Solar-powered oxygen, quality improvement and child pneumonia deaths: a large-scale effectiveness study

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ABSTRACT

Background Pneumonia is the largest cause of child deaths in low-income countries. Lack of availability of oxygen in small rural hospitals results in avoidable deaths and unnecessary and unsafe referrals.

Method We evaluated a programme for improving reliable oxygen therapy using oxygen concentrators, pulse oximeters and sustainable solar power in 38 remote health facilities in nine provinces in Papua New Guinea. The programme included a quality improvement approach with training, identification of gaps, problem solving and corrective measures. Admissions and deaths from pneumonia and overall paediatric admissions, deaths and referrals were recorded using routine health information data for 2–4 years prior to the intervention and 2–4 years after. Using Poisson regression we calculated incidence rates (IRs) preintervention and postintervention, and incidence rate ratios (IRR).

Results There were 18,933 pneumonia admissions and 530 pneumonia deaths. Pneumonia admission numbers were significantly lower in the postintervention era than in the preintervention era. The IRs for pneumonia deaths preintervention and postintervention were 2.83 (1.98–4.06) and 1.17 (0.48–1.86) per 100 pneumonia admissions: the IRR for pneumonia deaths was 0.41 (0.24–0.71, p<0.005). There were 58,324 paediatric admissions and 2259 paediatric deaths. The IR for child deaths preintervention and postintervention were 3.22 (2.42–4.28) and 1.94 (1.23–2.65) per 100 paediatric admissions: IRR 0.60 (0.45–0.81, p<0.005). In the years postintervention period, an estimated 348 lives were saved, at a cost of US$6435 per life saved and over 1500 referrals were avoided.

Conclusions Solar-powered oxygen systems supported by continuous quality improvement can be achieved at large scale in rural and remote hospitals and health care facilities, and was associated with reduced child deaths and reduced referrals. Variability of effectiveness in different contexts calls for strengthening of quality improvement in rural health facilities.

Trial registration number ACTRN12616001469404.

INTRODUCTION

Pneumonia is the leading cause of child deaths in low-income and middle-income countries, including in Papua New Guinea (PNG), a tropical country in the Western Pacific. Hypoxiaemia is the major complication causing death in childhood pneumonia. In previous studies in provincial referral hospitals, we showed that improved oxygen systems, which include a reliable source of oxygen therapy using oxygen concentrators, and pulse oximetry for detection of hypoxaemia, can reduce mortality from pneumonia by up to 35%. However, in rural areas in low-income countries, most sick children present to district hospitals and health centres, where there are no reliable sources of therapeutic oxygen. Hypoxaemia occurs in many other common childhood conditions that present to primary health facilities: sepsis, febrile encephalopathy, bronchiolitis, asthma, tuberculosis, HIV-related lung disease, malaria, perinatal problems, trauma, as well as obstetric emergencies and perinatal problems, trauma, and this limits the use of oxygen concentrators and other basic technology and provision of essential health services.

What is already known on this topic?

Pneumonia is the largest cause of death in children globally, and hypoxaemia is the major complication causing death.

Oxygen therapy is life saving, but most health facilities in rural areas in low-income countries do not have reliable oxygen supplies.

Many rural health facilities lack reliable power, and this limits the use of oxygen concentrators and other basic technology and provision of essential health services.

What this study adds?

It is feasible to scale up solar-powered oxygen therapy in rural health facilities in low-income and middle-income countries, and this requires multiple technical, clinical and management inputs and needs to be supported by continuous quality improvement.

Solar-powered oxygen therapy and quality improvement in rural health facilities reduces death rates from pneumonia and other common conditions in children and reduces referrals.

Variability of effectiveness of health interventions in rural health facilities and district hospitals calls for a stronger focus on quality improvement, education and problem solving, and much greater support for human resources.
across and chronic respiratory and cardiac disease in adults.9 10 
Therefore, reliable oxygen systems in rural health facilities may 
reduce deaths from pneumonia, reduce child mortality overall 
and greatly improve the way health clinics and hospitals serve 
the needs of communities.

