

Implementing an oxygen programme in hospitals in Papua New Guinea

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Abstract In Papua New Guinea (PNG), the most common cause of death among children under 5 years of age is pneumonia. Children with severe pneumonia need antibiotics and oxygen but oxygen shortages are common owing to the cost and complex logistics of transporting it in cylinders. Detection of hypoxaemia using clinical signs can be difficult, especially in highly pigmented children in whom cyanosis is difficult to recognise. Pulse oximetry is the most reliable, non-invasive way of detecting hypoxaemia. However, most hospitals in PNG do not have pulse oximetry. We proposed that the installation of a reliable, sufficient and cheap supply of oxygen in hospitals coupled with the use of pulse oximetry would make a significant difference to child survival rates in PNG. Oxygen concentrators, which extract oxygen from ambient air, were installed in the children's wards of five hospitals during 2005. Pulse oximeters were also introduced to enable better detection of hypoxaemia. This paper describes the technical aspects of this programme: the equipment used and the rationale behind choosing it, the installation, commissioning and testing processes. The ongoing training of clinical and engineering staff as well as two follow-up evaluations are described.

Introduction

Pneumonia is the major disease causing death in infants and children in PNG.¹ The lethal complication is usually hypoxaemia.^{2,3} Besides pneumonia, hypoxaemia also occurs in infants with other common diseases.^{4,5}

Pulse oximeters to detect hypoxaemia were introduced into five provincial and district hospitals, beginning in June 2004. Nurses and doctors were trained to use

pulse oximetry following a protocol for monitoring all children on admission and throughout their hospital stay. For the purposes of this study, and based on previous research into the normal values of SpO₂ for Papua New Guinean infants and children at various altitudes, hypoxaemia was defined as SpO₂ <90%.^{4,6} The normal values at sea-level are in the range of 95–98% but decrease to 93–96% in the PNG highlands (1500–1800 m).⁴

Oxygen shortages have commonly occurred in hospitals in PNG.⁷ Until now, oxygen has been available only as high-pressure gas in cylinders, and individual hospitals have been responsible for transporting them over long distances from regional depots. Limitations of transport

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and funding have led to shortages of oxygen in PNG hospitals.

Oxygen concentrators offer a reliable means of generating >85% oxygen from ambient air, provided that a continuous source of electrical power of 230 V/50 Hz is available. Table 1 compares the characteristics of oxygen concentrators and cylinders.

Five hospitals with suitable electrical power from the mains were identified and most also had back-up generators. Three of the hospitals were in the highlands (Mt Hagen, Kundiawa and Mendi) where pneumonia accounts for about 38% of all paediatric admissions. The other two hospitals (Maprik and Wewak) are in lowland/coastal areas and had a lower incidence of pneumonia (about 18% of all paediatric admissions).⁷

Methods

Structure of the programme

The programme consisted of four phases:

- (i) Retrospective analysis of records for 20,000 consecutive admissions of

infants and children under 12 years of age to the five hospitals.⁷

- (ii) Introduction of pulse oximeters in the five hospitals and training in their use, followed by a prospective study of the incidence of hypoxaemia and the resources available to manage it in 1300 children admitted to the five hospitals. This phase showed that hypoxaemia was very common in hospitalised children—40% of all children admitted to highland hospitals and 10% admitted to coastal hospitals had SpO₂ <90%. Additionally, clinical signs were poor predictors of hypoxaemia and there were major resource deficiencies in the supply of oxygen in all hospitals.⁷
- (iii) Installation and introduction of oxygen concentrators in the five hospitals, with training of nurses, doctors and hospital engineers/technicians in June and July 2005.
- (iv) Follow-up evaluation.

This paper describes the third and fourth phases. The technical basis for the selection of equipment, the steps in procuring,

TABLE 1. Comparison of oxygen cylinders and concentrators.

