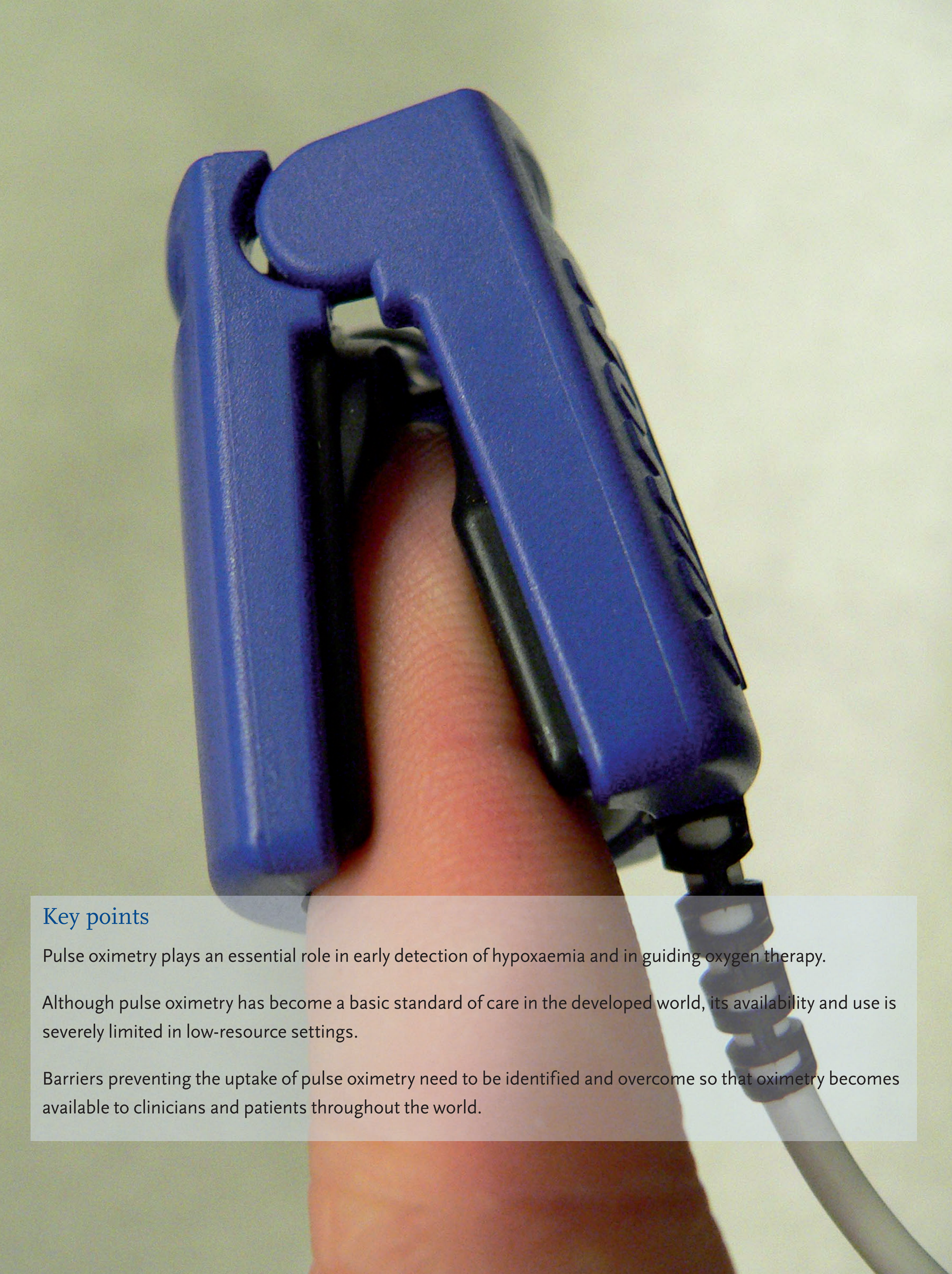

Key points

Pulse oximetry plays an essential role in early detection of hypoxaemia and in guiding oxygen therapy.