A major barrier to improving oxygen systems in rural and 
remote settings has been unreliability of power, such that 
concentrators are unable to function because of limited power 
and are damaged by surges in power. Other barriers include the 
long-term reliability of medical devices in such settings, costly 
and challenging logistics of installation of health infrastructure 
in regions where roads are poor or in remote islands. Lack of 
preventative maintenance and capacity for repairs is also a 
barrier to health technology in remote settings. Furthermore, 
there has been a lack of recognition of the importance of oxygen 
as an essential service, difficulties identifying hypoxaemia without 
pulse oximetry, limited training of health workers in the recogni-
tion and management of hypoxaemia and lack of financial 
investment in quality health services.

In PNG as in many countries, there is a significant child 
mortality gradient between rural and urban areas. To address 
this, health infrastructure and quality need to be improved, and 
oxogen and power are components of this. We report the results 
over 7 years of a large-scale study of solar-powered oxygen 
systems in 38 rural health facilities in nine provinces of PNG 
with a total population of over 1.3 million, where we aimed to 
overcome these barriers.

METHOD

The implementation of this programme has been described in 
detail elsewhere.11 In brief, we implemented a programme for 
 improving reliable oxygen and sustainable power in 38 remote 
health facilities, equipment used included Airsep Elite 5 L/min 
concentrators (Chart Industries, New York), Lifebox pulse oxim-
eters (www.lifebox.org), oxygen analysers (Maxtec O2 analyzer, 
Utah, USA) to monitor the performance of concentrators, 4.9 
kw solar power system using 18 240 W solar panels, which 
was designed to produce on average 11.44 kWh/day power 
and a battery back-up, designed to provide 3 days’ autonomy 
at 80% depth of discharge (see online supplemental appendix D).11 12 
Initial steps included community engagement, selection of 
participating health facilities, the specifications and design of 
the solar and oxygen systems, healthcare worker training, 
engineering and maintenance capacity, logistics and programme 
implementation.11 Community engagement involved meetings 
with provincial and district health staff to understand needs 
at the health facility level and where oxygen fitted into prior-
ities, and to hear the experiences of staff in caring for children 
with pneumonia and the potential effect of improving oxygen 
on referral patterns. We selected health facilities on the basis of 
high community burden of pneumonia, lack of reliable source of 
oxogen, limited or unreliable power, and staff being committed 
and enthusiastic to participate. The roll-out of the intervention 
occurred in 2015–2017: most of the facilities were covered 
throughout 2015 to March 2016, two in late 2016 and three 
in 2017.

The settings

The 38 health facilities had wards for overnight care of children. 
Most were in rural districts. The catchment population of the 
health facilities was 1.3 million, out of a total PNG population 
of 8.8 million. The median number of beds was 10 for children 
and 4 for newborns. Twelve of the health facilities had doctors.

All health facilities had one or more nurses: the median number 
was four. Eighteen of the health facilities had a trained paediat-
ric nurse, and the rest were general trained nurses. All health 
facilities had one or more community health workers (median 
number of seven).

Training and continuous quality improvement

We used the WHO guidelines for the Clinical Use of Oxygen in 
Children13 and the WHO Hospital Care for Children training.14 
The training was practical, repeated on several occasions (typi-
cally annually in a regional training course, but this involved 
different healthcare workers from these facilities each time) and 
was reinforced on health centre visits by the provincial paediat-
ricians. The content and delivery of the training is described in 
a previous paper but covered pneumonia care, oxygen 
therapy, the clinical management of other common illnesses in 
newborns and children, monitoring and supportive care.11 We 
taught healthcare workers how to monitor the performance of 
oxogen concentrators using oxygen analysers and about regular 
weekly maintenance. Training was hands-on and practical and 
emphasised continuous improvement, sharing of experiences and 
problem solving. Further details of the continuing education 
programme is described in online supplemental appendix II. Quality improvement was supported by district visits from 
the paediatrician and a technician trained in oxygen and solar 
equipment every 4–6 months and involved on-site training, trou-
bleshooting of identified problems, facilitation of local problem 
solving, audit and feedback.