	Oxygen cylinders	Oxygen concentrators
Power source required	No.	Yes, continuously.
Transport requirement	Regularly, by air only in chartered aircraft, heavy and costly to transport.	Only at time of installation.
Exhaustible supply	Yes, standard cylinders last 2–3 days at most with continuous use.	No, continuous supply as long as power supply is uninterrupted.
Establishment equipment costs	Oxygen flow-meter (c. \$400) and regulator (c. \$200 per cylinder) costs moderate.	Moderate up-front equipment cost (about \$US1000) plus installation and commissioning, training.
Ongoing costs	Cylinder refill costs relatively small (\$30) but frequent, costs of transport from refilling station to hospital.	Small: electricity, maintenance.
Maintenance	Minimal.	Considerable, both preventive maintenance and intermittent repairs. Spare parts required.
Training	In clinical use of oxygen and pulse oximetry, plus day-to-day trouble-shooting of cylinders and connections.	More, in preventive maintenance of concentrators, training of hospital engineers/technicians, clinical use of oxygen and pulse oximetry.

commissioning and installing the oxygen concentrators and associated equipment, and the training of clinical and engineering staff in the use and maintenance of the equipment are outlined. These management and technical aspects are described in detail in the hope that it will assist others planning similar programmes. Early evaluation of the sustainability of equipment is also described.

Results

Preparation for implementation

Identification of suitable oxygen concentrators and pulse oximeters. To identify suitable concentrators, we sought recommendations made by WHO and other agencies. A survey of oxygen concentrators, commissioned by WHO in 2003, compared the specifications of eight models from six different manufacturers.⁸ These concentrators delivered 4–8 L/min oxygen at a concentration >85%. The survey compared all the details listed in Table 2 which outlines the specifications for oxygen concentrators suitable for use in a children's ward in a developing country. Five AirSep *Elite* concentrators (AirSep Corporation, Buffalo, New York, USA) were purchased by the PNG National Department of Health, through the Health Services Support Programme (HSSP) funded by the Australian Government. Ten further AirSep *Intensity* concentrators were donated by the AirSep Corporation.

Less information on suitable pulse oximeters was available. We drew on the experience in one hospital in PNG where oximetry had been used effectively, and designed specifications for oximeters suitable for children's wards in developing countries (see Textbox 1). In 2004, each hospital received one oximeter and several sensor probes.

Procurement, planning and distribution. The oxygen concentrators and pulse oximeters were transported to Port Moresby by air and

then distributed within PNG by the National Department of Health (NDOH). We developed a model for estimating oxygen requirements in each hospital according to caseload (Table 3).

Flowsplitter. An important accessory for efficient use of oxygen concentrators in developing countries is a means of dividing the flow to serve more than one patient at the same time. Flowsplitters that have been used for this purpose typically have four separate orifices, all of which deliver an equal proportion of the total flow when opened by connecting the delivery tubing.

TABLE 2. *Specifications for oxygen concentrators suitable for use in a district hospital children's ward.*

Achievement of >85% oxygen concentration at flow range 4–8 L/min
Usual operation at 240 V ± 15%, 50 Hz power supply that does not exceed 450 watts. However, check local power supply requirements and compatibility
Efficiency at maximum flow not less than 800 L/kilowatt hour
The concentrator has 1 or 2 outlets with individual flow controls/indicators
Accuracy of flow indicator shall comply with ISO 8359:1996 clause 50.3 ¹²
Outlet pressure should not be less than 45 kPa
Concentrator should be fitted with a means to limit the total flow delivered to not more than 1 L/min above the maximum flow specified by the machine
Weight to not exceed 25 kg
Hour meter to record total running hours
Maximum operating altitude shall be not less than 2000 m with >85% oxygen concentration at maximum flow
Maximum operating temperature not less than 40°C
Maximum operating humidity not less than 95% relative humidity
Includes a list of all the spare or replacement parts for 40,000 hours of operation (e.g. compressor, sieve beds, valve spares kits)
Four-way flowsplitter together with all adaptors and connectors which can deliver flows of 0.5, 1.0 and 2.0 L/min
The concentrator should comply with ISO 8359:1996, ¹² IEC 60601-1 ¹³ and carry a CE marking
A user manual intended for hospital use and a service manual with a trouble-shooting guide should be provided
At least 12 months warranty

TEXTBOX 1. *Lessons on the purchasing and use of pulse oximeters suitable for children's wards.*