Although pulse oximetry has become a basic standard of care in the developed world, its availability and use is severely limited in low-resource settings.

Barriers preventing the uptake of pulse oximetry need to be identified and overcome so that oximetry becomes available to clinicians and patients throughout the world.

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Pulse oximetry in low-resource settings

Educational aims

- To increase awareness about the issues of making pulse oximetry available in low-resource settings
- To increase awareness of the World Health Organization Surgical Safety checklist and how this has triggered the concept of Global Oximetry.
- To discuss the relevance of increasing availability of pulse oximetry to areas other than operating theatres (such as medical wards) in hospitals in low-resource settings.

Summary

Pulse oximetry is used to detect hypoxaemia. It is widely used in both the pre-hospital and hospital settings in developed countries and has become a basic standard of care. There are substantial differences in healthcare between developed and developing countries and it has been recorded that surgery is associated with a much higher number of complications and deaths occurring in resource-limited settings. To address this issue, the World Health Organization (WHO) introduced the Safe Surgery Saves Lives Programme in 2007. With this programme, the WHO Surgical Safety Checklist was launched. Included in this checklist is the step to ensure that a pulse oximeter is on the patient and functioning. WHO now has the Global Pulse Oximetry Project, an initiative to promote the use of pulse oximeters in every operating room in the world. The Lifebox project is a charity that aims to help the supply of pulse oximeters at low cost to anaesthesia providers in low-resource settings.

Increasing availability of pulse oximetry in low-resource settings is relevant to all physicians because hypoxaemia is a common complication of many illnesses, particularly pneumonia. Pneumonia impacts developing countries disproportionately, and accounts for over 2 million deaths a year worldwide. Hypoxaemia is a recognised risk factor for death, correlates with disease severity and is difficult to detect clinically until cyanosis is present. Oximetry plays an essential role in early detection of hypoxaemia and in guiding oxygen therapy, which is often a scarce resource.

Statement of Interest
I.H. Wilson is president of the Association of Anaesthetists of Great Britain and Ireland and is a trustee of Lifebox.

HERMES syllabus link: Module D.1.4

Oximetry

Hypoxaemia can be detected using clinical signs, blood gas analysis or pulse oximetry.

Clinical signs are often unreliable in the diagnosis of the presence or absence of hypoxaemia. For example, cyanosis has poor sensitivity: the lack of cyanosis, despite severe significant central nervous system symptoms from hypoxaemia was recognised by J.S. Haldane in 1920 [1]. Blood gas analysis is expensive, invasive and provides a single measure in time only. Anaemia is a common condition in poorer parts of the world and makes the detection of cyanosis more difficult.

Oximetry is the determination of arterial oxygen saturation of haemoglobin by comparing absorbance of light of different wavelengths by blood. It relies on the principle that absorbance of light energy by haemoglobin depends upon its level of oxygenation. Oxygenated and deoxygenated haemoglobin (HbO and Hb respectively) have different absorbance spectra. Comparison of absorbances at different wavelengths allows estimation of the relative concentrations of HbO and Hb (*i.e.* arterial oxygen saturation (S_{aO_2})).

Pulse oximetry is the accepted standard for detecting hypoxaemia. It was introduced in the 1980s and is now widely used in modern healthcare systems as a basic monitoring tool. It is simple, non- invasive technique and when used correctly, can provide reliable monitoring without distress to the patient. Using a probe placed on the finger, toe or ear lobe, the absorption of light (emitted by light emitting diodes (LEDs)) passing through tissue is measured and processed to produce a reading of pulse rate and oxygen saturation.

Pulse oximeters are reliable and robust devices. The component parts include the probe, which is delicate and will generally last 6–12 months unless damaged, the power supply (mains or battery), the processor and the display.

Use of pulse oximeters

The importance of pulse oximeters was quickly recognised in many different clinical areas, particularly in intensive care, anaesthesia, respiratory medicine, paediatric and emergency care. Since the late 1980s they have been introduced into all clinical areas, including home therapy.

