

Anaesthesia equipment for resource-poor environments

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Summary

The design of anaesthesia equipment for use in hospitals in the developing world must take into account the local conditions, particularly whether reliable supplies of compressed oxygen and electricity are available. Designs should ensure that maintenance is feasible locally. International standards should encourage the design of suitable equipment to ensure safe anaesthesia for patients worldwide.

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A theatre in a developing country

The general theatre has a cement floor painted red and polished, with pale green-washed walls. The windows are open because of the stifling heat and flies hover overhead, occasionally coming to rest on the surgeon's mask or even the patient himself. The patient lies on an archaic-looking operating table. One end is supported on a trolley that prevents its faulty tilt mechanism allowing it to collapse to the floor. The surgeon is calmly rejecting numerous drapes that are riddled with holes and can serve no purpose in maintaining a sterile field.

At the other end, John, an anaesthetic clinical officer, is administering a general anaesthetic to a man of 25 years, who is undergoing a sigmoid colectomy for volvulus. He performs a rapid sequence induction with thiopental and suxamethonium and intubates using his own laryngoscope and a tracheal tube that has been used dozens of times before. The tube was scrubbed with soap and water and soaked in disinfectant between this patient and the previous one. John carries all his own equipment with him, along with a supply of drugs for the day – anything left in theatre will disappear by tomorrow. Normal saline is running in through an 18G cannula that the patient's family were asked to buy from the local pharmacy; the best we could offer from the department stores was a 22G.

The surgeon is keen to start operating as the procedure was delayed for 2 h waiting for supplies of sterile and non-sterile rubber gloves to arrive. Shortages of all consumables have been a major problem since additional financial support to the hospital and medical school from a European government programme was withdrawn 6 months ago. It appears that the infrastructure for procurement, storage and delivery of essential items dwindled during this time of plenty, when supplies were 'parachuted in' via alternative routes.

John administers 50 mg of pethidine – this may be the last analgesic the patient receives until the unpredictable visit of the night matron to the ward in 9 h time – and turns up the OMV to deliver 2% halothane. The inspired concentration must be estimated clinically because the halothane 'expired' 8 months ago and the clinical effect is unpredictable. The EMO vaporiser and a bottle of ether are on stand-by behind the anaesthetic machine, as we are down to our last bottle of halothane and the recent long-awaited delivery to Central Medical Stores contained only 18 bottles for the entire southern half of the country. The modern anaesthesia monitor, looking out of place in these surroundings, was purchased, along with eight others, by the European project. The screen has a psychedelic tinge to it and I suspect it is on its last legs – the service plan has expired and will not be renewed. The capnograph trace is flat, as the last remaining moisture trap has been 'borrowed' for use in ICU, where it will be circulated around the four beds. The ECG trace is true, but periodically interrupted as the long out-of-date electrodes require a small drop of thiopental to improve their conductivity. The oximetry probe is a paediatric one and roughly taped with grubby Elastoplast around the man's little finger.

John ventilates the patient using the Oxford Inflating Bellows as part of a draw-over system, aiming to keep him deeply anaesthetised and apnoeic using a high concentration of halothane. There are no muscle relaxants apart from suxamethonium. Emergency drugs, atropine and adrenaline, are drawn up on a redundant Boyle's machine, which acts as a trolley and equipment store. A lone size H oxygen cylinder is deep in dust in the corner and has been empty for several years.

John explains that the Glostavent is in use in the intensive care unit, ventilating a head-injured policeman. He requests a nasogastric tube, so I head to the locked anaesthetic store room where 10 or so years of unsorted donations to the department have piled up. After 15 min I find one at the bottom of a box of out-of-date NG feed. I can tell by the look on his face that John is torn between using this valued commodity for this patient or saving it for the next. The surgeon asks for some antibiotics to be given and we enquire whether he would like chloramphenicol, gentamicin or both, as this is all the pharmacy can currently supply to us. The ex-pat surgeon nods at his lockable trolley, packed with privately procured goods for use in this theatre only. A sense of irony hits me as I reach past his iPod and speakers for a vial of cefotaxime, taking care not to interrupt the tones of Steve Harley and Cockney Rebel.

The provision of safe anaesthesia requires trained anaesthetists, essential equipment, consumables and drugs. Improvement in anaesthetic equipment is commonly sited as a factor that would improve the quality of anaesthesia delivery [1].

