Equipment and monitoring in paediatric anaesthesia

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Burgeoning medical defence subscriptions, introduction of clinical governance and mandated audit reflect the ever-increasing expectations of parents when their children enter hospital. There have been many important advances in anaesthesia over the past decade and perioperative care for children is undoubtedly safer and of higher quality than it has ever been. In large part this has been due to the introduction of new, more predictable anaesthetic drugs, acceptance of basic monitoring standards, increased understanding of developmental pathophysiology and use of audit loops to identify and manage particular problem areas. Nevertheless, cost-effective innovations in medical equipment have made a significant contribution to the high but ever-improving quality of care we now offer our young patients.

Revolutionary inventions, such as the laryngeal mask airway, come rarely, but initiate fundamental changes in how we practice anaesthesia. Evolutionary innovations in medical equipment design occur much more commonly, often as a result of advances in other specialties. Developments in surgical technique and perioperative care mean that we now offer treatment to children who would have been termed inoperable only a decade ago: neonates with hypoplastic left heart syndrome are a prime example. Similarly, innovations in intensive care equipment and monitoring often have application in the operating theatre suite. In general, they remain beyond the scope of this review, which focuses on the advances in equipment design that have had a particular impact on paediatric anaesthesia. Editorial constraints mean that I am able to discuss only a relatively small number of medical innovations and hence some personal bias in the selection of the subject matter has been inevitable.

Equipment

Innovations in medical equipment that help paediatric anaesthetists improve the quality of patient care occur with ever increasing frequency. For obvious financial reasons, most technological advances in medical equipment are developed and marketed primarily for application in adults. Nevertheless, equipment innovation is occasionally directed principally at paediatric patients, with adult application being relatively less important. This section of the review concentrates on advances in medical equipment design that have done most to change paediatric anaesthetic practice in the past few years.

Advances in perioperative temperature control

Mean body core temperature of infants and children undergoing prolonged surgery tends to decrease because heat loss often exceeds heat production.1 Infants have a higher surface area/mass ratio than adults, which makes them more susceptible to cutaneous heat loss. Thermal radiation is the main mechanism for cutaneous heat loss while convection and conduction from exposed tissues are usually less important. However, evaporative losses arising from large
surgical incisions may become predominant. Infants placed in cool environments are usually able to maintain normothermia by a combination of peripheral vasoconstriction and brown fat thermogenesis. However, heat production in hypothermic paediatric patients may be lower than basal metabolic rate. Although thermoregulatory vasoconstriction is especially efficient in infants and children, they are similar to adults in being unable to increase their metabolic rate in response to mild intraoperative hypothermia, whether given inhalation or i.v. anaesthesia. Children who are hypothermic after operation tend to shiver, as non-shivering thermogenesis is largely replaced by shivering at about 1 yr of age.

Adult studies have shown that mild intraoperative hypothermia results in postoperative prolongation of spontaneous recovery from neuromuscular block, thermal discomfort, vasoconstriction and shivering, and prolongation of postanaesthetic recovery. In addition, patients with core temperatures less than 34°C demonstrate significant alteration in platelet function and increased bleeding after cardiac surgery.

Although paediatric studies have been unable to confirm that mild hypothermia (core temperature 34–36°C) impairs respiratory function or prolongs recovery in healthy infants and children undergoing minor surgery, these findings seem unlikely to apply to ill patients or those having more major surgery. Furthermore, recent clinical studies suggesting that hypothermia may predispose patients to wound infections, prolong hospitalization and increased mortality rate, makes maintenance of intraoperative normothermia a prudent strategy. Many of the strategies aimed at preventing perioperative hypothermia, such as warming the patient’s micro-environment, humidifying and warming inhaled gases, warming i.v. fluids and restricting evaporative losses, have been made easier by recent innovations in equipment and monitoring.

Irrespective of the temperature of the air surrounding the body, heat is lost by radiation to the nearest surface. Significant reductions in heat loss can be achieved by covering the skin, or the surface facing the skin, with a reflective material that is non-transparent to infrared radiation. Cutaneous heat loss can be reduced but not prevented by minimizing the area of exposed tissue and using a special insulating cover such as Thermadrape (Vital Signs Minnesota, Inc., USA). Although air trapped between the cover and the patient probably provides a large fraction of the insulation properties of the material, it remains a relatively inefficient method of preventing hypothermia compared with more active systems. Although impermeable covers also restrict evaporative losses, significant contribution to overall heat loss in most clinical situations is unlikely, as thermoregulatory sweating does not occur under anaesthesia in normothermic patients. The use of water-repellent surgical drapes does mean, however, that physiological fluids and surgically administered solutions do not reach the skin to provide another source of evaporative heat loss.