Data collection and sample size

We gathered data from each of the health facilities on all admis-
sions for children aged birth to 13 years of age: number of 
admissions and number of deaths, number of pneumonia admis-
sions and deaths, number of neonatal admissions and number of 
deaths, and number of referrals. Data were collected per year for 
each facility. The intervention was introduced in 2015–2017; 
most of the facilities were covered throughout 2015 to March 
2016, two in late 2016 and three in 2017. Preintervention data 
were for the years 2012–2016 depending on when the interven-
tion was introduced in the health facility. Postintervention data 
were gathered from the time of intervention installation in each 
facility until July–August 2019, when the last round of health 
facility visits was conducted.

The data were collected from the health facility admission and 
discharge record books, which are generally kept meticulously 
by senior nursing staff in PNG. Each facility has a record book, 
and details of every admission is entered manually; the data 
include patient name, contact address, diagnosis at admission 
and discharge, and outcome.

The primary outcome was a difference in mortality from 
pneumonia between preintervention and intervention eras. 
Secondary outcomes were overall paediatric mortality, neonatal 
mortality and rate of referrals.

In the process of initial engagement with health facilities and 
gathering baseline data, we assessed the quality of data. Initially, 
we gathered data from seven additional health facilities, which 
did not receive the infrastructure intervention, often for several 
reasons: poor road conditions that would not allow a vehicle 
carrying equipment to access the health centre (n=3); the health 
centre was in a state of disrepair (n=3); and there was inadequate 
baseline data quality (n=7).15 These seven health facilities were 
excluded and other health facilities that fulfilled the criteria for 
participation were chosen to replace them; hence, some facilities
received the intervention later, in 2016 and 2017. Data avail-
ability and quality were assessed throughout; the data on a given
health facility for a given outcome were used in the analysis if
the admission record book was complete and kept up to date. To
do this, we checked to see there were no missing pages or dates,
such as weeks or months missing when there were no entries and
no other explanation (such as the health facility was closed for a
period), and that basic data: name, date of birth/age, diagnoses
and outcomes were all filled in. Because some facilities had gaps
in data quality over the period of the study, only health facili-
ties that maintained good quality data in the preintervention
and postintervention eras were included in each analysis (pneumonia
deaths, overall paediatric mortality, neonatal deaths and refer-
rels). Thus, the number of health facilities with data that could
be used for each analysis differed (table 1 and Results).

Cost analysis
Detailed costs of the intervention were kept throughout the
project (table 2). These included costs of equipment and infra-
structure, logistics and installation, clinical, technical and quality
improvement training and maintenance. While there were econ-
OMIES of scale, we averaged costs for an individual health facility
to provide information on the indicative cost to conduct this
intervention out in any given health facility. The cost per life
saved was calculated as the overall costs divided by the estimated
number of deaths avoided.

Other data collected
We also gathered data on healthcare workers perceptions of the
programme, and maintenance requirements of the equipment,
and these will be reported elsewhere.

Statistical analysis
For each health facility, data were available for up to 4 years
preintervention and postintervention (details in online supple-
mental appendix II). For each variable collected, the average
number per year preintervention and postintervention was
 calculated by hospital; these averages were used in all analyses.
For the primary and secondary analyses, we included health
facilities if they had good quality data from both preinterven-
tion and postintervention eras. Thus, the number of health facilities with data that could be used for each analysis differed (table 1 and Results).

preintervention period, and the number of deaths averted in
subsequent years of observation was calculated by applying
the same mortality IR as in the preintervention period and the
IRR. Thus: number of deaths avoided = (preintervention IR ×
postintervention admissions) – (preintervention admissions ×
IRR × preintervention IR).

Data analysis was conducted using Excel (Microsoft) and Stata
version 16.1.