The exact requirements for providing a safe anaesthetic in resource-poor settings have never been defined. The closest we have to an international standard are the outdated guidelines published by the World Federation of Societies of Anaesthesiologists (WFSA) in 1993 [2]. A useful concept is to define the equipment for anaesthesia as that which allows safe, competent provision of general anaesthesia and spinal anaesthesia for an adult, and general anaesthesia for a child [1]. Hodges et al.'s paper describes the situation in Uganda and can be taken to be broadly representative of similar countries in sub-Saharan Africa where the lack of anaesthetic equipment is a major obstacle to the provision of safe anaesthesia in both district and central government hospitals. The essential requirements can generally be considered the equipment for delivering the anaesthetic (hardware and consumables), monitoring apparatus, other necessary consumables (such as cannulae and rubber gloves) and drugs (both anaesthetic and emergency).

Equipment for delivery of inhalational anaesthesia

Any anaesthetic machine must be appropriate to the environment in which it will be used. In the developing world this will often involve extremes of temperature, humidity and dust. Machines need to be physically robust, easy to understand and operate, require minimal servicing (which should be available locally) and have affordable, readily available spare parts. The machine should be capable of continuing to function without compressed

gases or electricity. Designs which do not address these issues lead to machines failing and being abandoned [3].

For many years plenum machines providing continuous flow techniques have been favoured by anaesthetists. These consist of a pressurised gas source delivering a continuous flow of carrier gas (usually oxygen) to deliver the volatile anaesthetic agent [3, 4]. Plenum vaporisers allow accurate delivery of volatile agents although they are complex, requiring compressed gas supplies and regular maintenance.

Potential advantages of continuous flow anaesthesia include the presence of a reservoir bag acting as a respiratory indicator, ease of use for inhalational induction, enabling the use of a T-piece for children and the application of continuous positive airways pressure (CPAP). Use of flow meters (rotameters) allows easy estimation of proportions of mixtures of gases delivered [4].

Compressed gas supplies required by continuous flow machines are problematic; without pressurised gas, plenum machines cannot function. Liquid oxygen systems are scarce and cylinders must be sourced and transported at significant expense. In addition, national supplies may not always be sufficient to meet the demands of all the hospitals, and rationing at the central source may occur [4]. Another reason that continuous flow machines have been favoured is because they allow the use of nitrous oxide [5]. Nitrous oxide is expensive and frequently unavailable [1], and from today's perspective would not be a high priority amongst the basic essentials of anaesthesia anywhere. A further disadvantage of continuous flow systems is that they are wasteful of fresh gases unless a circle breathing system is used. Soda lime supplies may prove problematic. The failure of continuous flow anaesthesia equipment in these environments has resulted in 'anaesthetic machine graveyards' within many hospitals throughout Africa [3].

In the last 30 years, draw-over anaesthesia has been promoted as a solution to these problems and is felt by many to be appropriate to resource-poor settings. A draw-over system consists of a low resistance breathing circuit with one-way valves to prevent rebreathing, a self-inflating bag or bellows to ventilate the patient, and a draw-over (low resistance) vaporiser. This system can be used to provide anaesthesia safely for any surgery. Systems are usually robust, portable, easy to assemble and require minimal maintenance.

During draw-over anaesthesia the carrier gas is drawn through the circuit, either by the patient's own respiratory efforts or by the bellows or self-inflating bag. The technique does not require pressurised gas supplies. The carrier gas is room air, with or without supplementary oxygen. Draw-over vaporisers, such as the EMO (Epstein, Macintosh, Oxford) and the OMV (Oxford Miniature Vaporiser) vaporisers [6, 7] have a low internal resistance with some degree of thermal compensation to

give a relatively constant output over a range of temperatures and tidal volumes (Fig. 1). They are also relatively easy to dismantle, clean and reassemble compared to modern plenum vaporisers.

Some efforts have been made to design apparatus that can be adapted to function in either a continuous flow or draw-over mode. Early attempts to adapt existing equipment were successful [8], although concerns exist about the risk of inappropriate circuit connections, valve jamming and subsequent barotrauma. In the setting of an adaptable system, a vaporiser that can function reliably under both continuous flow (plenum) and draw-over mode is required. The OMV is particularly suitable in this respect, more so than Ohmeda's PAC vaporiser, an alternative to the OMV which is no longer manufactured [9], or the EMO.