One proven effective method of reducing cutaneous conductive and convective heat losses is a forced-air patient warming system. One comparative study has shown that the Bair Hugger system (Actamed Ltd, UK) is the most efficient of the currently available devices. This system blows filtered warm air between specially designed flexible covers. The choice of cover blanket and accompanying drapes depends on the size of the patient and surgical access required. The under- or over-covers have a grid pattern of perforations through which low velocity warm air can come into direct contact with exposed skin. A specially designed paediatric blanket has been developed that allows easy surgical and anaesthetic access. The baby lies on the quilted two-ply blanket, which consists of a polypropylene inner layer and polyester outer layer (Fig. 1). The hose from the warming unit can be connected at either end of the blanket. Two plastic drapes included with each blanket can be used, together with the normal surgical drapes, to form a ‘tent’ that allows warm air to surround the patient, although the area around the patient’s head is not inflated. Adhesive barriers direct airflow away from the surgical field. A more conventional cover blanket can be placed over the chest, abdomen and/or legs of older children, the exact position depending on surgical access requirements. These disposable covers have cost implications which can be circumvented, at least in the postoperative period, by the use of reusable alternatives. Comparative studies have shown that forced-air warming systems are more effective than circulating water mattresses at preventing hypothermia in infants undergoing prolonged surgery. However, such systems are not problem-free: induced hyperthermia, thermal softening of tracheal tubes and thermal burns have been reported when warming unit outlet temperatures greater than 38°C were used. Another innovation in patient temperature management uses the same principle of air circulating through disposable covers used in the Bair Hugger to induce mild hypothermia. This forced air cooling system (PolarAir, Actamed Ltd, UK) is more effective than passive cooling at reducing the patient’s core temperature to 32°C.
more, the same system can subsequently be used to re-warm the patient.

**Monitoring core temperature**

At least one central temperature should be monitored during anaesthesia in young children. Fortunately, this has been made easier by the availability of new methods of measurement. A thermistor placed in the pulmonary artery provides the most accurate, continuous measurement of body core temperature, although this is only a practical proposition for paediatric patients undergoing cardiac surgery. In anaesthetized infants and children, oesophageal, rectal, axillary and tympanic membrane temperatures are not usually significantly different from each other and each provides a useful measure of central temperature. However, if body temperature is changing rapidly, as may occur during cardiac surgery, oesophageal temperature may provide more accurate and faster reacting monitor of central temperature than axillary or rectal temperature. An oesophageal stethoscope that incorporates a thermistor provides an excellent dual purpose monitor. Tympanic membrane temperature is also a good measure of core temperature, and intermittent instantaneous measurement using an infrared detection thermometer has proved to be reliable in clinical practice, although patency of the external auditory meatus is necessary for accurate measurement. Other innovations in temperature monitoring include a thermistor incorporated into the end of a urinary catheter. Bladder temperature correlates better with pulmonary artery temperature than tympanic membrane temperature, although adult clinical studies suggest that a high urinary output is required for a rapid response. Nevertheless, for infants and children who require an indwelling urinary catheter, this technique is probably the best method for continuous monitoring of central temperature. For some cardiac and neurosurgical operations, an estimate of brain temperature is also required, as brain temperature does not always correlate with temperatures monitored at other central sites. A probe in the nasopharynx behind the soft palate may give only a poor estimate of brain temperature, particularly if the probe is exposed to leakage of gases from around the tracheal tube: oesophageal or tympanic membrane temperature is better at providing a rapidly responsive and accurate estimate of hypothalamic temperature.

**Humidification of inspired gases**

Although only approximately 15% of metabolic heat production is lost through the respiratory tract, it is always worthwhile humidifying inhaled gases if anaesthesia is likely to last more than 1 h, as significant tracheal mucosal damage may otherwise result. As the specific heat of all gases is low, it is difficult to transfer significant amounts of heat to patients by warming inspired gases. In any event, about 75% of respiratory heat loss results from the high latent heat of vaporization of water, so it is more important to humidify inspired gases than to warm them. Methods of humidifying gases can be divided broadly into passive and active. One commonly used example of the former is the heat and moisture exchanger (HME). These devices use either a hygroscopic or a hydrophobic membrane to trap expired warm water, which is then available to warm and humidify the inspired gases. Large tidal volumes can saturate a membrane before expiration is complete and hence the HME is most effective when tidal volumes are small. Clinical studies have shown that the humidification provided by an HME increases over time, and at least 1 h is usually required to achieve full saturation and maximum effect. Once fully saturated, a HME can produce more than 75% relative humidity in the patient’s airway, similar to many active humidification devices. A HME is less effective than an active humidifier in preventing decreases in central temperature, but significantly better than using no humidification. A modern paediatric HME adds little deadspace or resistance to flow even when fully saturated. Recently, more sophisticated devices have become available that not only have heat and moisture exchanging qualities but that also act as an effective barrier to bacteria and viruses. These heat and moisture exchanging filters (HMEF) use a hydrophobic membrane composed of coated ceramic fibres, which is deeply pleated to maximize surface area and absorption surface. The membrane surface acts as a liquid barrier because the intermolecular forces between individual water molecules are stronger than those between the water molecules and the hydrophobic membrane, and therefore the water molecules tend to collect together on the surface of the membrane to form droplets. The very fine ceramic fibres are not sieves but depth filters, and the porosity of the membrane is related to the distribution, density and size of the fibres. The ‘pores’ are large enough to allow the passage of air with little resistance but at the same time are small enough to filter small viruses effectively. These HMEF have proved to be especially valuable in the intensive care unit, as their use has been shown to reduce ventilator tubing bacterial colonization compared with active humidifier systems using water heaters.