In addition to monitoring for hypoxaemia, pulse oximeters can be used to ensure the most efficient use of oxygen therapy, which is especially important in resource-limited settings, where oxygen may be scarce. Furthermore, oximetry is considered essential in neonatal practice to prevent the devastating complication of blindness due to retrolental fibroplasia, which is caused by excess use of oxygen.

Pulse oximetry for anaesthesia and surgery

For more than 20 years, the use of pulse oximetry for anaesthesia monitoring during surgery has been a standard of care in the developed world. Pulse oximeters are used in nearly every procedure that involves anaesthesia or sedation. The safety of anaesthesia improved dramatically following the availability of routine oximetry, and the risk of mortality from anaesthesia reduced from around 1:10,000 to 1:100,000–1:200,000. Other developments happening around the same time, including capnography, training, drugs and equipment, also contributed to improving patient safety during anaesthesia. However, these safety practices have not been routinely instigated in the developing world. Estimates suggest that more than half of operating rooms are not equipped with pulse oximeters.

It has been estimated that over 230 million surgical procedures are performed around the world each year [2]. In the developed world, 3–16% of hospitalised surgical patients have major complications and nearly 1% experience permanent disability or death as a result of their operation [3, 4], If these numbers are extrapolated globally, at least 7 million people develop serious complications and 1 million die; 50% of these complications are thought to be preventable [5].

Due to substantial differences in the safety of surgery between developed and developing countries, a disproportionate number of complications and deaths are likely to occur in resource-limited settings. Anaesthesia death rates in these settings are reportedly 100- to 1,000-times higher than in the developed world [6]. For example, a mortality rate of 1:133 has been recorded in Togo, mostly hypoxia related [7].

The WHO Surgical Safety Checklist

To improve the safety of surgery, WHO launched the Safe Surgery Saves Lives programme in 2007 [8]. One goal was to define a minimum set of surgical safety standards that could be applied in all countries and hospital settings. The result was the WHO surgical safety checklist, which was launched in June 2008 [9]. The checklist is simple and can be completed in less than two minutes.

Over 280 professional bodies, hospitals and ministries of health have approved the checklist, which includes a set of basic steps to follow before, during and after surgery. Examples of the steps include: confirming patient identity, recording medication allergies, administering antibiotics on time, counting instruments, sponges and needles and ensuring that a pulse oximeter is on the patient and functioning.

At the time of the checklist launch, WHO released preliminary results from over 1,000 patients in eight pilot hospitals across the world. The checklist nearly doubled the chance that patients would receive proven standards of surgical care and substantially reduced complications and deaths [10].

The WHO decided that pulse oximetry should become a standard of care and feature as a requirement on the checklist. Following the publication of the checklist, the WHO and the World Federation of Societies of Anesthesiologists (WFSA) confirmed oximetry as a standard of care for all patients undergoing anaesthesia and surgery [11, 12].

Despite the establishment of pulse oximetry as a monitoring standard, the technology is still not currently available in many operating rooms around the world. WHO started the Global Pulse Oximetry Project, an initiative to improve the availability of pulse oximeters in every operating room in the world.

Although it has been estimated that around 77,000 operating rooms need pulse oximeters in resource-poor settings, the overall figure is much higher. If all clinical areas are taken into account, the numbers of oximeters required has been estimated at over 1,000,000 [13].

Barriers to achieving global pulse oximetry

The relatively high initial cost of pulse oximetry technology has been a significant barrier in many developing world settings. Markets in resource poor areas are small and manufacturers do not find it profitable to make the investment in developing a sales infrastructure in many economies.

Operating theatres have to compete for funds with other parts of the hospitals and capital investment is often low, limiting the availability of all equipment that might not be considered absolutely essential.

Where pulse oximeters have been purchased, the costs are generally higher than in well-resourced settings due to the difficulty of market creation and resultant small numbers of orders.

