertension. The variations of $S\bar{v}O_2$ were more predictive than variations in SaO_2, or the numbers themselves.[79] Problems with measuring $S\bar{v}O_2$ include baseline drift leading to the need for frequent recalibration and inaccurate reading if the catheter becomes advanced onto the pulmonary artery wall.

Difficulties in insertion by flotation can be expected in those patients with a dilated myocardium, poor ventricular contraction or severe tricuspid regurgitation. However, in neonates and infants the catheters are usually inserted surgically and the main complications are of bleeding and cardiac tamponade after their removal. There are a number of reported complications of percutaneous insertion.[71] These include the complications of insertion of a CVP (see earlier), unless directly inserted surgically, and the insertion of the catheter itself (Table VII).

There have also been recent reports of innominate vein perforation[83] and pulmonary artery rupture during cardiopulmonary bypass necessitating emergency right middle lobectomy.[84] Pulmonary artery rupture usually presents with haemoptysis. Predisposing factors include catheter migration, peripheral location of the tip, and overinflation of the balloon.

TABLE V Causes of decreased $S\bar{v}O_2$

1 Decreased oxygen delivery
– Decreased arterial oxygen saturation (or tension)
– Decreased cardiac output
– Decreased haemoglobin concentration
2 Increased oxygen consumption
– Hypermetabolic states
– Fever
– Shivering
3 Right to left shunts

TABLE VI Causes of increased $S\bar{v}O_2$

1 Left to right shunt
2 Decreased oxygen consumption
– Sepsis (due to A/V shunting)
– Cyanide poisoning (impairment of cellular respiration), e.g., nitroprusside infusion

TABLE VII Complications of insertion of a pulmonary artery catheter

Dysrhythmias[80]
Thrombosis and thromboembolism[81]
Endocarditis[82]
Cardiac valve damage
Intracardiac knotting and catheter migration
Pulmonary haemorrhage[80]
Pulmonary infarction[82] (often due to a continuously wedged catheter)
Myocardial perforation[80]

Left atrial pressure monitoring

Catheters can be inserted at the end of surgery directly into the left atrium to give a direct measure of left atrial pressure, and in cases without severe mitral valve disease, an accurate estimate of LVEDV and left ventricular filling. Complications include thrombosis and embolisation, air embolism and bleeding after removal.[85]

Cardiac output determination

This is rarely measured in paediatric patients, unlike adult cardiac surgery, because pulmonary artery flotation catheters are used infrequently.

METHODS OF MEASUREMENT

Thermodilution

Thermodilution measurement remains the commonest method used and has an excellent correlation (r = 0.91

0.97), when 1–3 ml of iced or room temperature injectate is used, with values obtained by the Fick Method or dye dilution in infants and children. Accuracy is improved by avoiding pre-aspiration of blood and filling the catheter lumen with fluid at the temperature of the injectate.[86] If intracardiac shunting is present, left to right shunts produce early recirculation of injectate, but, via extrapolation, left and right ventricle outputs and shunt fractions can be accurately calculated. However, shunting at extracardiac levels (e.g., ductus arteriosis) or right to left shunting mean this method cannot be used.[46] There are several other sources of inaccuracies (Table VIII).

TABLE VIII Sources of inaccuracies in thermodilution cardiac output estimation

Rewarming injectate prior to injection. The temperature of the injectate should be monitored at the point of entry into the circulation.
Baseline temperatures in the pulmonary artery fluctuate with respiration. Therefore reproducibility is enhanced by injecting during the same point in the respiratory cycle.
During CPB, systemic cooling and rewarming may cause inaccuracies in baseline temperatures leading to underestimation of cardiac output.[87]
Cardiac output curves should be recorded and observed. Abnormal curves can result from prolonged injection, patient motion or electrocautery, intra- and extra-cardiac shunts, frequent PVCs and pulmonary and tricuspid valve disease.

Fick method

In this technique, pulmonary blood flow can be calculated from the measurement of oxygen uptake across the lungs and the arterial minus the venous oxygen content difference. However, expired air must be collected for three minutes, and arterial and mixed venous blood samples analysed for oxygen saturation levels and Hb concentrations.[46] Results are not instantaneous. In addition in many forms of congenital heart disease pulmonary blood flow may not reflect cardiac output.

Indicator-dilution method

The indicator-dilution method is derived from the Fick method where a known amount of an inert indicator such as indocyanine green is injected into the venous blood, is unaffected by the lungs and rapidly metabolized by the liver. It is measured by a photodensitometer in continuous arterial sampling and curves of dye concentration over time can be constructed. The cardiac output can be derived from the amount of dye injected and the average concentration of dye over time. Different shaped curves occur with left to right or right to left intracardiac shunts.[46] Under ideal conditions the dye dilution method is highly reproducible but a steady state of 20 to 30 sec is needed, and the ease and beat-to-beat measurement by thermodilution has meant it is rarely used in cardiac surgery.

Doppler

The Doppler principle relies on the fact that a frequency shift is produced when sound waves are reflected by a moving target and this Doppler shift is proportional to the velocity of the target. If the angle of the ultrasound beam is parallel with the moving target then velocity is directly proportional to frequency. However, any deviation of the Doppler signal from parallel, if not taken into account, can lead to potential errors, although deviations of 20° or less introduce an error of only 5 to 10%.[89] This accounts for the errors often found with non-visual oesophageal[89] or tracheal[90,91] Doppler probes, or with single-plane transoesophageal echocardiography, where the Doppler beam can only be aligned in one plane. Transoesophageal measurement of pulmonary blood flow with both pulsed (single pulses)[92] and continuous wave[93] Doppler have been found to have a close correlation with thermodilution measurements. However, both these studies were limited in their ability to view the pulmonary artery adequately in 25% and 13% of patients respectively and, again, pulmonary blood flow may not indicate cardiac output. Some of these limitations may be overcome by the recently described transgastric method of measuring aortic flow.[94] This technique was successful on 88% of occasions with correlation coefficient of R = 0.91 with thermodilution.