Anaesthetic breathing circuits had not previously been thought to be a likely vector for cross-infection, although revisions to infection control policies are now changing following a report of nosocomial hepatitis C infection allegedly caused by contaminated anaesthetic circuitry. The use of HMEF in the operating theatre may make the current requirement to use once-only disposable anaesthetic breathing circuits unnecessary, although the deadspace of the smallest HMEF (45 ml) has, for the present, restricted their use to children >15 kg in weight.

Most active humidification systems incorporate a method of ensuring that after warming and humidification, the inspired gas is not allowed to cool so that water condenses before the humidified gas reaches the patient’s airway (‘circuit rainout’). This means that the proximal part of the inspiratory limb of the anaesthetic circuit has to be heated, usually with an internal heating element. In order to prevent the possibility of thermal burns to the patient,
the temperature of the inspired gas must be monitored continually and a servo mechanism used to control the temperature of the water heater. Elimination of unwanted condensation by heated wire circuits results in reduced relative humidity compared with unheated circuits, but prevents delivery of excessive water to the patient.\textsuperscript{38} Active humidifier systems not only help prevent a decrease in central temperature during prolonged surgery, but can also help increase central temperature.\textsuperscript{8, 11}

**Fluid warmers**

Rapid large volume transfusion results in significant hypothermia unless the fluid is adequately warmed.\textsuperscript{7} Many devices providing efficient warming at high flow rates have been developed for adults, but these are not always entirely satisfactory for use in children because of their large priming volumes. The design of fluid warmers for paediatric use in the past few years has improved and there are many high efficiency warmers currently available that have small priming volumes and low-flow resistance. However, heat transfer between the fluid and environment increases the tendency for infused fluids to cool as the rate of infusion is reduced and the length of tubing between the warmer and patient increases.\textsuperscript{34} Cooling of previously warmed fluid not only minimizes the potential for heat conservation, but also may result in gas coming out of solution causing bubble formation.\textsuperscript{100} Although commercial gas eliminators are available, they should not be used when the infusion fluid is pressurized. The cooling effect of low-flow transfusion has been overcome largely by new fluid warming systems, such as the Hotline (Kimal plc, Uxbridge, UK), which circulates warm water around a 2-m long patient delivery line (Fig. 2). Normothermic fluid can be delivered at flow rates as low as 75 ml h$^{-1}$ using this system.\textsuperscript{81} This is not usually a cost effective solution, however, unless relatively large volumes of fluid are being administered at low flow rates to small children. Insulating and minimizing the length of the delivery tubing is a less effective but cheaper solution to what is usually a relatively minor problem.

**Advances in airway management**

The introduction of the laryngeal mask airway (LMA) has resulted in a fundamental change in adult and paediatric anaesthetic practice: this simple but effective aid to airway management is now used in most adults and children requiring anaesthesia for imaging or minor surgery. The LMA has been the subject of several reviews and hence I have concentrated on those aspects of its use in paediatric anaesthetic practice that remain controversial.

Although a small size (1) LMA, recommended for use in infants less than 8 kg in weight, has been available for many years, the technique remains relatively unpopular in this particular age group. Trainees have more problems with LMA insertion in infants than in children,\textsuperscript{60} but the incidence of problems related to LMA insertion by experienced anaesthetists is similar in all age groups.\textsuperscript{65} Correct placement, as determined by fibreoptic laryngoscopy, is less likely in infants than children.\textsuperscript{65} Furthermore, the potential for epiglottic injury and delayed airway obstruction secondary to movement of the LMA appear to be more likely in infants than in children.\textsuperscript{65} The use of a laryngoscope to correctly position the LMA may be less traumatic than repeated blind attempts.\textsuperscript{30} Prolonged anaesthesia in spontaneously breathing infants may be associated with airway closure, atelectasis and increasing alveolar–arterial oxygen tension gradient. Furthermore, LMA use in infants and small children increases the deadspace/tidal volume ratio resulting in rebreathing and hypercapnia,\textsuperscript{24} so that positive pressure ventilation together with positive end-expiratory pressure is usually advisable. Therefore, it is not surprising that many paediatric anaesthetists have tended to avoid using the LMA in this age group, as maintaining an effective seal around the larynx in infants may prove more problematic than in older children.

Nevertheless, effective manual ventilation using the size 1 LMA has been described in neonates requiring delivery room resuscitation,\textsuperscript{76} and infants undergoing anaesthesia for hernia repair.\textsuperscript{24} Significant air leakage may occur in up to 40\% of infants ventilated via an LMA, although oxygenation and carbon dioxide elimination can usually be maintained at normal levels.\textsuperscript{29} However, although the majority of any air leak around an LMA is vented to the atmosphere via the pharynx,\textsuperscript{45} the potential for causing gastric insufflation and subsequent aspiration has made this technique a continuing subject of controversy. Use of the LMA results in a high incidence of reflux to the upper oesophagus, possibly related to decreased lower oesophageal sphincter pressure.\textsuperscript{76} As even a perfectly positioned LMA may not prevent aspiration of gastric fluid that has refluxed to the upper oesophagus, its elective use should be limited to fasted patients not at particular risk of gastro-oesophageal reflux.