Sample size calculations
The sample size calculation was based on an anticipated 25% reduction in the primary outcome of pneumonia mortality,

Table 1: Summary of admissions and deaths for all children, pneumonia, births, neonatal deaths and referrals

<table>
<thead>
<tr>
<th></th>
<th>Total paediatric admissions</th>
<th>Paediatric deaths</th>
<th>Pneumonia admissions</th>
<th>Pneumonia deaths</th>
<th>Births</th>
<th>Neonatal deaths</th>
<th>No of paediatric referrals</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Pre-intervention</strong></td>
<td>31 158</td>
<td>1392</td>
<td>10 228</td>
<td>377</td>
<td>33 633</td>
<td>370</td>
<td>2262/21 455 *</td>
</tr>
<tr>
<td><strong>Post-intervention</strong></td>
<td>27 166</td>
<td>867</td>
<td>8 705</td>
<td>153</td>
<td>30 776</td>
<td>349</td>
<td>1062/22 235 *</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td>58 324</td>
<td>2259</td>
<td>18 933</td>
<td>530</td>
<td>64 409</td>
<td>719</td>
<td>3397</td>
</tr>
</tbody>
</table>

*Total admissions denominator is different because the two provincial referral hospitals were excluded from this analysis.
from an estimated baseline of 4%–3%, with 90% power, requiring 7295 children with pneumonia in each arm. The study was also adequately powered to detect a 20% reduction in both overall paediatric mortality and referrals to tertiary centres.

**Ethics approval and consent to participate**
The project was registered by Australian New Zealand Clinical Trials Registry. The study protocol is published. The data collection was based on routine reporting, so no individual patient consent was required by the ethical review committees.

**RESULTS**

Table 1 shows the admissions, deaths for the preintervention and postintervention eras, overall, for pneumonia, births and neonatal deaths, and referrals. On-line appendix III shows the data for each health facility.

**Pneumonia admissions and deaths**

Thirty-six health facilities had good quality preintervention and intervention data for pneumonia admissions and deaths. In the preintervention era, there were 10 228 pneumonia admissions and 377 pneumonia deaths (IR 2.83 deaths per 100 pneumonia admissions, 95% CI 1.98 to 4.06). In the postintervention era, there were 8705 pneumonia admissions and 153 pneumonia deaths (IR 1.17 deaths per 100 pneumonia admissions, 95% CI 0.48 to 1.86). Pneumonia case numbers were significantly lower in the postintervention era than in the preintervention era: a median of 63 pneumonia cases (IQR 24–134) in the preintervention era and 37 (IQR 14–87) in the postintervention era. The estimated IRR for pneumonia deaths postintervention was 0.41 (0.24–0.71, p<0.005). If the pre-era mortality and IRR are applied to the postintervention era, there were 145 pneumonia deaths averted in the first 3 years [(0.0283×8705) – (0.41×0.028 × 8705)].

Figure 1 shows the change in incidence of pneumonia deaths in all health facilities. There was heterogeneity in outcomes between facilities, including five health facilities where the pneumonia death IR increased.

**Overall paediatric admissions and deaths**

Thirty-seven health facilities had good quality preintervention and intervention data for overall paediatric admissions and deaths. In the preintervention era, there were 31 158 paediatric admissions and 1392 deaths (IR 3.22 deaths per 100 paediatric admissions, 95% CI 2.42 to 4.28). In the postintervention era, there were 27 166 admissions and 867 deaths (IR 1.94 deaths per 100 paediatric admissions, 95% CI 1.23 to 2.65). Paediatric case numbers were similar in the preintervention and postintervention eras: a median of 115 (IQR 72–309) in the preintervention era and median of 121 (IQR 34–263) in the postintervention era. The estimated IRR for paediatric deaths postintervention was 0.60 (0.45–0.81, p<0.005). If the pre-era mortality rate was applied to the postintervention era, there were 348 deaths averted in the first 3 years [(0.0322×27 166) – (0.6×0.0322 × 27 166)]. Figure 2 shows the change in incidence of paediatric deaths in all health facilities. Again there was variability in effectiveness by site.