The fragility of the probe is another problem; in many settings, donated oximeters lie unused in cupboards due to broken probes, which have not been, or cannot be replaced. Spare probes may be prohibitively expensive in this setting, as a single import.

Affordability is not the only factor affecting accessibility of pulse oximetry in low-resource settings. As with all equipment, challenges of distribution within country including importation and taxation costs, coupled with inadequate supply chains pose difficulties. An absence of a reliable electricity supply is common, requiring battery function.

Many countries have a serious lack of trained healthcare workers. This difficulty is greatest in sub-Saharan Africa, which has 11% of the world's population and 24% of the world's disease burden, but only 3% of the world's healthcare workers. Although pulse oximetry is a simple technique, there is still a requirement for interpretation by someone trained in their use. 75% might be considered an excellent exam result, but it is a dangerously low oxygen saturation. Training is required to understand the implications!

The realities of workforce and training have been highlighted in anaesthesia. In 2007, Uganda had around 15 physician anaesthetists for a population of 27 million. The UK has 12,000 physician anaesthetists for a population of 60 million. Due to the severe shortage of physician anaesthetists in Uganda, most anaesthetics are administered by 350 anaesthetic officers in the country who have received only

Educational questions

1. Light is absorbed by haemoglobin at different frequencies. Which of the following statements are true?
   a. Absorption of light by oxyhaemoglobin is greater at 660 nm than 940 nm
   b. For deoxyhaemoglobin, absorption of light is much greater at 660nm than 940nm
   c. At 860nm, both oxyhaemoglobin and deoxyhaemoglobin have the same rate of absorption
   d. Carboxyhaemoglobin absorbs light at 660nm
   e. Methaemoglobin absorbs light at the same frequency as deoxyhaemoglobin

2. Which of the following statements regarding oxygen transport in the blood are true?
   a. pO_2 depends on the amount of O_2 bound to Hb
   b. Each Hb molecule can bind to four O_2 molecules
   c. Hb binds to O_2 more avidly at lower pH
   d. The Bohr effect refers to the effect of temperature on the Hb–O_2 dissociation curve
   e. In the lungs, the Hb–O_2 dissociation curve is shifted to the left

3. Which of the following statements about pulse oximetry are true?
   a. Burns from LEDs may occur in poorly perfused patients
   b. Pulse oximeter accuracy is between $\pm$2% between 90–100% SpO_2
   c. Acute changes are not detectable
   d. Pulse oximeters detect saturation and adequacy of ventilation
   e. External fluorescent lighting can interfere with pulse oximetry readings

4. What is the leading cause of death in children under 5 years of age?
   a. Gastroenteritis
   b. Pneumonia
   c. Malaria
   d. Acute asthma
   e. Meningitis

1–2 years of anaesthesia training. Electrical supplies were constant for only 20% of providers and 10% of anaesthetic providers worked without an oxygen supply. The item most frequently unavailable for 75% of providers was a pulse oximeter [14].

Pulse oximetry outside the operating theatre in low-resource settings

The launch of the WHO Surgical Safety Checklist has meant that much of the focus on pulse oximetry availability in low-resource settings has been on operating theatres. Data on availability of pulse oximetry on wards and other areas of hospitals in low-resource settings is lacking.

Hypoxaemia is a major cause of morbidity and mortality associated with chronic and acute lung disease in children and adults. Oxygen has been available as therapy for hypoxaemia and used with significant clinical benefit for more than a century. It is a life-saving therapy in many critical serious illnesses that can and should be widely available. Unfortunately, oxygen therapy is often scarce in low- and middle-income settings that have by far the greatest burden of death due to lung disease.

Every year, nearly 9 million children die mostly from preventable or treatable diseases, and more than 95% of these deaths occur in developing countries. Pneumonia is the leading cause of death in children under 5 years of age, responsible for an estimated 18% of all deaths in this age category. Hypoxaemia is a major fatal complication of pneumonia [15]. If pneumonia is combined with hypoxaemia, as happens in 13% of cases, children are 5-times more likely to die than are those with only pneumonia [16].