Transoesophageal and epicardial echocardiography

INTRODUCTION

In the last 20 years ultrasound imaging has become an important method of non-invasive diagnosis. Echocardiography is the use of high frequency pulsed ultrasound to create images of the heart and surrounding structures. Ultrasound waves are reflected and refracted at the junction of tissues with different densities such as endocardium and blood to cause echoes. These are recorded, by the same transducer that produces the ultrasound waves, to form an image. In M-mode a single crystal is used to get a single-plane view of the myocardium whereas two dimensional (2D) images of the heart are obtained from multiple crystals forming ultrasound as a phased array. Pulsed and continuous wave Doppler are incorporated into echocardiographic probes allowing detection and measurement of flow velocities. In colour flow Doppler different colours are assigned to pulsed wave signals depending on speed and direction. The magnitude of the velocity is portrayed by the intensity of the colour and this technique allows visualisation of abnormal blood flow such as in regurgitant valves or intracardiac shunts

and also allows appropriate positioning of Doppler beams.

All these techniques were first developed for transthoracic echocardiography. The oesophagus was initially used as an alternative imaging window where obesity, chronic lung disease or chest deformity precluded adequate transthoracic viewing. However, other advantages of TOE include the ability to use high frequency probes (lack of chest wall structures which attenuate signal) leading to superior image quality, and excellent imaging of posterior structures such as the pulmonary veins, left atrial appendage, and descending aorta. Disadvantages include the semi-invasiveness and the need for further expensive equipment.

INTRAOPERATIVE ECHOCARDIOGRAPHY

Intraoperative echocardiography is not a new technique, one of the first descriptions being with M-mode technique in 1972 for commissurotomy of the mitral valve.[95] Epicardial echocardiography, produced by the surgeon holding a sterile transducer directly onto the epicardium of the heart at operation, has been found to be increasingly useful in congenital heart surgery both to confirm preoperative diagnosis and the success of operative repair. In Ungerleider's large prospective epicardial series of 328 patients (the smallest being 1.8 kg) prebypass examinations with 2D, Doppler and colour flow Doppler studies demonstrated previously unappreciated anatomy in 18% of patients and were believed to play a role in surgical planning in 44%. Postbypass studies allowed for immediate surgical revision in 7% of patients and predictors of postoperative problems in others.[96] A further study of only 50 patients by Hsu *et al.* showed no new findings preoperatively but 4.5% of patients were reoperated upon for residual shunts.[97]

The advantages of TOE compared with epicardial echocardiography are to allow continuous on-line assessment, the operative procedure is not interrupted, and there is no introduction to the potential risk of infection. With the advent of smaller probes there has been an explosion of publications on the use of TOE not only intraoperatively but also in the diagnosis of complex congenital heart lesions, where in some circumstances it provides information unavailable by other means.

Muhiudeen *et al.* in San Francisco compared intraoperative epicardial and TOE examinations in the full spectrum of congenital heart defects (Figures 8 and 9) (shunt, regurgitant and obstructive lesions).[98,99] They found an excellent correlation between the two techniques, although the single plane TOE probe had inadequate imaging of the right ventricular output tract (a problem which was considerably improved by the use of a biplane probe in two patients with tetralogy of Fallot). Both

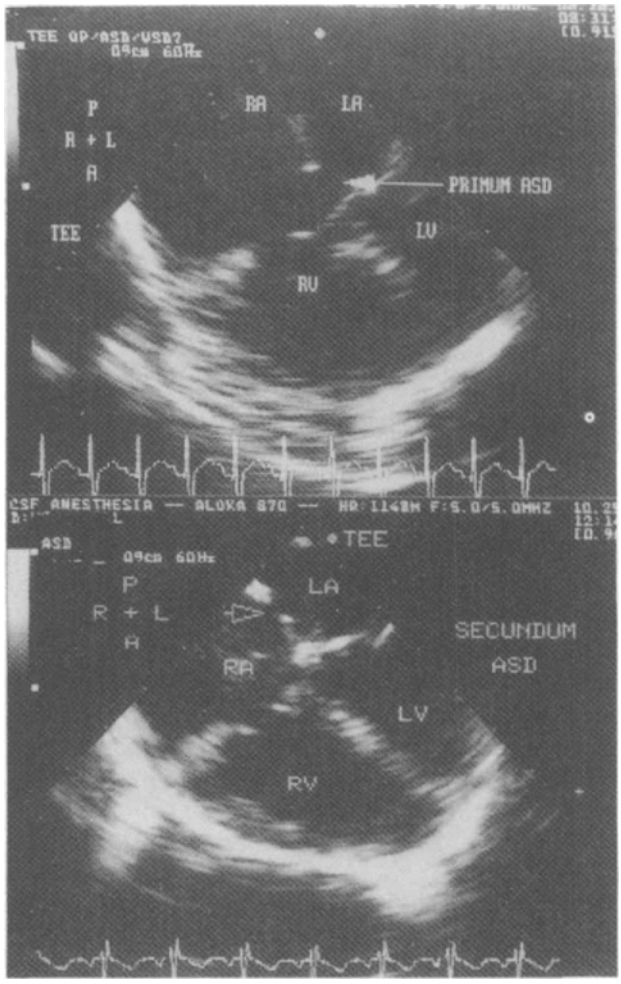

FIGURE 8 Interatrial communication viewed from the transoesphageal four-chamber view. Each is inidcated by an arrow in the respective figure. Top: ostium primum atrial septal defect (ASD). Bottom: ostium secundum ASD. RA = right atrium; LA = left atrium; RV = right ventricle; LV = left ventricle. (Reproduced with permission from *Muhiudeen et al.*: Intraoperative echocardiography for evaluation of congenital heart defects in infants and children. Anesthesiology 1992; 76: 165–72.)

techniques tended to overestimate the severity (classifying it as moderate instead of mild) of residual valvular regurgitation when comapred with postoperative precordial assessment, in five of 30 patients, reflecting the difficulties of accurately estimating the regurgitant fraction during the haemodynamic changes after cardiopulmonary bypass. This problem also occurs in adults during mitral valve repair[100] and is one not unexpected in children.[101,102]

With the advent of smaller probes, paediatric TOE has become an important diagnostic tool in congenital heart disease[103–109] leading to increased demands for general anaesthesia. The intraoperative use and indications for TOE have increased dramatically for the monitoring of