It is inadvisable to use neuromuscular block in conjunction with the LMA, as although the increased thoracic compliance may allow reduced inspiratory pressures, positive pressure ventilation may remain ineffective because of malposition or movement of the LMA, resulting in a poor cuff seal. In young children, the airway seal provided by the size 2 LMA is normally easy to maintain, and
average cuff leak pressure ranges between 17 and 26 cm H$_2$O.\textsuperscript{31, 39} Although gastric insufflation is largely pressure-dependent,\textsuperscript{114} positive pressure ventilation even at low pressures may cause minor gastric insufflation in a high proportion of patients.\textsuperscript{39} Hence it is important to ensure that external venting of gas leak around the LMA is not prevented by mouth closure secondary to over-zealous tube fixation.\textsuperscript{114}

The introduction of the reinforced LMA has allowed use of this technique during adenotonsillectomy, although insertion of the Boyle–Davis gag may still cause airway obstruction in a small proportion of patients.\textsuperscript{113, 118} The LMA may be better than the tracheal tube in protecting the lower airway from aspiration of blood during surgery.\textsuperscript{118} For spontaneously breathing patients, the ordinary LMA has the advantage of providing less resistance to flow than the corresponding size of tracheal tube: paradoxical inspiratory movement is significantly less when breathing through an LMA.\textsuperscript{83} Analogous comparative work using reinforced LMA, which have a significantly smaller internal diameter than the ordinary LMA, has not yet been undertaken.

Use of nitrous oxide increases LMA cuff pressure significantly,\textsuperscript{18} and may cause it to exceed the capillary perfusion pressure of the adjacent pharyngeal mucosa.\textsuperscript{61} One adult clinical study found that the incidence of dysphagia was significantly higher after LMA insertion compared with tracheal intubation, although overall minor laryngopharyngeal morbidity was similar between the two groups.\textsuperscript{85} The incidence of airway problems after removal of the LMA is the same whether performed in the awake or anaesthetized child and is similar to that after extubation.\textsuperscript{89}

In addition to routine airway management during short duration anaesthesia, the LMA has been advocated as an aid to the introduction of a flexible fibreoptic bronchoscope, as the method has the advantage of allowing visualisation of the vocal cords in a spontaneously breathing patient.\textsuperscript{5, 106} Furthermore, larger scopes can be passed through the LMA than through the nose or comparable size of tracheal tube. The LMA is also proving a useful aid in the initial resuscitation of neonates\textsuperscript{76} and in managing children with abnormal airways\textsuperscript{87} or predicted difficult intubation.\textsuperscript{2} Finally, the LMA may prove advantageous in instances when children with upper respiratory infections require surgery, as the incidence of respiratory complications after tracheal intubation in such children is higher than after insertion of the LMA.\textsuperscript{101}

Advances in perioperative pain control

Parents have high expectations of the efficacy of postoperative pain relief for their children.\textsuperscript{88} Similarly, there has been an increasing acceptance among paediatric anaesthetists and surgeons that all infants and children, without exception, require adequate analgesia after surgery. Fortunately, this has become easier, not so much because of the introduction of new drugs, but because of new methods of administering conventional drugs and better assessment of their effects.

Patient- and nurse-controlled analgesia

Increasingly sophisticated patient-controlled analgesia (PCA) devices are now widely available in most hospitals. PCA is usually the method of choice for infusion of opioids and/or local anaesthetic drugs in adults. Similarly, the use of PCA devices is increasing in children old enough to comprehend their use, the minimum age being approximately 6 yr. A study comparing PCA with a continuous opioid infusion found that in children aged 9–15 yr, pain relief given by PCA was superior to that given by continuous i.v. infusion, probably because of increased opioid consumption by patients using PCA.\textsuperscript{17} However, the difference between the two methods of drug administration was not statistically significant in children aged 5–8 yr. Although the PCA-induced increase in opioid consumption produced lower respiratory rates and oxygen saturations than those observed in the control group, excessive sedation or dangerous respiratory depression did not occur.\textsuperscript{16} Large clinical studies have recorded an incidence of clinically significant respiratory depression in adults using PCA of 0.2–2.0%.\textsuperscript{59, 99} Although continuous monitoring with pulse oximetry is routine for infants and children receiving a continuous infusion of opioid, opinions vary as to the efficacy of such monitoring in children having PCA. Hourly observations by nursing staff of level of sedation, pump function and pain score are usually sufficient.\textsuperscript{69}

Current PCA pump technology allows a summary of all infusion data to be reviewed at any time either during or after PCA use, and stored data can be downloaded to a computer or printer for subsequent analysis. In addition, some PCA devices can store data from connected monitors such as a pulse oximeter and, in the future, a feedback loop allowing low saturations to reduce or stop PCA infusions are envisaged. Other recent innovations include ambulatory drug delivery pumps that use smart card technology. Each program card not only stores all infusion data but also contains software that enables the pump to change function and deliver different infusion regimens, such as continuous, intermittent or PCA. All PCA devices can use a wide range of program settings and can also be used for nurse-controlled analgesia (NCA) in children deemed unsuitable for PCA.