Even conditions that are rarely complicated by hypoxaemia contribute considerably to the global hypoxaemia burden because they are so common. For example 3–5% of all hospitalised cases of malaria have hypoxaemia. Of 13,183 children aged $\geqslant$60 days admitted to a district hospital in rural coastal Kenya, 5.3% were hypoxaemic and the most frequent final diagnoses among hypoxaemic children were malaria (35%), pneumonia (32%), malnutrition (10%) and gastroenteritis (7%) [17].

Apnoea and hypoventilation may occur in otherwise healthy premature babies due to immature respiratory drive, and in babies of any gestational age with sepsis, asphyxia, seizures or hypoglycaemia. Cautious oxygen therapy, to avoid the preventable complication of fibrolental hyperplasia, is often necessary for these common conditions that cause the large proportion of the neonatal deaths occurring globally each year [18].

Therefore, oxygen is a therapy that is a basic requirement to save lives of seriously ill patients and is included on the WHO "Essential Medicine" list. Despite this, it is frequently unavailable in primary health facilities and small hospitals.

Clearly where oxygen supplies are limited, the best use of a scarce resource has to be made. Oximetry accurately determines the need for oxygen, how much is required and for how long.

Pulse oximetry specifications

Having adopted the concept of Global Oximetry, WHO developed specifications for pulse oximeters that would be suitable for the environment of resource poor hospital operating theatres (table 2) [19].

Pulse oximetry probe design and prices

There is a wide range of oximetry models on the market. They differ in cost, durability, accuracy and the variety of information they are able to provide. Units available for sale generally fall into three distinct groups:

1. Finger probe pulse oximeters intended for personal use or spot checks.
2. Hand-held units or stand-alone units intended to measure just oxygen saturation and pulse rate only.
3. Multimodal units, which incorporate other parameters such as electrocardiography (ECG), capnography and blood pressure monitoring.

The finger probe pulse oximetry units are currently available from US$20–50. They are able to measure SpO_2 and pulse as a waveform and a numeric digital display. They are lightweight and are even available from

Table 1. Causes of hypoxaemia

Neonates	Children	Adults
Respiratory distress syndrome	Pneumonia	Chronic obstructive pulmonary disease
Birth asphyxia	Meningitis	Acute asthma
Sepsis	Acute asthma	Pneumonia
Apnoea	Acute sepsis	Sepsis
Hypoventilation	Severe malaria	Shock
		Major trauma
		Anaphylaxis
		Acute heart failure
		Pulmonary embolism
		Pleural effusion
		Pneumothorax
		Lung fibrosis
		Carbon monoxide poisoning
		Obstetric and surgical emergencies
		Sickle cell crises

Amazon. Although these units are ideal for personal use and may be used in some limited clinical settings, they are not ideal for the operating theatre environment.

In the operating theatre, the specifications require a more robust model with a screen that is easy to read and an audible signal. Long lasting rechargeable batteries are essential to cope with long power cuts. (Replacement batteries (*e.g.* AA cells) are often expensive and not easily afforded. A cable running from the probe to the readout device means that the screen can be positioned at a distance from the patient and a variety of probes can be attached depending on need (*e.g.* infants or adults). Currently prices vary considerably depending on the features of the machine.

Oximetry requirements for the operating theatre are likely to be different to those required for the ward or outpatient setting. In the ward or clinic setting, where spot checks of oxygen saturation are performed, less sophisticated and cheaper pulse oximetry models may be more appropriate.

Multimodal monitors are increasingly common in Europe. On the ward, a single unit will monitor S_{pO_2}, pulse rate and non-invasive blood pressure. In theatre, capnography and gas analysis is included. These units are more complex and expensive, costing up to £10,000 for theatre monitoring.

The mobile phone oximeter is being developed using a specialised probe and custom software for a Smartphone. User-friendly software has signal-processing algorithms for oxygen saturation, respiratory rate and heart rate from the plethysmographic waveform. This product may find use in developing countries where mobile phones are widely available. The device and software is still undergoing development and evaluation [20].