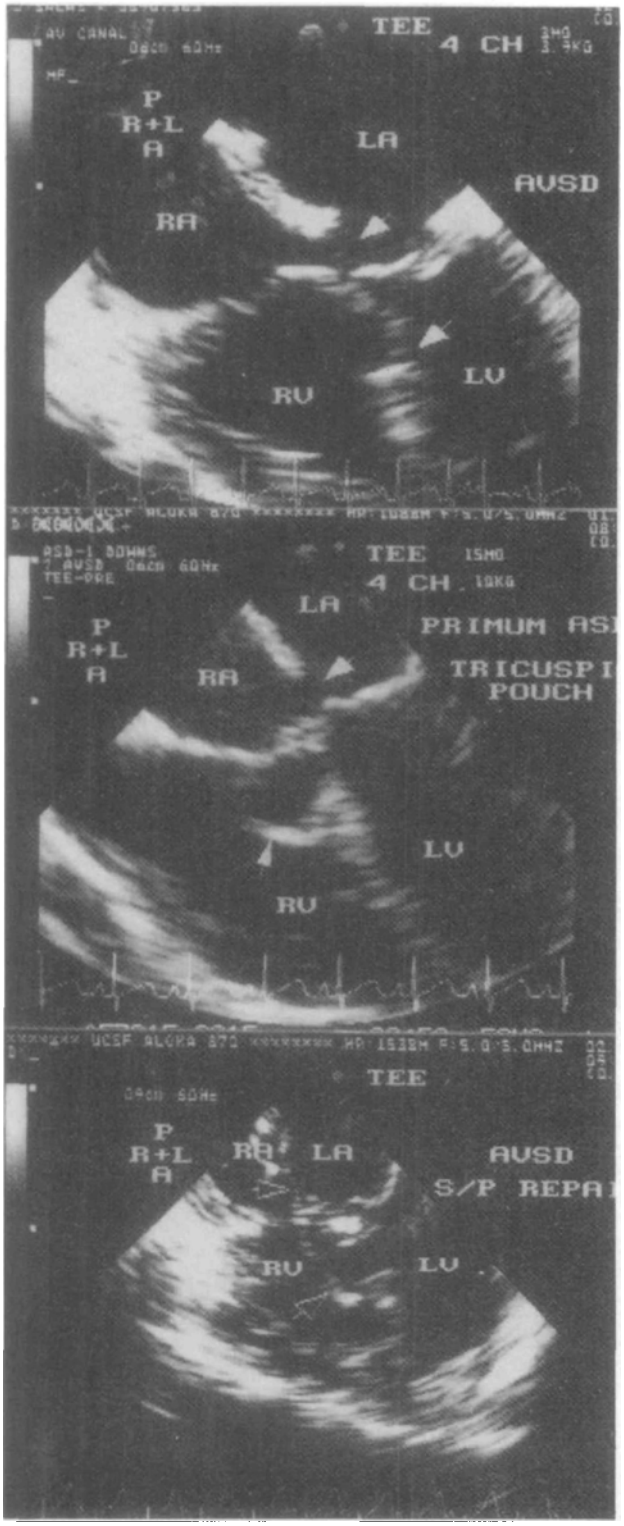

FIGURE 9 Transesophageal echocardiographic view of a complete atrioventricular septal defect (AVSD). *Top*: TOE four-chamber of a complete AVSD. There is minimal bridging of the anteriosuperior bridging leaflet, of which the chordal attachments to the ventricular septum is shown by the lower solid arrow. *Middle*: a divided atrioventricular valve, ostium primum atrial septal defect (top arrow), tricuspid pouch (bottom arrow), and a very small ventricular septal defect just inferior to the atrioventricular valve at the crest of the ventricular septum. *Bottom*: TOE four-chamber post bypass echocardiogram of a complete AVSD with the atrial (top arrow) and ventricular (bottom arrow) septal patch. RA = right atrium; LA = left atrium; RV = right ventricle; LV = left ventricle. (Reproduced with permission from *Muhiudeen et al.*: Intraoperative echocardiography for evalution of congenital heart defects in infants and children. Anesthesiology 1992; 76: 165–72.)

TABLE IX Indications for perioperative transoesophageal echocardiography

Surgical repair at venous level
Surgical repair at atrial and atrioventricular level[113]
Atrioventricular valve repair/replacement
Mustard/Senning procedures[114]
Fontan-type procedures[115–117]
Tetralogy of Fallot[118]
Anatomical correction of transposition of the great vessels
Detection of intramyocardial air[120]
Continuous monitoring during the early postoperative phase (especially for assessing adequate ventricular preload)
Diagnosis and management of early postoperative complications such as cardiac tamponade that can, on occasion, be limited to the left ventricular and only viewed by TOE.

left ventricular function and cardiac valve surgery in adults and may have similar development in children for the conformation of preoperative diagnosis and the assessment of adequacy of repair.[108–112] There are many areas where intraoperative TOE has been found to be particularly useful[108,109] (Table IX).

The use of TOE during the Fontan procedure would seem particularly useful as atriopulmonary and cavopulmonary anastomosis are posterior structures poorly visualized by epicardial echocardiography. In a study by Fyfe *et al.*[115] eight of 19 patients were found to have abnormalities; stenosis of the cavopulmonary connection, unsatisfactory atrial fenestration, patent ductus arteriosus, residual cava-atrial shunting, atrial thrombi, and poor ventricular function; which lead to surgical revision or alterations in medical therapy. In a separate report from the same group TOE was also able to demonstrate six instances of thrombus formation in the inferior vena cavae, right atrium and cavopulmonary anastomosis in 30 patients following the Fontan procedure which were not visualized by conventional transthoracic echocardiography (Figure 10).[116] Stümper *et al.*[117] employed pulsed Doppler interrogation of pulmonary artery and pulmonary venous flows to show that the determinant of flow through the Fontan circulation lies in the systemic venous pressure with variations in patterns of pulmonary artery flow being due to the function of any incorporated right heart chamber and changes in intrathoracic pressure with