**Referrals**

Thirty-five health facilities had good quality preintervention and intervention data for referrals; two were excluded as they were provincial hospitals that were the recipient hospital of referral from health centres and district level hospitals, not from where onward referrals were made. These two provincial hospitals made no onward referrals in the intervention era. Another health centre was excluded because of inadequate data quality on referrals. In the preintervention era, there were 2262 children referred from these 35 health facilities to provincial or tertiary hospitals (10.5% of all 21 455 paediatric admissions from these 35 health facilities). The preintervention IRR for referrals was 11.29%. In the postintervention era, there were 1062 referrals (4.8% of all 22 235 paediatric admissions in these 35 health facilities). The postintervention IRR for referrals was 4.14 (2.29–6.00). The estimated IRR postintervention was 0.37 (0.25–0.53). Based on the preadmission rate of referrals, the number of referrals avoided was 1582 (0.113 × 22 235 – (0.37×0.113 × 22 235)).

**Births and neonatal deaths**

For births and neonatal deaths, 35 health facilities had good quality data in the preintervention and intervention eras. In the preintervention era, there were 33 633 births and 370 neonatal deaths (mortality rate 12.3 neonatal deaths per 1000 births, 95% CI 11.2% to 13.5%). In the postintervention era, there were 30 776 births and 349 neonatal deaths (mortality rate 11.5 deaths per 1000 births (95% CI 10.4 to 12.8). The estimated preintervention and postintervention IR were 7.9 per 1000 births (5.7–10.9) and 8.8 per 1000 births (5.5–12.1), respectively. The estimated IRR for neonatal deaths postintervention was 1.11 (0.76–1.62, p=0.58).
Global child health

Costs
It is relatively inexpensive to provide oxygen concentrators and pulse oximeters; however, solar power is expensive, especially in remote areas, as are implementation costs. The cost per health facility was approximately US$58,932, including oxygen and solar equipment, installation and logistics, maintenance and training over 4 years (Table 2). Over the course of the formal training, on-site support and continuous quality improvement, all health workers who manage children in these 38 facilities had training and hands-on assessment of skills.

The total cost of US$2,399,416 (average of $58,932 in each of the 38 health facilities) means that cost per paediatric death averted was $6,435.

DISCUSSION
How to reduce the high rates of pneumonia mortality among children in remote and rural settings in low-income countries, how to achieve sustainable energy and green health facilities and how to improve quality of healthcare for poor communities are three big issues in health globally. This study showed that a solar-powered oxygen programme supported by quality improvement was associated with reductions in overall paediatric mortality by 40%, mortality from pneumonia by over 50% and a reduction in referrals from health centres and district hospitals across nine rural provinces in PNG. The broader message is that investment in basic infrastructure, training and quality improvement can save lives in low-income and middle-income countries, even in remote areas.

The infrastructure included oxygen concentrators, pulse oximetry, oxygen analyzers and solar power. While previous studies have shown oxygen in referral hospitals in developing countries improve outcomes,5 16 17 no study has been done at large scale involving primary healthcare in district healthcare settings, where mortality has been measured. Quality improvement inputs included training in clinical paediatric care and oxygen therapy, small group problem solving and sharing of experiences between healthcare workers, audit and feedback. The quality improvement approach as well as the appropriate infrastructure enabled most health facilities to improve; in the absence of quality improvement in health systems, technology is likely to fail or be suboptimal in effectiveness.

There was variability in the effectiveness of the intervention by health facility, while most health facilities demonstrated a reduction in mortality from pneumonia and overall paediatric deaths, 5 health facilities experienced an increase in the IR for pneumonia and 11 health facilities experienced an increase in the overall paediatric mortality. The numbers of cases contributed by each of these facilities individually were small and therefore prone to IR changes with one or two additional deaths. This is except in one larger district hospital (Kainantu) where case ascertainment of deaths may have been greater in the postintervention era, and the postintervention pneumonia mortality was 3.8% out of nearly 1000 pneumonia admissions, comparable with many good medium-sized provincial hospitals. It is a fact however that the intervention was not as effective in some health facilities as it was others, and we identified some health facilities early as not functioning well enough to sustain this improvement.

The reasons are varied, which underlines that a quality improvement approach is needed, where local gaps can be identified and addressed, and emphasises that there are basic health system and health facility pre-requisites for any health care initiative to succeed.