The choice of units will always be a balance between utility, reliability and price. However the barriers to purchase at a competitive price will always disadvantage the small order typically placed by healthcare providers in low-resource settings.

Following the WHO initiative, the WFSA conducted a tender exercise to try to source a suitable low-cost pulse oximeter for widespread use by colleagues overseas, selecting a model from Acare, Taiwan (fig. 1).

Lifebox

To facilitate the availability of these oximeters, the Lifebox Project, a charity developed by the WFSA, the Association of Anaesthetists of Great Britain and Ireland (AAGBI) and the Harvard School of Public Health (HSPH), aims to help the supply of pulse oximeters at low cost to anaesthesia providers in not-for-profit hospitals in low-income and low-middle income countries. Details can be found at www.lifebox.org where oximeters are available for $250 including delivery.

In addition, Lifebox provides education in the use of oximetry. This is essential, as many clinicians who have not used this technology

Table 2. Pulse oximetry specifications for hospital operating theatres

Environmental issues and other specifications	Oximeters should comply with relevant standards such as International Electrotechnical Commission (IEC) 69691-1 and International Standards Organisation (ISO)9919:2005. Units should work reliably in a wide range of operating temperatures (*e.g.* 10°C to 40°C) and humidities (*e.g.* relative humidity 15–95%).
Physical features	Units should be robust enough to withstand falls of 1 m onto concrete. Portability and ease of handling is desirable.
Power supply	Units must be able to be powered by rechargeable batteries, normal batteries and mains supply electricity.
Ease of use	Oximeters should be intuitive and simple to use. Interfaces should be language free to the extent possible, although it may be suitable to have configurable language displays.
Alarms	Alarms indicating breaches of safe limits of oxygen saturation should be audible and supplemented with a visible change of display (such as flashing). Ideally an alarm should indicate sensor misplacement.
Oxygen saturation	Arterial oxygen saturation should be measured between clinically relevant limits (*e.g.* 70–100%) with reasonable accuracy (*e.g.* ±2% of true saturation).
Pulse display	The device should have a plethysmograph display of the pulse (either waveform or bar graph). The unit should measure pulse rate between clinically appropriate limits (*e.g.* 20–200 beats·min^{-1}) to ±3 beats·min^{-1}. The pulse rate should also be displayed numerically and be represented by an audible tone, which changes as saturation levels deteriorate.
Display	The readout should be clearly visible from 5 m.
Sensors/probes	Probes should be as robust as possible. A range of sensors covering various sizes and ages of patient should be available, and all probes should be reusable.
Warranties and maintenance	The expected life of the oximeter and probes should be specified and appropriate warranties provided. User and service manuals should be provided, electronically and by hard copy, in a variety of languages.

previously may be unaware of the normal oxygen saturation levels and how to manage a falling saturation. Instruction and information in the use of the WHO Surgical Safety Checklist is also provided.

Lifebox is an innovative approach to procurement for hospitals and ministries. By receiving pooled purchases, a manufacturer is able to construct a more viable business model. The role of specialist professional groups is key to creating demand and also to stimulating donations to the project. Delivery, customs and warranty are all potential issues, but oximetry is a particularly reliable and low-cost technology, suitable for this approach.

Importantly, as Lifebox does not work in wealthy established markets (part of the

Figure 1
The Lifebox Pulse Oximeter.

charitable status), the market for major manufacturers has not altered, but rather new markets are being developed.

Conclusion

There is no doubt that pulse oximetry should become as readily available to clinicians throughout the world as the mobile phone. The technology provides immediate detection of falling levels of oxygen and in the UK and other wealthy settings, are mandated as a part of theatre monitoring.

Patients' lives are saved daily by the availability of pulse oximetry and by healthcare workers trained to react to oximetry readings. It is time that oximeters were universally available and affordable anywhere in the world, not only to patients undergoing surgery and anaesthesia, but also to medical patients. This is a vital patient safety initiative and will need the cooperation and leadership of many people to make this happen.