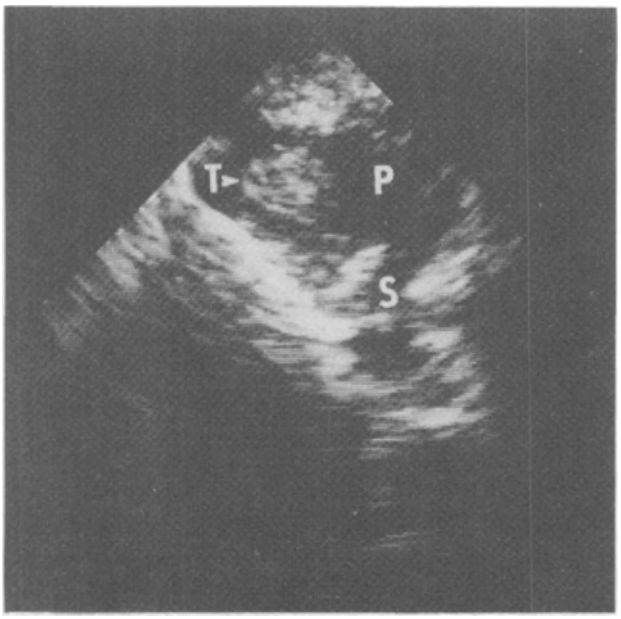

FIGURE 10 Transoesophageal echocardiographic image showing large thrombus (T) in proximal right pulmonary artery (P), which could not be seen on surface echocardiography. S, superior vena cava. (Reproduced with permission from *Fyfe et al.* The utility of transesophageal echocardiography during and after the Fontan operations in small children. Am Ht J 1991; 122: 1403–15.)

respiration. Pulmonary venous patterns of flow were independent of the type of Fontan procedure employed.

Other areas where TOE has proved useful in the operating room include: the use of colour flow Doppler to show decrease in a right to left shunt across the VSD in a patient with tetralogy of Fallot with increasing end-tidal halothane concentrations;[118] the management of patients with mechanically assisted circulation;[119] the detection of intramyocardial air in the myocardium perfused by the right coronary leading to right heart dysfunction with ST segment depression which resolved after ten minutes with reinstitution of CPB and phenylephrine;[120] monitoring of interventional cardiac catheterisation for procedures such as balloon atrial septostomy;[108,109] and allowing for the continuous monitoring of cardiac function immediately after the transfer from operating room to ICU, permitting rapid diagnosis of postoperative hypotension from right or left ventricular failure, cardiac tamponade or hypovolaemia with more accuracy than haemodynamic monitoring.[121]

There is also a recent report on the use of TOE in detecting cardiac preload changes by measuring end-systolic and end-diastolic volumes after venesection followed by transfusion in paediatric patients.[122] This reveals that TOE may have the potential for accurate blood volume assessment during large intraoperative fluid movements. Particular paediatric indications include the immediate postoperative period after cardiac surgery to assess the optimum CVP in relation to the degree of left ventricular filling particulary in patients with high right ventricular pressures such as tetralogy of Fallot. Also intraoperative in major neurosurgery and spinal corrective procedures.

TABLE X Complications of paediatric transoesophageal echocardiography

Minor
Sore throat
Damage to teeth
Displacement of endotracheal tube
Mild oesophageal bleeding[109]
Dysphagia
Brief arrhythmia[109]
Major
Serious arrhythmia
Pulmonary hypertension[109]
Tracheal[123] or bronchial obstruction[124]
Aortic compression[125]
Oesophageal trauma and perforation[126]

SAFETY AND COMPLICATIONS

Epicardial echocardiography appears to have relatively few problems once the operator (often the surgeon) has mastered the technique although arrhythmias and hypotension have been described.[96]

Similarly, TOE has a low complication rate (Table X), no deaths or episodes of bacterial endocarditis being described in any paediatric studies. Oesophageal perforation and death have been described in one adult patient in 10,419 examinations.[126] Opinions vary as to the risk of bacterial endocarditis. Weintraub *et al.*[108] and others[127] claim that prophylaxis should be used as per the American Heart Association recommendations for endoscopy whereas others[109,128,129] claim the risk of bacteraemia is negligible. At least one report of 418 cases by Stümper *et al.*[109] described no episodes of bacterial endocarditis without using prophylaxis, and this problem is largely resolved by the use of routine intraoperative prophylactic antibiotics.

Contraindications to TOE in children have been expressed by The Society of Pediatric Echocardiography[127] (Table XI). Stümper's large study (again not all intraoperative) also showed that if children with upper gastrointestinal disease and spinal disorders were excluded then a complication rate of 1.4% was achieved.[109] These included self-terminating supraventricular arrhythmias in three, mild oesophageal bleeding in two, and one episode of a pulmonary hypertensive crisis in a sedated child. Other complications described include an inability to pass

TABLE XI Contraindications to paediatric transoesophageal echocardiography[127]

Absolute
Vascular ring[108]
Perforated hollow viscus
Active gastrointestinal bleeding
Unrepaired tracheoesophageal stricture
Oesophageal obstruction or stricture
Relative
Cervical spine injury or deformity
Postoesophageal surgery
Oesophageal varices or diverticulum
Oropharyngeal deformity
Severe coagulopathy

TABLE XII Guidelines for transoesophageal echocardiography training from the Society of Pediatric Echocardiography[127]

1 Six months training with performance and interpretation of at least 400 paediatric echocardiographic studies, half of which are on patients less than one year old.
2 Twenty-five to thirty supervised transoesophageal probe insertions with the majority of patients under two years of age.
3 Direct supervision of probe manipulation and image acquisition and interpretation in 30–50 studies. Familiarity with monoplane and biplane probes is desirable.
4 Continuing competence by performing at least 50 paediatric studies a year.

the probe in 1–5% of patients[108] which may be avoided by using a smaller probe or by the use of a laryngoscope with direct vision of the oesophagus to avoid trauma.[130] The effect of using different-sized probes on the rate of complications was examined by Stevenson and Sorenson.[123] They found a complication rate of 5.5% with the paediatric probe (used in 79% of cases) which showed no difference in the complication rate of 2.6% found with the larger probe. Use of the adult-sized probe was recommended in patients >20 kg, although it was used in patients down to 14.7 kg without complication.