Hospitals need an anaesthetic machine that is versatile and adaptable with features that meet the requirements of anaesthetists in their particular setting. The optimum specification depends on whether reliable electricity and compressed oxygen supplies are available [3]. A single anaesthetic machine specification for an entire country may prove inappropriate if conditions vary between different sites. No single solution will prove practical in all settings and those involved with writing international standards should take this into account. Whenever possible, anaesthesia providers should be trained using the same equipment and the techniques that they will use during their employment. In reality, machines are often designed on the basis of manufacturing profitability and selected by those unaware of local conditions.

Oxygen concentrators in anaesthesia

A major advance that has reduced dependence on cylinder gas supplies has been the development of oxygen concentrators. These produce oxygen at 95% concentration by passing atmospheric air through zeolite to adsorb nitrogen. Concentrators became commercially available during the late 1960s initially for military and domiciliary use. Early machines were bulky and relied on a supply of compressed air [10]. Portable versions were developed which have proved reliable in the setting of delivery of home oxygen [11] and anaesthesia [12, 13]. Currently, oxygen concentrators are available in a variety of sizes ranging from domestic models with flows of up to $4 \text{ l}\cdot\text{min}^{-1}$ to large installations supplying the requirements of an entire hospital.

Draw-over anaesthesia, in conjunction with an oxygen concentrator, has been used extensively in sub-Saharan Africa [14] and has also been studied under laboratory conditions [15]. Newer concentrators have the additional ability to pressurise air, which can be used to drive a

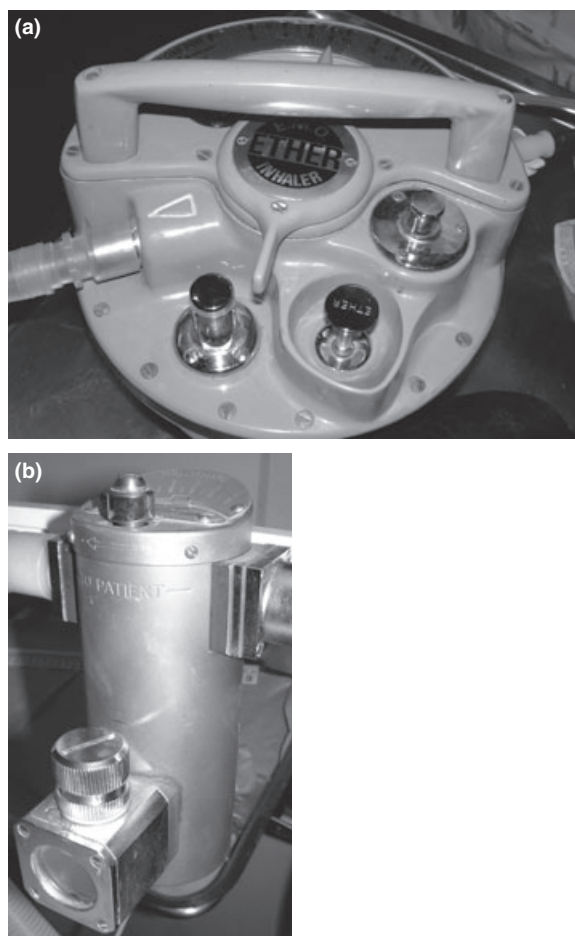


Figure 1 An EMO ether vaporiser (a) and an Oxford Miniature Vaporiser, OMV (b).

ventilator or an air rotameter; examples of anaesthetic machines using this technology include the Oxyvent [16] and the Glostavent [17]. The Dameca MP-2 is another example of a portable anaesthesia machine that can be used in draw-over or continuous flow mode [18]. Oxygen concentrators require electricity from a mains supply or generator – a basic requirement for a functioning hospital anywhere in the world. Recently, a concentrator with the capability to compress oxygen into a cylinder has been developed (Invacare corporation, Elyria, OH; <http://www.invacare.com>). To our knowledge this concept has not yet been incorporated into an anaesthetic machine.

Many believe that the optimum strategy should be to provide a machine that can function as a continuous flow machine using compressed gas from its own concentrator/compressor, which can easily be converted to a draw-over apparatus, in the event of concentrator failure or prolonged loss of electrical power.