- Know the voltage range and the frequency of the mains power source in which the pulse oximeter will be used. Models are typically available for 240 V 50 Hz, 240 V 60 Hz, or 120 V 60 Hz.
- There are many types of oximeter, including hand-held and table-top devices. Desktop models cost c. US\$1000, smaller versions \$100 or less. Hand-held models might be more liable to theft and the internal battery might not be re-chargeable from mains power.
- Weight, operating temperature and operating humidity should all be considered.
- A hard, robust casing is necessary to prevent damage.
- Accuracy range is usually $\pm 2\%$ at SpO₂ 70–100%.
- Range of heart rate measurements 0–250/min.
- It is important that the internal battery can be re-charged by mains power.
- Duration for which the oximeter can run on the internal battery should be c. 8 hrs.
- A plethysmographic display (either a waveform or a liquid crystal bar-graph) is useful for determining accuracy of measurement. The pulse oximeter should comply with ISO 9919:2005, IEC 60601-1,^{12,13} and carry a CE marking.
- The factor limiting pulse oximetry is the oxygen sensor probes. With appropriate care, good quality probes can last 12 months. Suppliers should be selected on the basis of a guarantee of 12 months product use. Oximeters can be bought with a commitment to supply sensor probes for 5 years to ensure machines do not fall into disuse because the probe malfunctions.
- Sensor probes with soft casings are available that can be used interchangeably on neonates, infants and older children.

To calculate the flow to each patient, the total flow setting on the flow-meter of the concentrator is divided by the number of delivery tubes connected to the flow-splitter.

A consequence of this arrangement is that patients receiving oxygen from tubing connected to one flow-splitter will all receive it at the same flow. Therefore, to maximize the

TABLE 3. *The basis for oxygen provision in the five hospitals.*

Hospital	Concentrators	Total paediatric beds supplied with oxygen	Pneumonia cases/mth*	Estimated oxygen requirement (days/mth) [†]	Maximum oxygen provision (patient days/mth) [‡]
Mt Hagen	1E + 3I	28	78	120	840
Kundiawa	1E + 2I	20	36	55	600
Mendi	1E + 2I	20	34	52	600
Wewak	1E + 2I	20	14	22	600
Maprik	1E + 1I	12	13	20	360

E, AirSep *Elite*; I, AirSep *Intensity*. * There are seasonal variations in case-loads; these monthly averages are derived from several years' data. [†] Estimated oxygen requirement (patient days/mth) = average case-load of children with pneumonia \times % of hospitalised pneumonia cases with hypoxaemia (55%) \times average duration of hypoxaemia for children with pneumonia (2.8 days). [‡] Maximum oxygen provision (patient days/mth) is with all concentrators and outlets used (i.e. all beds supplied with oxygen \times 30 days/mth). Given the marked seasonal variation in case-load and that hypoxaemia also occurs in PNG in some common conditions other than pneumonia, especially in newborns and young infants, it was considered that the estimated oxygen requirement based on pneumonia should be the minimum provided.

number of children who could receive oxygen at the same time, children requiring the same flow would have to be in adjacent beds. This is consistent with the ideal of cohorting the sickest children in a high dependency area of the ward. Flowsplitters of this kind were significantly cheaper and more easily mounted on the concentrator than previous models and one aim was to evaluate the performance of the new design.

Delivery tubing and nasal prongs. As a consequence of the choice of flowsplitter, it was necessary to provide identical delivery tubing and nasal prongs for each patient connected to the same flowsplitter. A single 7.5-m length of non-crush delivery tubing was used for each patient and was connected to nasal prongs by an in-line connector to enable the prongs to be changed for each patient. Three types of prongs (for neonates, infants and children) were provided in appropriate numbers for 2 years of use. An appropriate regimen was developed for cleaning and testing nasal prongs to permit re-use.

Implementation

A national oxygen team. The implementation process was planned by the NDOH. A team was assembled for installation and training in the highland and coastal hospitals and consisted of a paediatrician, a consultant biomedical engineer, a biomedical engineer from the NDOH and an administrator. Two days were spent at each hospital and 1 day was required for travelling between hospitals.

Commissioning. The oxygen concentrators were unpacked at each hospital, carefully inspected for damage and individually tested for conformity to the manufacturer's specification using a protocol designed for the project. Oxygen concentration at a series of increasing flows was recorded using an independent oxygen analyser (Hudson RCI, <http://www.hudsonrci.com/>). The maximum delivery pressure was checked with a calibrated gauge at zero flow.