TRAINING

Concerns have been expressed by both cardiologists and anaesthetists about the adequacy of training, and the decision-making of anaesthetists, using TOE.[131-134] Anaesthetists applying TOE in cardiac surgery should be adequately trained in general transthoracic echocardiography before interpretation of TOE and the American Society of Echocardiography has recently issued guidelines for the training of TOE with recommendations for the anaesthetist to have an adequate training in transthoracic echocardiography, preferably for at least six months, in a recognized teaching setting and, most importantly, to develop a close working relationship with a cardiologist to whom he can easily turn for advice.[135] Further guidelines for paediatric TOE have recently been published by the Society of Pediatric Echocardiography.[127] Training for anaesthetists should follow the guidelines for paediatric cardiology trainees (Table XII).

Some workers such as Ungerleider *et al.*[136] feel that the cardiac surgeon and not the anaesthetist should be performing and interpreting the echocardiography during surgery as they are better able to relate the findings to the intraoperative repair. During the course of 621 epicardial echocardiographic examinations the number of patients needing surgical revision decreased from 8% to 2% and these revisions became 100% successful indicating an enhancement in the operative repair which Ungerleider felt was due to the increased information and not due to increased experience alone. However, a large number of physicians feel that the advantages of TOE over epicardial echocardiography mean that, as Skarvan has recommended,[137] future cardiac anaesthetists should undergo basic training in general echocardiography, and echocardiographic laboratories will have to provide appropriate training positions.

A rapid method of TOE assessment is described by Acampora *et al.*[138] and a description of the related anatomy of TOE views is described by Seward *et al.*[139] Basic textbooks are beginning to appear[140,141] and form a useful introduction to TOE for anaesthetists. Labovitz and Pearson are anaesthetists and their text relates particularly to anaesthetic practice; but there is little mention of congenital heart disease.[141]

PRESENT LIMITATIONS AND THE FUTURE

The present limitations of TOE are critically reviewed by Seward *et al.*[142] and related more to paediatric usage by Weintraub *et al.*[108] and Stümper *et al.*[109] Many of the limitations of the single plane probe (which only allows transverse views) such as visualization of the right ventricular outflow tract, apical muscular ventricular septum, and ascending aorta[109] have been removed by the advent of the bi-plane probe where a second transducer is placed perpendicular to the first allowing longitudinal views.[141,144] Pulsed and continuous-wave Doppler have already been incorporated into small probes and the ability to position the Doppler signal to assess more accurately the flow should be improved by increased steerability.[145] An exciting new development is the multi-plane probe[146] which allows transverse, longitudinal and oblique views form one probe position and therefore is optimal for visualization of complex structures, Doppler flow mapping and would seem to be ideal for three-dimensional conceptualization and computer reconstruction of intricate congenital heart disorders. Perhaps the

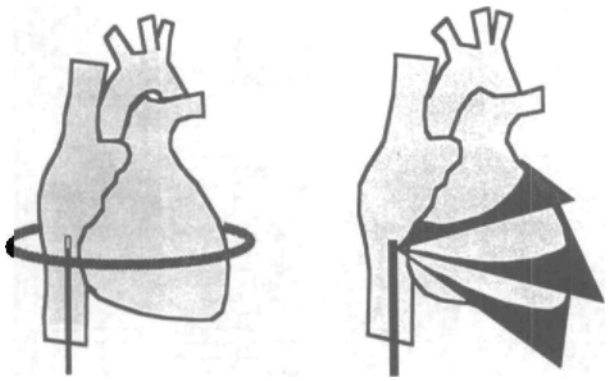

FIGURE 11 Possible intracardiac echocardiographic approaches to imaging of the whole heart with the ultrasound device placed in the right heart. One approach could be the use of an ultrasound catheter with a frequency low enough to provide an adequate depth of field for whole-heart-imaging from the right atrium or the venae cavae (*left*). Another approach could be the use of miniaturized transoesophageal-type of ultrasound probe advanced into the inferior vena cava or the right atrium (*right*). (Reproduced with permission from *Pandian et al.*: Intravascular ultrasound and intracardiac echocardiography: concepts for the future. Am J Cardiol 1992; 69: 6H–17H.)

most interesting future developments include intravascular imaging and miniaturized probes in central venous cannulae. In future, these will not only be able to give complete intraoperative scanning without affecting the surgical field but will also remain in the patient until they leave the intensive care unit (Figure 11).[108,147,148]

CONCLUSIONS

Intraoperative TOE has been shown not only to confirm preoperative diagnosis but also to visualize unexpected new findings, and to provide data which influenced the anaesthetic management and surgical procedure. The use of TOE in children was initially limited by probe size but miniaturization and the development of the bi-plane probe, Doppler and colour flow has enormously increased its potential and it seems likely that the indications for intraoperative TOE will continue to increase. As it would seem unlikely that a cardiologist will be available in the operating room at all times, anaesthetists will have to develop the requisite skills which will probably be incorporated into their training in the future.

Intracardiac imaging[148] and real-time 3D imaging[149] are exciting potentials for the future and these may eventually replace our invasive monitoring of today.

Monitoring the brain

INTRODUCTION

Neurological injury remains an area of considerable morbidity after congenital heart surgery.[33,150] A definitive monitor of cerebral function has yet to be found, and assessment of neuropsychiatric outcome, especially in children, is difficult. Therefore, the appraisement of the effects of alterations in treatment can be complex. There is still controversy over the use of hypothermic circulatory arrest (HCA) compared with "low-flow" bypass. Greeley *et al.*[151] have advocated "low-flow" (pump flows $<$ or $= 1.2\ L^{-1} \cdot min^{-1}$, i.e., half normal) bypass over HCA. This followed studies that showed delayed recovery of cerebral blood flow (CBF) and cerebral oxygen consumption ($CMRO_2$) after HCA: changes that do not occur after "low flow" CPB. Recent support has come from a large prospective study of 171 patients with D-transposition of the great vessels who underwent arterial-switch operations and were randomized to HCA or "low-flow." The HCA patients had incresaed ictal activity both clinically and on EEG, and greater brain creatine kinase release. The effect of this on long-term neurological outcome awaits follow-up.[152] Many physiological variables affect CBF and $CMRO_2$, e.g., PaO_2, $PaCO_2$, brain temperature, blood viscosity, intracranial pressure, CVP and mean arterial pressure when outside the autoregulatory range.[153] There are also difficulties in the measurement of CBF and $CMRO_2$ and what levels we accept as normal.[153,154] Therefore cerebral monitoring is an area of much controversy.