Paediatric clinical studies have indicated that nurse- and parent-controlled analgesia, using PCA devices, appear to be as good as PCA in providing effective postoperative analgesia for patients of all ages.\textsuperscript{48, 116} Many major paediatric centres are now using these techniques in neonates, and published studies evaluating the comparative efficacy and safety of NCA in this age group are awaited with interest. The increased potential of NCA compared with PCA to produce respiratory depression means that it is advisable to monitor all patients receiving NCA with pulse oximetry, in addition to the minimum monitoring described above for PCA.
Epidurals

Although epidural analgesia has been used in children for more than 45 yr, the relatively recent introduction of paediatric Tuohy needles and catheters has facilitated this method of analgesia in neonates and generated renewed enthusiasm for its use in infants and small children. However, although lumbar and thoracic epidural anaesthesia in infants is being promulgated by a few centres, the higher incidence of serious complications in this age group has meant that the technique still remains relatively unpopular for infants. Advancement of a catheter from the caudal space to the lumbar or thoracic epidural space have been used as methods to reduce the likelihood of nerve damage during catheter placement in anaesthetized patients, although the incidence of catheter misplacement can be high. However, placement of an epidural or paravertebral catheter under direct vision by the surgeon at the time of surgery has made the technique much easier and safer for infants undergoing thoracic surgery or children undergoing spinal surgery. Furthermore, the use of PCA or NCA to regulate administration of opioid and local anaesthetic drugs into the epidural or paravertebral spaces has proved a useful option. The potential of epidural opioids to produce respiratory depression and local anaesthetic drugs to produce paralysis means that it would appear sensible to monitor continuously all patients receiving epidural infusions with pulse oximetry, in addition to the minimum monitoring described above for PCA. However, i.v. or epidural administration of opioids to young children does not appear to be associated with an increased incidence of clinically significant desaturation episodes in the postoperative period. Hence, continuous monitoring of oxygen saturation would appear unnecessary in healthy children receiving epidural opioids, although this advice should not be extended to infants or sick children.

Spinals

Although lumbar epidural anaesthesia is possible even in small neonates, spinal anaesthesia is technically much easier and more efficacious. Short spinal needles of 22–25-gauge, depending on the size of the infant or child, offer a reasonable compromise between ease of dural puncture detection and postoperative complication rate. Smaller gauge needles may reduce slightly the incidence of postoperative backache and headache in older children, but they increase failure rate. The duration of spinal anaesthesia after a single injection varies between 1 and 2 h depending on the solution used. Major abdominal and thoracic and meningomyelocele surgery can be undertaken using spinal anaesthesia as the sole anaesthetic technique if the surgeon is consistently fast. Prolonged operative procedures may be undertaken during spinal anaesthesia using 28-gauge subarachnoid microcatheters. Unfortunately, these microcatheters cannot be used for postoperative analgesia as after approximately 12 h their presence is associated with an unacceptable incidence of para-catheter cerebrospinal fluid leak. Unlike adults, neonates tolerate high thoracic spinal anaesthesia with minimal haemodynamic changes because of their decreased cardiac vagal activity, although coordinated intercostal muscle activity may be suppressed. The resurgence of interest in the use of spinal anaesthesia in paediatric anaesthetic practice has resulted largely from increasing awareness that preterm babies of <60 weeks post-conceptional age have a substantially increased risk of post-anaesthesia respiratory complications. This problem can be ameliorated by using spinal anaesthesia in this at-risk patient group and avoiding the use of sedative drugs. Using both spinal and epidural anaesthesia combines the advantages of spinal anaesthesia with the potential for providing safe and effective postoperative analgesia.

Monitoring

Technological advances have allowed an increased ability to control administration of anesthetic agents and monitor their effects on the patient. In theory, such intense monitoring provides real-time information that enables us to predict and prevent, rather than react to untoward events. However, determined efforts have been unable to prove that even the introduction of pulse oximetry improves outcome, let alone the use of more invasive monitoring such as pulmonary artery catheterization. It is probably the ability to use the information pertinently and effectively that determines whether or not increasing the sophistication of monitoring for the individual patient will actually improve their outcome.

Advances in haemodynamic monitoring

Infants and children undergoing major surgery, whether thoracic, abdominal, spinal or cranial, usually benefit from direct intra-arterial and central venous pressure monitoring. The increasing popularity of more invasive monitoring has been a result of the ease of obtaining appropriate equipment, often disposable, and wider appreciation of the advantages to be gained by a beat-by-beat monitoring of the systemic circulation and right ventricular preload. There is now little excuse for children undergoing major surgery to become hypovolaemic at any stage during operation: attempts at estimation or measurement of major blood loss become redundant if central venous pressure is being monitored. Furthermore, safe administration of potentially noxious drugs is only possible using a central venous cannula: problems with chemical interactions of drugs have been substantially reduced since the introduction of narrow diameter triple-lumen catheters.