One of the *Intensity* models was initially found to produce low oxygen concentrations and another *Intensity* model gave a continuous alarm. These problems were communicated to the manufacturer by email whose response allowed rectification within 24 hours. Both problems were caused by kinks in tubing. All 15 concentrators met the manufacturer's specifications and none was damaged in transit. Hospital engineers, paediatricians and nurses were involved in these commissioning activities as a means of training them in the functioning of concentrators.

Installation. Oxygen concentrators were installed at each hospital with assistance from the local hospital engineers or technicians. A suitable location was identified during discussions with nurses and doctors from the wards. Hospitals were advised to ensure that a back-up oxygen supply of at least one cylinder was available.

The concentrators were installed with a 4-way flowsplitter connected in line with each flowmeter so that the *Elite* model served four beds and the *Intensity* model served eight. Typically, there were two or four beds on either side of the concentrator. In one hospital, only three beds could be supplied from one flow-meter because of the layout of the ward.

For each bed, 7.5 m of oxygen-delivery tubing was mounted inside a 32-mm diameter electrical conduit which was then fastened to the wall by saddle clamps. A tee fitting was positioned at each bed so that one delivery tube was led to that bed. Excess delivery tube was loosely coiled and mounted on a cup hook screwed into the wall. It was important to keep the delivery tubing for each bed of equal length to ensure equal resistance. The ends of the conduit were capped and sealed to prevent colonisation by insects and collection of dust.

Testing after installation. Following installation of all the delivery tubing for one concentrator outlet (with one flow-meter), a flow of 4 L/min was set and the flow from

each delivery tube was checked using a test flow-meter with a maximum scale of 2 L/min. In all cases, equal flows of 1 L/min were seen from each outlet. Further checks on each machine showed four equal flows of 0.5 L/min from a total flow of 2 L/min.

After this demonstration of equal flow from the delivery tubing, nasal prongs were attached to each tubing outlet, and flow from the prongs was checked by immersion under water. A difference of bubbling rate between 0.5 and 1 L/min was observed.

Training. Training material for nursing and medical staff and technicians was developed and refined during the project. The training process consisted of an introductory PowerPoint presentation for users and technicians, followed by a hands-on session with small groups. Multiple training sessions were held at each location to cover shift workers. Signed attendance sheets were completed in each hospital.

User maintenance of these oxygen concentrators is very simple and requires only one filter to be washed at weekly intervals. The manufacturer states that no technical maintenance is required until the compressor is replaced after about 20,000 hours of operation. A training course on compressor refurbishment and replacement is being planned for local and national technicians.

Short instructions for use were laminated and copies attached to each concentrator. It was strongly recommended that 'No Smoking' signs be displayed beside each concentrator.

Follow-up evaluation

A review of the programme using a WHO assessment tool was conducted in August 2006, 14 months after initial installation. All but one of the 15 oxygen concentrators were functioning to the manufacturer's specifications (providing >85% oxygen when set to a maximum flow of 5 or 8 L/min). One concentrator, which was not being used by staff because they said it did not make

children better, was producing a low concentration of oxygen because of moisture in the sieve beds. In the following 14 months, a further four concentrators malfunctioned. The causes of equipment failure were worn-out seals from a compressor (1), loose connections leading to leaks between valves and sieve beds (1), a faulty feed valve solenoid (1) and accumulation of moisture in the sieve beds owing to over-running the concentrators at flows exceeding maximum (1). A further six concentrators, all at high-altitude locations, had no faults but could only produce 85% oxygen concentration at 7 L/min.

Several pulse oximeter sensor probes had failed and been replaced by clinical staff, without interruption to use. One oximeter was not functioning because of dirt between the infra-red light source and the digital sensor probe cover, and a loose connection of the re-chargeable battery of another oximeter had limited its use as a portable device.

In the 1st 2.5 years, therefore, equipment failure not immediately recognised and corrected by clinical staff occurred in one-third of concentrators and two of five oximeters. In general, there was under-use of pulse oximetry. This was addressed by the oxygen team and given greater emphasis during training for expansion to three more hospitals in 2007. Regular visits to the hospitals by the oxygen team and regular communication allowed problems to be identified and addressed as they arose.