ELECTROENCEPHALOGRAM (EEG)

The EEG is a scalp recording of the spontaneous electrical potentials generated by the pyramidal cells of the cerebral cortex. Quantification of EEG wave forms is by frequency and amplitude. Frequency bands are divided into delta (0–3 Hz), theta (4–7 Hz), alpha (8–13 Hz) and beta ($>$13 Hz). The EEG response to anaesthetic agents varies but, generally, anaesthetic induction decreases alpha and increases beta followed by theta and delta activity with deepening of anaesthseia. Hypoxia and cerebral ischaemia lead to profound frequency slowing and eventually electrical silence. The computer-processed EEG has facilitated intraoperative monitoring. The best validated method is power-spectrum analysis involving conversion of a given period of EEG from voltage against time to plot of power (amplitude squared) against frequency. Data can then be displayed in several ways including compressed spectral array (CSA). The CSA can be more easily visualized than raw EEG data for sudden changes in frequency and amplitude that can be a monitor of cerebral ischaemia[155] (Figure 12). If the EEG has not become isoelectric prior to circulatory arrest then therapeutic interventions can further decrease EEG activity (Figure 12). A characteristics recording is seen during cooling of the patient (Figure 13). Levy, in an editorial,[156] proposed that EEG's were of little use except to ensure

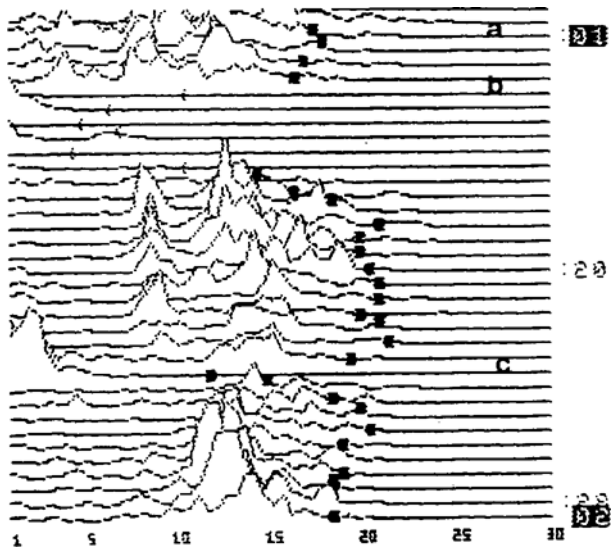

FIGURE 12 Example of Compressed Spectral Array. A three-dimensional display of the EEG. Frequency from 1–30 Hz is on the horizontal axis. Amplitude (0–160 millivolts) and time every 30 sec is compressed on the vertical axis. At point "a" CPB is commenced. At point "b" the CSA suddenly became isoelectric at the same time as the pressure on the aortic cannula rapidly increased to 250 mmHg systolic pressure. Cardiopulmonary bypass was discontinued with return of the CSA. At point "c" the carotid arteries were clamped to stop potential embolisation, with the reinstitution of CPB. The patient had an intimal dissection of the aorta due to the aortic cannula; this was repaired and the patient made an uneventful recovery.

electrical silence prior to HCA. This followed a report by Bashein *et al.*[157] which failed to show any statistical correlation between EEG changes either with hypothermia or delayed neuropsychiatric follow-up. This conflicted with earlier work[158] and led to some criticism,[159,160] as only two-channel EEG recordings had been used and not a multi-channel system with quantitative EEG monitoring. In reply, Bashein and Levy agreed that further prospective, randomized, blinded-observer investigations with standardized neuropsychiatric testing were needed. No firm conclusions can be drawn as to the routine EEG monitoring and its usefulness remains controversial.

TRANSCRANIAL DOPPLER (TCD)

The Doppler principle has already been described. The TCD probe is placed over a "cranial window" such as 1–5 cm anterior to the ear over the temporal bone to monitor the velocity of blood flow in the middle cerebral artery. The diameter of the artery is assumed to be constant and therefore flow velocity approximates cerebral blood flow. There is a good correlation with classical CBF techniques. The TCD has a number of advantages and disadvantages (Table XIII).

Several recent trials have used TCD to assess CBF during HCA and "low-flow" CPB.[161–163] Findings include: linearly decreasing CBF with decreasing nasopharyngeal temperature[161,162] and during deep hypothermia

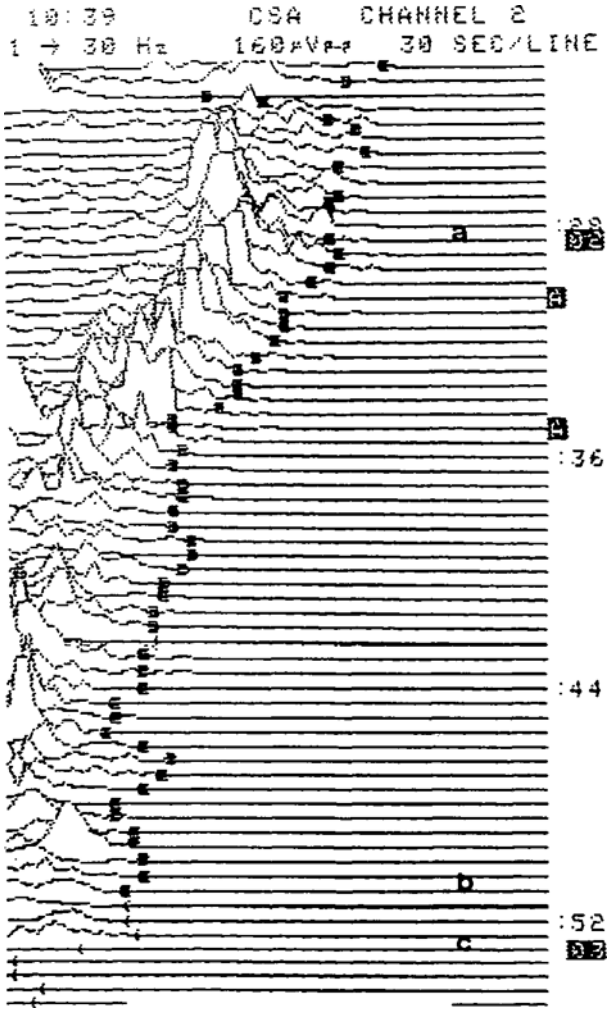

FIGURE 13 Example of CSA during cooling of a patient to 18°C before circulatory arrest. Cooling commences at point "a." At point "b" circulatory arrest occurs and the CSA is still not isoelectric therefore propofol 3 mg · kg^{-1} is given at point "c" and the CSA becomes isoelectric.