Monitoring of urine output, arterial pressure, capillary refill time and core–peripheral temperature gradient can be used to assess cardiac output in children, but there are occasions when these simple measures may be misleading. Clinical studies have shown that neither temperature gradients nor capillary refill time provide a consistent guide to either cardiac output or systemic vascular resistance. It
appears that even senior clinicians in possession of all routine haemodynamic and biochemical data cannot reliably furnish an accurate estimate of cardiac output in children.\textsuperscript{103} Knowledge of cardiac output in the individual patient may not always result in significant changes in treatment and/or outcome, but for critically ill patients requiring major surgery there may be significant benefits in being able to optimize cardiac output and other related variables.

\textit{Intermittent monitoring of cardiac output}

Intermittent measurement of cardiac output is the conventional method of tracking clinically significant changes in global perfusion during the perioperative period. Estimation of cardiac output in adult anaesthetic practice traditionally involves injection of cold dextrose into the right atrium and measuring the thermal decay curve in the pulmonary artery by use of a thermistor tipped catheter. However, the relatively large size of flotation catheters precludes their use in small children and infants. Use of directly placed pulmonary artery thermistor probes is possible in even the smallest neonate, but is feasible only after cardiac surgery or cardiac catheterization. The significant advantage of the COLD system (Pulsion Medical Systems KG, Munich, Germany) is that the thermistor probe only requires placement in a peripheral artery and hence can be used in any size of patient requiring non-cardiac or cardiac surgery. The 1.3-gauge probe can be inserted into an existing 20-gauge peripheral artery and hence can be used in any size of patient requiring non-cardiac or cardiac surgery. The 1.3-gauge probe can be inserted into an existing 20-gauge arterial cannula, usually in the femoral or brachial artery. The monitor calculates cardiac output from integration of the area under the thermal decay curve produced after bolus injection of cold 5% dextrose into a central venous cannula. Clinical studies have indicated that there is close correlation between cardiac output measurements made using femoral and pulmonary artery catheters.\textsuperscript{63} The COLD system tends to overestimate cardiac output, presumably because of loss of thermal indicator volume from the circulation as it traverses the lungs and aorta before arriving at the peripheral artery. However, the COLD method has the advantage of being less affected by respiratory variability in comparison with the conventional pulmonary artery technique.\textsuperscript{110} As with all thermodilution techniques, the method produces invalid results in patients with significant intracardiac right-to-left shunts or tricuspid regurgitation, although compensation for relatively small shunts is possible.

\textit{Continuous monitoring of cardiac output}

It is now possible to monitor continuously cardiac output in infants and children using measurements of oxygen consumption calculated by a metabolic monitor and arterial and mixed venous oxygen saturations provided by pulse and fiberoptic oximetry.\textsuperscript{121} This method, which uses the Fick principle, requires a probe to be inserted into the pulmonary artery and hence is suitable only for children undergoing cardiac surgery. Furthermore, the method generates values for cardiac output that correlate poorly with cardiac output generated by a conventional thermodilution technique when cardiac output is very low. Another method of continuous cardiac output measurement now used increasingly in adults uses a thermal coil wrapped around a catheter positioned in the right ventricle that intermittently warms the blood as it flows by: the change in temperature is then detected by a thermistor in the pulmonary artery.\textsuperscript{64} This catheter may also incorporate a fibreoptic cable that allows continuous monitoring of mixed venous saturation, but such systems require relatively large multi-lumen flotation catheters of a size that preclude their use in children less than 6 yr of age.

Measurements of changes in thoracic bioimpedance with each cardiac cycle have been used successfully in adults to provide continuous estimation of cardiac output. Unfortunately, in the past, this method has been conspicuous by its unreliability and relative inaccuracy, particularly in the very young and/or very sick. However, enhanced pattern recognition algorithms and improved reactance measurements used by these rather expensive monitors mean that their use is gradually extending into the paediatric sector.\textsuperscript{74} Multicentre clinical studies in adults requiring intensive care have indicated that recent software improvements have significantly enhanced the overall performance and reliability of these devices.\textsuperscript{98} Furthermore, this method now appears to allow safe and reliable measurements of cardiac output to be performed during surgery, even in the presence of electrical interference.\textsuperscript{102} Paediatric clinical studies are awaited with interest.

Adult studies have indicated that continuous wave Doppler ultrasound can detect changes in aortic flow >11% under ideal conditions.\textsuperscript{70} However, techniques using Doppler ultrasound to measure cardiac index have inherent inaccuracies of ±18% and tend to underestimate cardiac output in small infants.\textsuperscript{46} This is because although body surface area is usually proportional to aortic cross-sectional area in normal children, accurate measurement is difficult, particularly in infants. Clinical studies have confirmed that mean ascending or descending aortic flow velocity is directly proportional to cardiac index over a wide range, although scatter of results tends to limit clinical use to that of a trend monitor.\textsuperscript{51 71} Hence absolute measures of cardiac output produced by determining mean aortic flow velocity and estimating aortic cross-sectional area (using algorithms produced using healthy children with a normal aorta) are often relatively inaccurate and are not recommended. Nevertheless, transoesophageal Doppler probes allow continuous haemodynamic monitoring of descending aortic flow during surgery and early clinical studies indicate that changes in cardiac index, rather than absolute values, can be monitored reliably using this device.\textsuperscript{51 71} The smallest probe currently available has a diameter of approximately 6 mm (ODM, Deltex Medical Ltd, UK), a size that may tend to restrict its use to older children, although ongoing clinical studies using this probe are being conducted in infants.