References

1. Haldane JS. Discussions on the therapeutic uses of oxygen. *Proc Royal Soc Med* 1920; 13: 76.
2. Weiser TG, Regenbogen SE, Thompson KD, *et al.* An estimation of the global volume of surgery: a modeling strategy based on available data. *Lancet* 2008; 372: 139–144.
3. Gawande AA, Thomas EJ, Zinner MJ, *et al.* The incidence and nature of surgical adverse events in Colorado and Utah in 1992. *Surgery* 1999; 126: 66–75.
4. Kable AK, Gibberd RW, Spigelman AD. Adverse events in surgical patients in Australia. *J Qual Health Care* 2002; 14: 269–276.
5. Haynes A, Weiser T, Berry W, *et al.* A surgical safety checklist to reduce morbidity and mortality in a global population. *New Eng J Med* 2009; 360: 491–499.
6. Walker IA, Wilson IH. Anaesthesia in developing countries- a risk for patients. *Lancet* 2009; 371: 968–969.
7. Ouro-Bang'na Maman AF, Tomta K, Ahouanbévi S, *et al.* Deaths associated with anaesthesia in Togo, West Africa. *Tropical Doctor* 2005; 35: 220–222.
8. World Health Organization. Safe Surgery Saves Lives. www.who.int/patientsafety/safesurgery Date last accessed: August 31, 2012.
9. World Health Organization. WHO surgical safety checklist and implementation manual. www.who.int/patientsafety/safesurgery/ss_checklist/en/index.html Date last accessed: August 31, 2012.
10. World Health Organization. New checklist to help make surgery safer. www.who.int/mediacentre/news/releases/2008/pr20/en/index.html Date last accessed on August 31, 2012.
11. Merry AF, Cooper JB, Soyannwo O, *et al.* International standards for a safe practice of anaesthesia 2010. *Can J Anaesth* 2010; 57: 1027–1034.
12. World Health Organization. WHO guidelines for safe surgery 2009. Safe surgery saves lives. http://whqlibdoc.who.int/publications/2009/9789241598552_eng.pdf Date last accessed: August 31, 2012.
13. Howitt P, Darzi A, Yang GZ, *et al.* Technologies for Global Health *Lancet* 2012; 380: 507–535.
14. Hodges SC, Mijumbi C, Okello, et al. Anaesthesia services in developing countries: defining the problems. *Anaesthesia* 2007; 62: 4–11.
15. Duke T, Graham SM, Cherian MN, *et al.* Union Oxygen Systems Working Group. Oxygen is an essential medicine: a call for international action. *Int J Tuberc Lung Dis* 2010; 14: 1362–1368.
16. Ashraf H, Jobayer M, Alam N. Treatment of childhood pneumonia in developing countries. www.intechopen.com/books/health-management/treatment-of-childhood-pneumonia-in-developing-countries. Date last accessed: August 31, 2012.
17. Mwaniki MK, Nokes DJ, Ignas J, *et al.* Emergency triage assessment for hypoxaemia in neonates and young children in a Kenyan hospital: an observational study. *Bull World Health Organ* 2009; 87: 263–270.
18. Lawn JE, Cousens S, Zupan J, *et al.* 4 million neonatal deaths: When? Where? Why? *Lancet* 2005; 365: 891–900.
19. World Health Organization. WHO Global Pulse Oximetry Project background document. www.who.int/entity/patientsafety/events/08/1st_pulse_oximetry_meeting_background_doc.pdf Date last accessed: August 31, 2012.
20. World Health Organization. Compendium of new and emerging technologies that address global health concerns 2011. Mobile phone pulse oximeter. www.who.int/medical_devices/innovation/new_emerg_tech/en/index2.html Date last accessed: August 31, 2012.

Suggested answers

1. b, d, e.
2. b, e.
3. a, c, e.
4. b.