TABLE XIII Advantages and disadvantages of transcranial doppler

Advantages
Non-invasive
Portable
Inexpensive during use
Disadvantages
Difficulty finding signal (10%)
Disrupted by patient movement
Reveals trends not absolute values
Lack of validation during hypothermia

(<20°C), cerebral autoregulation becomes uncoupled as CBF and mean arterial pressure are linearly related.[32] Burrows and Bissonnette showed that, after HCA, a higher cerebral perfusion pressure was necessary to re-establish CBF.[163] These findings have been discussed in a recent editorial.[164] Another use for TCD has been to show microemboli in the middle cerebral artery during CPB.[165] These may contribute to postoperative cerebral dysfunction.

JUGULAR VENOUS BULB SATURATION (SjO_2)

The SjO_2 can be measured by inserting a catheter or an oximeter catheter into the jugular vein and then passing it retrogradely into the jugular bulb, as has been described elsewhere.[166] This technique has been shown to be successful (97% on *x*-ray) and safe (3% carotid puncture in a large number of paediatric patients[166]). Measurement may be performed intermittently by blood sampling or more usefully by passage of an oximetry catheter for continuous monitoring.[167] The SjO_2 has been used as an indicator of $CMRO_2$ by calculating CBF (discussed elsewhere[153]) and multiplying it by the oxygen content difference between the arterial (radial) and jugular bulb.[153,154] The SjO_2 is the cerebral equivalent of the $S\bar{v}O_2$ and indicates the balance between oxygen supply and demand and a decreased SjO_2 may indicate cerebral ischaemia.[168] This may be due to inadequate protection by hypothermia as has been discussed (see Temperature Monitoring). However, a critical level and duration of SjO_2 has yet to be related to postoperative neurological dysfunction.[168] Nakajima *et al.*[167] observed a decrease in SjO_2 only during the rewarming period and the decrease of saturation was related to the "rewarming speed" indicating that this may be a critical period for cerebral oxygen supply and demand. This study has similar findings to that of Croughwell *et al.*[169] Other workers, however, have found decreases in SjO_2 during brain cooling[37] (see Temperature Monitoring).

NEAR-INFRARED SPECTROSCOPY

Near-Infrared Spectroscopy (NIR) is a new non-invasive method of measuring brain oxygenation via haemoglobin saturation (HbO_2%). Near-infrared wavelengths of light (700–1000 nm) are readily transmittd through biological tissue and attenuated by the iron-porphyrin in oxyhaemoglobin and deoxyhaemoglobin or the copper in cytochrone c oxidase.[170,171] The small optical probe which transmits and senses is usually placed on the forehead 2 cm above the supraorbital ridge, for imaging the frontal-temporal cerebrum. Regional oxygen saturation is measured; in the cerebral microvasculature which is composed of 20% arterial, 5% capillary and 75% venous blood with a normal level of HbO_2 of about 70%.[46] Advantages of the technique are that it is noninvasive and directly measures oxygenation within the cerebral microcirculation. Disadvantages are that only a 10 ml hemispherical volume of brain is monitored[170] and that other areas of the brain and global oxygenation could well have different levels of oxygenation. Kurth *et al.*[171] measured cerebrovascular HbO_2% and total haemoglobin concentrations with NIR in 17 neonates undergoing cardiac surgery as they were cooled to 15°C, underwent HCA, and were rewarmed. Results show that HbO_2% increased during CPB cooling, decreased curvilinearly for 40 min of HCA, remained stable during 40–70 min of HCA, and was restored to pre-HCA values on recirculation within three minutes. As nasopharyngeal temperature increased during rewarming HbO_2% decreased to pre-CPB levels by 15 min. The findings of HbO_2% increase during cooling corresponds to the findings of Greeley *et al.*[32] that $CMRO_2$ decreases more than CBF, but differs from the work of Kern *et al.* who showed a decrease in SjO_2 at the end of cooling.[36] The decrease in HbO_2% during rewarming may relate to the studies showing decreasing SjO_2.[167,169] A recent study has also shown good correlation between SjO_2 levels and HbO_2%.[172]

CONCLUSIONS

There are inherent problems with all these monitoring techniques and abnormalities have to be related to hard evidence of neurological injury. Current evidence suggests that cerebral cooling and rewarming may be critical times of oxygen supply and demand to the brain, but further hard evidence is needed in this area of intense research.

Monitoring of cardiopulmonary bypass and its effects

BLOOD GAS MEASUREMENT

The monitoring of CPB is largely the role of the perfusionist. However, there are many areas of overlap of responsibilities and the anaesthetist's management of the patient during this critical period may have profound effects. One such area of monitoring and management is of arterial CO_2 which can have critical effects on CBF.[153] Carbon dioxide has an effect on CBF, albeit depressed, during deep hypothermia (18–22°C) in children under one year.[173] The correction of arterial blood gases for the temperature of the patient (pH-stat) was the normal practice for many years. Blood gas analysis is performed at a constant 37°C. Recently, however, workers such as Murkin *et al.*[174] have found uncoupling of $CMRO_2$ from CBF and Stephan *et al.*[175] suggested an increase in neurological dysfunction in pH-stat-managed adult patients. A study using TCD has also shown that in alpha-stat (temperature uncorrected) managed CPB the CBF ve-

locity is less subject to wide pressure alteration than pH-stat.[176] Therefore, many centres have changed to alpha-stat management of arterial blood gases. However, a randomized study in adults by Bashein *et al.*[177] was unable to find a difference in neuropsychological testing after seven months of follow up, between patients managed by alpha or pH-stat. There remains much controversy over which method to use.[178]