Another recent innovation, using COLD system technology (see above), is the PiCCO monitor (Pulsion Medical
Advantages in being able to rapidly determine electrolytes, also facilitates arterial blood-gas analysis. The significant placement of a cannula to measure systemic arterial pressure tends to remain in the province of the paediatric cardiologist rather than the anaesthetist. At present, probe size limits to miniaturization in other areas of technology suggests that it will not be too long before TOE is available for use in neonates. Logistical problems regarding the availability of paediatric cardiologists may be circumvented somewhat by use of computer networks and/or video links.

**Echocardiography**

For children undergoing complex cardiac surgery, intermittent use of intraoperative transoesophageal echocardiography (TOE) is becoming increasingly common. TOE is particularly valuable in confirming preoperative diagnoses, seeing unexpected new findings and assessing operative repair, in addition to data that may help in anaesthetic management. Nevertheless, TOE appears more suited to analysis of structure than function, and hence tends to remain in the province of the paediatric cardiologist rather than the anaesthetist. At present, probe size limits the technique to infants >4 kg in weight, although increasing miniaturization in other areas of technology suggests that it will not be too long before TOE is available for use in neonates. Logistical problems regarding the availability of paediatric cardiologists may be circumvented somewhat by use of computer networks and/or video links.

**Advances in arterial blood-gas monitoring**

Placement of a cannula to measure systemic arterial pressure also facilitates arterial blood-gas analysis. The significant advantages in being able to rapidly determine electrolytes, acid–base status and blood-gas tensions during major surgery become even more pronounced in the postoperative period.

New methods of measuring blood gases that are based on fibreoptic technology compare favourably with the traditional blood-gas analyser, which uses three electrochemical electrodes to measure pH, $PCO_2$ and $PO_2$ (Table 1). Fibreoptic technology uses three optical sensors or optodes to make these same measurements, and these sensors can be miniaturized to allow insertion directly into the patient’s existing arterial cannula. An alternative method incorporates optodes in the extracorporeal arterial cannula, enabling blood to be drawn past the sensors, analysed and then re-injected back into the patient.

In both *in vivo* and *ex vivo* systems, a fibreoptic cable connects the disposable sensor to the monitoring instrument. Optical fibres carry light of a specific wavelength from the instrument to the optodes, which have chemical indicator dyes located at their tips. This dye is either fixed within a polymer or is separated from the blood by a membrane. Hydrogen ions, carbon dioxide and oxygen diffuse from blood into the sensor and chemically interact with indicator dyes that are specific for each analyte. In fluorescence-based systems, the wavelength of excitation light delivered by the instrument is different to the light emitted by the sensor. Chemical indicator dyes for measuring pH, for instance, may use the effect of the sensor absorption spectrum being modulated by the change in hydrogen ion concentration, which results in modulation of the light emitted by the optode. Sensors for measuring oxygen tension use suppression of the fluorescent emission spectrum caused by collision of oxygen molecules with the fluorescent dye. The instrument monitors the light emitted by the sensors and converts it into a numerical display.

**Continuous monitoring of blood gases**

The Paratrend 7 (Diametrics Medical Ltd, High Wycombe, UK) is probably the best known example of a system that provides continuous blood-gas tensions and pH. The Paratrend 7 sensor element is 0.5 mm in diameter and can be introduced into an artery or vein through a 20-gauge cannula. The sensor array consists of three plastic fibre optodes and a thermocouple (Fig. 4). The sensors are staggered within the last 25 mm of the element, which protrudes out of the tip of the cannula to sit in free flowing blood. The polyethylene outer sheath, which uses covalently bound active heparin to minimize fibrin deposition, allows passage of aqueous ions from the blood to the sensing area of the element through micropores filled with a polyacrylamide gel. The original sensor consisted of a modified Clarke electrode for measurement of $PO_2$, was renowned for ‘drift’, and required frequent re-calibration. The new system uses fluorescent optical sensors, resulting in greatly improved performance and stability. Furthermore, the mean *in vitro* response times for measurement of pH, $PCO_2$, and $PO_2$ in the original Paratrend 7 were more than 70 s, but these have been reduced to <15 s in the new system. The sensors are calibrated *in vitro* in a special disposable tonometric chamber before insertion. Subsequent
Table 1 Advantages of optical sensor measurement of arterial blood gases over traditional electrochemical analysers. Adapted from Gifford and Bartnik, with permission from the Optical Society of America

- Optical sensors are stable for many days. Electrochemical analysers are prone to drift and require re-calibration several times each day
- Pre-analytical error is decreased
- Transportation of blood-gas sample to the laboratory is eliminated
- Therapeutic turn-around time is decreased
- Blood-gas measurements can be made as often as desired with no incremental cost
- Exposure of staff to blood is eliminated
- Patient blood loss is eliminated
- Disposal of potentially hazardous waste is eliminated
- Risk of nosocomial infection may be decreased

Fig 4 Cross-section through a Paratrend 7 sensor element (courtesy of Diametrics Medical Ltd, High Wycombe, UK).