The Glostavent (Diamedica, Barnstaple, Devon, UK – <http://www.glostavent.com>) has been developed in an effort to fulfil all the requirements of anaesthetists working in isolated hospitals in the developing world (Fig. 2). It combines an oxygen concentrator, gas driven ventilator, low resistance vaporiser, modified draw-over breathing circuit, uninterruptible power supply (UPS) and a reserve oxygen cylinder. Under normal circumstances, when electricity is available, the concentrator supplies both oxygen for the patient and compressed air to drive the ventilator. The UPS enables it to continue to function normally despite wide voltage fluctuations. If the electricity supply fails completely, the reserve oxygen cylinder automatically becomes the source of oxygen for the patient and pressure to drive the ventilator, so that mechanical ventilation can continue without interruption. In this mode it is extremely economical; a standard size E cylinder can drive the ventilator and supply oxygen for 12 h.

The Glostavent can be used in either draw-over or continuous-flow mode, with any breathing circuit, on any size of patient using most of the commonly used inhalational agents. It can be used either as an anaesthetic machine in the operating room or as a ventilator in an ICU or recovery unit. It is easy to maintain and service using locally available skills.

Dr Roger Eltringham has assisted in the development of the Glostavent over a number of years but has no financial interest in the product.

Equipment maintenance

In small hospitals, maintenance facilities are rarely available and ideally equipment should be designed to permit a



Figure 2 The Glostavent.

reasonable level of user servicing to ensure an uninterrupted anaesthesia provision. This requires user training, tools and a reliable source of commonly required spare parts. Purchase or donation of an anaesthetic machine should take this into account. Ideally, maintenance facilities at larger hospitals will support smaller hospitals. In many places these do not exist, and systems for maintenance of medical equipment should be developed.

Monitoring equipment

Basic monitoring is essential to maintain safety during anaesthesia and is often limited to the presence of the anaesthetist with a precordial stethoscope. Pulse oximetry has probably been the single most significant advance in



Figure 3 A mountain of ECG electrodes threatens to block the anaesthetic store room door, with an example of other inappropriate donated equipment (inset).

anaesthesia in the past 30 years, but it remains largely unavailable in poorly resourced countries. The survey of Hodges et al. showed that in Uganda, 74% of anaesthetists currently work without oximetry [1]. This simple non-

invasive device has the ability to transform care during anaesthesia.

Monitoring equipment should be robust, with the most vulnerable components, such as oximeter probes and moisture traps for capnographs, readily and cheaply available as replacements. Oxygen analysers are considered an essential item in western countries [19], but are frequently absent in resource poor settings, usually because batteries or fuel cells cannot be replaced. ECG monitoring is less essential given the low prevalence of ischaemic heart disease.

Blood pressure measurement is mandatory, and whilst manual measurement using a sphygmomanometer is satisfactory, the additional hands-free luxury of an automated device allows the anaesthetist to attend to other aspects of the anaesthetic. Again, the major reason for failure of these automated machines is the lack of replacement parts, such as the plastic clips that connect the cuff to the tubing of the machine. Gas monitoring (capnography and agent monitoring) is useful and in many countries is now a prerequisite to safe monitoring during anaesthesia. However, machines with this capability need regular servicing and recalibration, which is seldom available in the developing world.

Consumables and drugs

Regional and hospital departments responsible for purchasing, storage and distribution of essential equipment and drugs are frequently inefficient and poorly organised (Fig. 3). Stock levels may not be accurately known and so continuous supply of essential drugs and disposables

OJB, Anaesthetic officer

I qualified as an anaesthetic officer after 1 year of training and travelled back to the mission hospital to practise on my own. One month later, a 22-year-old patient presented with a painless, mobile swelling in the right hypochondrium. The doctor examined the patient and recommended an explorative laparotomy.

After explanation and obtaining her consent, we took the patient to the operating room. At that time (1995) the commonest anaesthetic was either ketamine drip or draw-over anaesthesia with halothane and a facemask. I discussed the case with my senior in the station and decided on the latter.

We had a laryngoscope available but I was unable to intubate the patient as we only had paediatric tracheal tubes (I had requested them but this was still being looked into). The only monitoring I had for the operation was my precordial stethoscope, blood pressure cuff, my eyes, my fingers and my perception.