Our study was a before-and-after study. The limitations of the design include the possibility of secular trends in case numbers and mortality rates over time, ascertainment bias and altered thresholds for hospital admission. We took many steps to avoid bias, including using the same mechanism of data collection in the pre-era and post-era and using the most complete data collection method possible. Clinical staff knew about the evaluation of the solar oxygen system; however, they did not know that outcome data were derived from ward admission record books. The accuracy with which data were recorded did not change during the study. There were significantly fewer children with pneumonia admitted in the postintervention era, and this requires some consideration.

Among interventions that may have reduced child pneumonia numbers and overall child deaths in PNG, the Haemophilus influenzae type b conjugate vaccine was introduced in 2008, and the pneumococcal conjugate vaccine (PCV-13 valent) was introduced in 2014. Coverage was very low in the early years for PCV-13; an estimated 20% of children had received PCV-13 in 2015 and 2016. This increased to 36% in 2017 and remained static at 35% in 2018–2019.18 PCV coverage rates may even be overestimated as they are based on DTP-3 data, the assumption being that all children receiving DTP-3 will also have received PCV, as it is given at the same time. At least in the early years, distribution of PCV-13 was not as uniform as DTP. Independent evidence from the PNG Demographic and Health Survey 2016–2018 indicated only 35% of children had received all basic vaccinations by 12–23 months of age (including PCV-13).19 We do not have specific data on PCV-13 coverage from the districts in which this study was conducted, and in these remote districts lower than national average, coverage is likely. However, conjugate vaccines may have changed the proportion of children with bacterial pneumonia and lowered the risk of mortality in the era 2016–19 compared with 2012–15.

Other secular trends, such as overall falls in child mortality, may affect preintervention and postintervention studies conducted over long periods of time. Comparison of the Demographic and Health Surveys data between 2006 and 2016–2018 shows a reduction in estimated overall child mortality (74 to 49 per 1000 live births) and infant mortality (57 to 33 per 1000 live births) in PNG.16 It is possible that this oxygen programme contributed to that reduction given the scale of the project, involving health facilities serving 1.3 million people, about 14% of the 8.8 million population of PNG, and the regions where child mortality has historically been highest. However these overall improvements in child mortality may partly account for some of the outcomes we observed.

We did not collect other demographic data that may help explain the trends observed; however, PNG DHS provide data on health-related behaviour, social and economic changes. Between 2006 and 2016–2018, there was no evidence of an improvement in care seeking for an acute respiratory infection in the country overall, and the proportions of women delivering in a health facility, and breastfeeding rates, were both unchanged.16 Parental educational attainment improved in PNG in that time, and mobile telephone ownership has increased markedly. While these may partly account for the lower overall child mortality rates in that time, there were few other changes over the years 2006 to 2016–2018 that might influence pneumonia rates or care seeking. Housing materials remained similar; water and sanitation in rural areas remained unimproved for the majority of rural populations.20 Rural communities, including those in this study, remain far more disadvantaged in every statistic. Advances in health outcomes are aggregates of progress in many sectors;
CONCLUSIONS

In low-income countries, solar-powered oxygen and a continuous quality improvement programme may reduce child mortality and deaths from pneumonia, allow healthcare to be provided closer to the community in which people live and be transformational for rural health services. However, this will only be effective if quality improvement can identify and address gaps and support staff to improve. Clinical quality improvement requires increases in human resources, education and structure, and these need strengthening in most low-income and middle-income countries.

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Contributors All authors contributed substantially to several aspects of this study. TD designed the project in collaboration with IH, JK, MK, DP and MS, who gathered the preintervention data in their provinces. FP led the clinical training in respective provinces, along with provincial paediatricians, and gathered the postintervention data. EN, HG and RI supported the design and administrative aspects of the project. Statistical analysis was done by SD and TD. The paper was written by TD, with input from SD and all authors, who reviewed and approved the final manuscript.

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Patient consent for publication Not required.

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Provenance and peer review Not commissioned; externally peer reviewed.

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Trials Registry: ACTRN12616001469404. Additional results data are available in the online supplementary appendices.

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