Fig 5 Diagrammatic representation of the GEM SensiCath system (©1998 Optical Sensors Incorporated, MI, USA). Reprinted with permission.

calibration is performed in vivo, by adjustment to match conventionally acquired blood-gas results, although this should not be necessary more than every 48 h, as drift should be <10% over this time. Clinical studies have confirmed close and reliable correlation with conventional electrochemical blood-gas analysis for up to 1 week. Arterial pressure monitoring and sampling can be performed via a ‘Y’ connection in the line. Insertion of the Paratrend 7 element into a 20-gauge arterial cannula does not result in pressure trace dampening, although a continuous flush of heparinized saline 1 ml h⁻¹ is recommended to maintain line patency. A range of dedicated umbilical arterial catheter systems, which use the same sensor, is now available for use in preterm infants (Neotrend, Diametrics Medical, UK). The same fibreoptic sensor technology has been applied for use in brain injured patients: by inserting the sensor through a transcranial bolt into cerebral tissue, direct continuous monitoring of substrate delivery to the brain is now possible (Neurotrend, Diametrics Medical, UK). Although these sensor systems remain relatively expensive for short-term patient use, they become cost effective in patients requiring more prolonged monitoring and provide useful information unobtainable by any other means.

Intermittent monitoring of blood gases
An alternative approach to blood-gas monitoring with blood conservation using fibreoptic technology is offered by the SensiCath system (Optical Sensors, Inc., Minneapolis,
USA). In this case, the sensor optode and thermistor are incorporated into the extracorporeal arterial line in a closed system. Blood is drawn by syringe into the sensor array and then, after a 60 s analysis time, is returned to the patient (Fig. 5). A fibreoptic cable connects the sensor to a monitor, which can be used as a stand-alone device or interfaced with a bedside patient monitor. Calculated bicarbonate, base deficit and oxygen saturation are displayed in addition to the directly measured variables. Clinical studies have demonstrated that the system produces precision performance comparable with conventional blood-gas analysis.62 The manufacturers specify a minimum sensor life of 72 h or 100 measurements, although accuracy and precision are usually maintained for much longer.

Another interesting advance in biochemical monitoring has come with the introduction of the i-STAT portable clinical analyser (Hewlett-Packard Ltd.). This hand-held device uses single-use disposable cartridges that contain a biosensor array, calibration and fluidics systems, and a waste chamber. Several cartridge configurations are available, each with different test combinations allowing accurate determination of blood gases, electrolytes, urea, lactate, ionized calcium, packed cell volume and glucose. Ion-selective electrodes are used to measure ammonium ions, electrolytes, ionized calcium, pH and P CO2. (Urea is hydrolysed to ammonium ions in a reaction catalysed by urease.) Glucose oxidation is catalysed by glucose oxidase to produce hydrogen peroxide, which is oxidized at an electrode to produce an electric current proportional to glucose concentration. Conductivity of the solution, after correction for electrolyte concentration, is related to packed cell volume. PO2 is measured using a sensor similar to a conventional Clark electrode. Bicarbonate, base excess, anion gap and haemoglobin concentrations are also calculated using standard formulae. Laboratory studies using split samples and comparison with published performance standards have established that the analytical performance of the i-STAT system is consistent and acceptable.66 Linearity is obtained over the whole of the clinically relevant range for all electrolytes, with a coefficient of variation <3.5%. Comparisons with conventional blood-gas analysers have been equally robust.73

The i-STAT would appear to be particularly useful during inter-hospital transport of patients19 and for selected patient use during anaesthesia in isolated venues and for out of hours emergencies.92 A blood sample of <0.5 ml is required and the result is displayed within 2 min. The portable device may hold a series of results in memory for subsequent downloading onto a computer and/or printer. The i-STAT cartridge can also be inserted into a compatible blood-gas module incorporated into Omnicare or Viridia CMS patient monitors (Hewlett-Packard Ltd) and the results displayed on screen. At present, the current price of the consumables makes this system cost effective only for selected patients.

**Conclusion**

Traditionally, anaesthesia has been a relatively low-cost speciality, and managers seldom understand that anaesthetists may require expensive equipment to perform their duties safely and effectively. Let us hope that sufficient economic growth, together with the relevant political policies, will continue to allow us to fully appreciate the potential benefits that technological advance can bring to our work. It seems certain that succeeding innovations in medical equipment will continue to offer significant assistance in the constant drive to improve the quality of care we offer our young patients requiring anaesthesia. However, it remains to be seen if the increasing availability of sophisticated, real-time physiological monitoring will lead to significant improvements in outcome, but there should be no doubt that these questions will be asked.

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