Ten minutes into the operation, I realised the facemask was filling up with fluid. When I removed the facemask to check, the whole buccal cavity was full of stomach contents. By now the patient was not breathing and had become cyanosed. I performed a head tilt, chin lift and aggressive suction to the pharynx but I think I was rather late.

I managed to re-establish respiration, but on auscultation I could hear added sounds in the basal areas of the lungs.

The operation was completed and the patient was taken back to the ward for further observation but later died that night. I strongly believe that this patient died of aspiration of acidic stomach contents. I will never forget this patient who died because I did not have a tracheal tube.

cannot be relied upon and may be interrupted without warning. In the authors' experience all drugs and consumables, however essential, are susceptible to periods of shortage and absence; examples are halothane (in many countries the sole inhalational agent in use), suxamethonium (other muscle relaxants are seldom available), oxytocin, intravenous cannulae, intravenous fluids, sterile and non-sterile gloves, spinal needles and ketamine [1]. The result is that many single-use pieces of equipment, such as tracheal tubes, are used repeatedly, far in excess of the manufacturer's guidelines, often without satisfactory disinfection between patients.

Halothane and ether are still widely used in some countries, mainly because they are relatively inexpensive. Halothane is appropriate for use during both induction and maintenance of anaesthesia. Ether does not depress respiration, which is useful if no oxygen is available. It is an excellent analgesic and does not depress the cardiovascular system, which is helpful in the shocked patient. Ether has some significant disadvantages and is no longer used in the developed world – it is pungent and has high lipid solubility with very slow onset and offset, making it difficult to use for inhalational induction. Significant postoperative nausea and vomiting is associated with its use and it is flammable in air and explosive in oxygen [7]. Although not cheap, at about US\$50 per 200-ml bottle, the decrease in use of halothane in the developed world has led to a fall in its profitability to manufacturers. The loss of this excellent agent to anaesthesia practice would be catastrophic given the expense of the newer agents.

Donations and foreign aid

Nearly 80% of healthcare equipment in developing countries is funded by international donors or foreign governments [20]. Inadequate consideration of the resources needed to keep donated equipment operational may even add to the financial and manpower burden that they were intended to assist. Equipment fails because of misuse (due to lack of training), lack of servicing and maintenance, inadequate utilities (water and electricity) and poor consideration of the adverse environment (heat, humidity and dust). Guiding principles to minimise these issues include effective communication with the recipient (including an expressed and validated need of the recipient), integration with existing healthcare priorities, and avoidance of double standards in quality – if an item is unacceptable in the donor country, it is unacceptable as a donation [20]. Recommendations more specific to anaesthesia are given by the WFSA [21].

To be genuinely sustainable, projects supporting developing countries must be funded by an organisation

or government department that commits to long-term financial support for the project. True sustainability is only achieved where the ultimate goal is that the project is taken over, run and financed by the country's own administration and staff. In the author's experience (BM), even projects lasting 7 years or more, rapidly dwindle once the financial and staffing support is withdrawn [4]. Often the financial surge that accompanies a period of donor support from a foreign Government or NGO (non-governmental organisation) creates an artificial abundance of this equipment and consumables. In reality, a change of government in the donor country can lead to rapid withdrawal of support and the resultant situation may be worse than before the intervention. In many situations, the country's own systems and infrastructure for purchasing and distribution of even basic necessities becomes crippling inadequate, whilst money and resources are being obtained from an alternative source. Money often reaches individual departments and facilities in a piecemeal fashion, and it is only in recent years that donor agencies have tried to co-ordinate networks, working with local healthcare organisations to oversee the activities of numerous small donors.

Conclusion

Widespread safe anaesthesia will remain unachievable until robust functioning health systems are established that can reliably provide anaesthetists in all types of hospitals with the basic requirements for anaesthesia, such as oxygen, electricity, equipment and consumables. Further research and development by industry and individuals is needed to design equipment optimally suited to the austere conditions of the developing world. A commitment by industry to maintain the production of low cost anaesthesia equipment, drugs and consumables, suited to use in the developing world, would contribute greatly. Increased awareness of the obstacles to effective donation of equipment to developing countries is required, as is the development of schools of biomedical engineering to make best use of available equipment and allow sustainable development in the years ahead.

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