Key lessons learned are described in Textboxes 1 and 2.

Discussion

We have described the technical aspects of implementing a programme for effective detection of hypoxaemia and provision of oxygen in hospitals in PNG and outlined some of the lessons learned. Previous studies of oxygen concentrators suggested them to be much more cost-effective than

TEXTBOX 2. *Lessons learned in the PNG oxygen programme.*

A high-dependency area within a hospital ward where oxygen can be given and near where nurses are most available helps cohort the sickest children in one place.

A multi-disciplinary oxygen team, including a biomedical engineer, a paediatrician or child health nurse and an administrator is desirable to support the organisational, technical and training aspects of oxygen systems. This team provides an important national resource for information and uniform planning.

Technical expertise in procurement, commissioning and installation is important. WHO provides a comparison of specifications for oxygen concentrators for eight different models considered suitable for health facilities in developing countries. The quality of machines on the world market varies widely.

Uniformity of equipment is important where possible to ensure compatibility of spare parts and to limit confusion among health workers and engineers. Spare parts (including filters and sieve beds) should be provided for at least 5 years of operation (or 40,000 running hours).

To get the most out of each concentrator they should be used with a flowsplitter that allows the provision of oxygen to several children at the same time; costing for flowsplitters should be included in the initial costing of each concentrator purchased.

Flow at the end of the delivery tubing should be regularly checked using a flow-meter to ensure that patients are receiving the intended flow of oxygen.

Building local capacity for maintenance and repair within hospitals and the ministry of health is vital; relying on local agents to service equipment might lead to long delays and high costs. Preventive maintenance is essential; failure to do so results in costly repairs and down-time of equipment.

Training should be provided for nurses, doctors and hospital engineers on-site when equipment is being installed in hospitals. Training takes 1–2 days and needs to be reinforced by regular in-service training by the oxygen team. Repeated in-service training is especially important in countries with high staff turnover.

Simple guidelines should be provided for the clinical use of oxygen and the regular preventive maintenance of oxygen concentrators.

Communication and co-operation are necessary between the health department's clinical, bio-engineering and administrative departments, between the national health department and provincial hospitals, and with outside agencies.

Education of parents about the need for oxygen is important to alleviate anxieties. It is very useful to show parents the pulse oximeter reading as it is being done and explain to them when the child's oxygen levels are low. It is also useful to show them the clinical signs (such as chest indrawing or cyanosis of the gums or tongue). When oxygen is then applied, parents will see that the SpO₂ increases and the child's respiratory distress improves, giving parents confidence in the treatment.

oxygen cylinders, but follow-up to just 1 year after installation has been reported.^{9–11}

It is likely that more than a year after introducing new technology new issues affecting function and sustainability will arise. This evaluation has demonstrated that oxygen concentrator systems can be sustained in the medium term in a resource-limited setting. Despite very limited health resources, 2.5 years after implementing the programme concentrators are functioning in all involved hospitals in PNG. Oxygen can be provided as a continuous source using concentrators where there is a continuous

power supply, and pulse oximetry enables the effective detection of oxygen requirements in children.

The experience demonstrates, however, that in such settings sustaining technology and incorporating it into clinical care is a challenge. The strengths of the programme include the team approach adopted and the commitment of those involved.

The success of such programmes depends on many factors which include: expertise in procurement; commissioning and installation of equipment; management capacity in planning and implementation; human

resources (clinical and engineering) and training; simple guidelines and clinical protocols and equipment maintenance, reinforcement and follow-up. A systems and quality approach, drawing on expertise across administrative, clinical and biomedical engineering disciplines is necessary. Ideally, such programmes should be based on local understanding of the burden and epidemiology of acute respiratory disease and hypoxaemia.

With increasing global focus on the management of pneumonia, we hope that more countries will consider developing similar programmes.

Conflict of Interest

Although AirSep donated some of the oxygen concentrators, they had no influence on the study design, data analysis, writing up or decision to publish. None of the authors has been funded by any company involved in this project. There are no conflicts of interest.

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