Continuous blood gas monitoring during CPB by optical fluorescence has been shown to be acceptably accurate[179] and has formed a standard of care in many institutions.[180]

BLOOD GLUCOSE MEASUREMENT

The blood glucose concentration is also thought to be important during times of cerebral ischaemia, with high blood levels being associated with increased neurological injury. Therefore, glucose-containing fluids are usually avoided during cardiac surgery. However, a recent study showed improved perioperative fluid balance with glucose-containing prime for CPB.[181] This study and others are reviewed by Lanier.[182] The majority of evidence is that glucose worsens outcome after global and focal ischaemia and, therefore, should be kept at normal levels during CPB, despite apparent benefits in fluid management.[182,183]

MONITORING THE IMMUNE, GASTROINTESTINAL AND HEPATIC SYSTEMS

Cardiopulmonary bypass causes profound effects on the body, which in most cases are tolerated extremely well. However, a few patients will, despite excellent surgery and anaesthesia, present with the "postperfusion syndrome." The patient may show signs of prolonged pulmonary insufficiency, excessive accumulation of extravascular water, coagulopathy, and to a variable degree renal and other organ dysfunction. These are hypothesized to be a result of complement and cytokine activation.[184] The inflammatory response to CPB is the subject of an excellent review by Butler *et al.*[185] The complement system, kallikrein cascade, neutrophil degranulation, oxygen-free radical production and cytokine synthesis are all activated and interconnected by CPB. Monoclonal antibodies to endotoxin and tumour necrosis factor (TNF) have been developed for use in septic shock and these are released as a result of CPB[186] and may be used to prevent organ dysfunction in the future.

Other areas, apart from the immune system, that are being investigated as important areas for monitoring during CPB include the gut, and hepatic blood flow. The gut is now being focused on as being critically involved in the development of multiple organ failure[187] and gastrointestinal complications have been shown to cause morbidity and mortality after CPB in adult patients.[188] The measurement of intramucosal pH of the stomach by gastric tonometry, using a saline-filled balloon at the end of a nasogastric tube in the stomach, has been shown to reflect accurately gut blood flow in animals and is being investigated as an important monitor in the intensive care unit[189] and during CPB in adults.[190] A recent study found a decreased intramucosal pH (<7.35) with an increase in systemic endotoxin during hypothermic CPB in adults.[191] Paediatric tonometers are currently under development.

Hepatic blood flow has been reviewed by Mathie.[192] He reminds us that hepatic arterial flow is maintained by autoregulation but portal blood flow has no protection during hypotension.

The effect of CPB on paediatric gut and hepatic blood flow has not been investigated but it would seem likely the same hypothesis of ischaemia leading to translocation of gut organisms apply, although the child is unlikely to have atherosclerosis of mesenteric arteries.

Monitoring of coagulation

Postoperative haemorrhage and coagulopathies remain major causes of morbidity and mortality in paediatric patients and there has been recent interest in various inhibitors of fibrinolysis and the best way of monitoring their effects. The changes that occur in the coagulation system as a result of CPB are complex and the subject of a recent comprehensive review.[193] Platelet dysfunction occurs as a result of exposure to artificial surfaces, loss of membrane receptors due to mechanical trauma, and possibly from plasminogen which causes proteolytic cleavage of platelet membrane glycoproteins. Neonates unlike adult patients, have to deal with considerable reductions in clotting factor concentrations and platelet numbers due to haemodilution alone, and the effect of CPB on their coagulation system has been comprehensively reviewed by Kern *et al.*[194]

Monitoring of coagulation during CPB, as discussed by Reich[195] has been traditionally by the activated clotting time (ACT) and in the immediate postoperative period by the prothrombin time (PT), partial thromboplastin time (PTT), fibrinogen and fibrinogen degradation products (FDP's). These tests may have limitations in their ability to monitor the interaction between the coagulation cascade and the platelet surface caused by altered platelet function and give no information on platelet-fibrin interactions, clot retraction and lysis. Additionally, routine monitoring of coagulation requires blood samples to be sent from the operating room and take considerable time to complete. There has been renewed interest, therefore, in the thromboelastogram (TEG) as a rapid and more complete measure of the coagulation and fibrinolytic sys-

tem. The TEG involves placing 0.35 ml whole blood in a rotating metal cuvette heated to 37°C. A piston is suspended in the sample, and the rotational motion is transferred to the piston as fibrin strands form between the walls of the cuvette and the piston. The clot formation is then electronically recorded on a continuously moving paper allowing various measurements to be made of clot formation and retraction. The TEG is the subject of a recent review by Mallett and Cox.[196] In adult cardiac surgery reports have conflicted as to the usefulness of the TEG in predicting postoperative haemorrhage and the need for reoperation.[197,198] A paediatric study showed that the TEG predicted, with 100% accuracy, those patients who developed excessive postoperative bleeding and the specificity of TEG predicting future bleeding was 73%.[199] Another study has shown that most of these abnormalities may correct with infusion of platelets.[200] The variability in these results and the fact that aspirin, which causes known platelet function abnormalities, appears not to affect the TEG has lead the authors of the paediatric trial to recommend caution in the use of the TEG until further extensive studies are performed.[201]

The serine protease inhibitor aprotinin has been shown in one study, to reduce postoperative bleeding in paediatric patients,[202] whereas another trial found it unhelpful.[203] Aprotinin is under investigation in many paediatric centres. A recent study reveals that the ACT is prolonged by aprotinin alone, therefore when anticoagulating with heparin during CPB the ACT should be greater than 750 sec when aprotinin is being used.[204]

Conclusions

Paediatric cardiac anaesthesia monitoring has shown great advances in recent years particularly in transoesophageal echocardiography, but there are many unanswered questions, particularly with reference to improved monitoring of cerebral function, coagulation and the immune system. The next decade will no doubt see great advances in these areas.

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