Environmental Sustainability in Hospitals; an Exploration within Anaesthetic and Intensive Care settings.

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ABSTRACT

In many nations healthcare is responsible for increasing consumption of financial and environmental resources both as absolute amounts and as proportions of GDP. It is debatable whether such resource use is sustainable in the longer term. Hospitals comprise the most resource intensive section of healthcare, using large amounts of energy and water, procuring substantial amounts of equipment and items and discarding enormous amounts of waste. In increasingly financially and environmentally constrained healthcare systems such hospital resource use will receive heightened scrutiny. There is increasing advocacy in several nations to improve hospital environmental (and thus financial) sustainability. Nevertheless, the research base to guide how to achieve greater hospital sustainability is limited.

The operating room (OR) and intensive care unit (ICU) are disproportionate users of hospital resources as they function at high activity for prolonged durations. This thesis explored environmental sustainability within operating theatres and the ICU through the lens of the three Rs: Reduce, Reuse, Recycle. Each of these themes is enormous in its scale, thus in each chapter examples of studies which could be performed for each theme were listed, followed by detailed studies of specific areas. The first study (Chapter 3) was a before-after examination of reducing the frequency of decontaminating anaesthetic breathing circuits. Reducing circuit decontamination frequency from daily to weekly did not increase bacterial circuit contamination numbers or frequency. As a result, the hospital reduced its circuit decontamination from daily to weekly, making environmental and financial savings.

Reuse within the OR and ICU was explored. A comparison was made between single use and reusable items. Why some surgical metalware were labelled as single use was examined; the single use metalware was found to have the same chemical composition as reusable stainless steel, but was less polished than the reusable variant. The environmental and social repercussions of the increasing displacement of reusable with single use equipment were explored.

The method of ‘cradle to grave’ life cycle assessment (LCA) was used to compare the environmental footprint of reusable and single use central venous catheter (CVC) insertion kits. In particular, the CO_2 emissions and water use of the reusable CVC insertion kits were found to be considerably greater than the single use kits, a finding at odds with many other studies of reusable versus single use hospital equipment. The outstanding finding from this LCA was that steam sterilisation of the reusable equipment was the major contributor to energy use, CO_2 emissions and water use.

Further studies were completed of the electricity and water use of the hospital steam sterilisers. A large proportion of the steam sterilisers’ energy and water requirements occurred when idle (in standby). Further, the sterilisers had many light loads, which was an inefficient use of resources. How staff use steam sterilisers was found to have large resource use implications.

Recycling was examined through an analysis of what would most likely make it feasible, followed by audits of what recycling was actually occurring in the OR and ICU. A survey of anaesthetists found that the vast majority of them did not see recycling occurring in their operating theatres, but that most wished to commit time and effort to doing so. Before-after recycling audits in the OR and ICU showed that recycling could be effective (from 15-15% of all waste and free from contamination with infectious and general waste) and at least revenue neutral. The opportunities for recycling within the ICU were less than for the operating suite.

This thesis has highlighted that many aspects of our understanding of hospital sustainability are immature and that there are large research opportunities in the field. The methods used in the thesis are generalisable to many hospitals in developed and developing countries. The studies within could be the foundation for future research to guide healthcare administrators, clinicians, engineers and others to consider environmental sustainability to be business as usual for hospitals. Hospital staff will continue caring for patients as their raison d’être. To complement such patient care in an increasingly resource constrained world there is much opportunity to reduce financial costs; improve efficiency and reduce energy, water and pollution; and augment any associated social benefits by improving hospital environmental sustainability.

DECLARATION

This is to certify that:

1. the thesis comprises only my original work towards the PhD except where indicated in the Preface,
2. due acknowledgement has been made in the text to all other material used,
3. the thesis is fewer than 100,000 words in length, exclusive of tables, maps, bibliographies and appendices.

Signature ……..… ……......

PREFACE

Several associated manuscripts and publications occurred during the PhD candidature and were begun after PhD commencement. In addition, several studies that were begun or completed prior to PhD commencement are mentioned in the thesis, but do not form individual chapters and provide only background information to the included chapters. The thesis chapters closely draw upon the following papers:

Chapter	Publication Title
2	McGain F, Naylor C. Environmental sustainability in hospitals – a systematic review and research agenda. Journal of Health Services Research and Policy. 2014;19(4):245-252.
2	McGain F, Cox NR, Cecchin SR, McAlister S, Barach PB. Sustainable cardiac services - From the catheterization laboratory to the operating room and beyond. Progress in Pediatric Cardiology. 2012; 33: 81–84.
2	McGain F, Story D, Kayak E, Kashima Y, McAlister S. Workplace sustainability: the “cradle to grave” view of what we do. Anesthesia and Analgesia 2012 May;114(5):1134-9.
3	McGain F, Algie CM, O'Toole J, Lim TF, Mohebbi M, Story DA, Leder K. The microbiological and sustainability effects of washing anaesthesia breathing circuits less frequently. Anaesthesia. 2014;69(4):337-4.
4	McGain F, Sussex G, O’Toole J, Story D. What makes metalware single use? Anaesthesia and Intensive Care. 2011; 39(5):972-973.
5	McGain F, McAlister S, McGavin A, Story D. A life cycle assessment of reusable and single-use central venous catheter insertion kits. Anesthesia and Analgesia. 2012 May;114(5):1073-80.
6	McGain F, Moore G, Black J. Australian Health Review. 2016 (in press).
7	McGain F, Moore G, Black J. Hospital steam sterilizer usage: could we switch off to save electricity and water? Journal of Health Service Research and Policy. 2016 Jan. 16 (epub ahead of print).
8	McGain F, White S, Mossenson S, Kayak E, Story D. A survey of anesthesiologists’ views of operating room recycling. Anesthesia and Analgesia. 2012 May;114(5):1049-5.
9	McGain F, Jarosz KM, Nguyen M, Bates S, O’Shea K. Auditing Operating Room Recycling: A Management Case Report. Anesthesia and Analgesia

	Case Reports. 2015 Aug 1;5(3):47-50.
9	Kubicki M, McGain F, O'Shea K, Bates S. Auditing an ICU recycling program. Critical Care and Resuscitation. 2015 Jun;17(2):135-40.

For Chapters 7 there is a manuscript in press These are entitled 'Steam sterilisation's energy and water footprint', and 'Hospital Steam Steriliser Usage: Could we switch off to save electricity and water?' For both manuscripts the authors are McGain F, Moore G and Black J.

I contributed more than 50% for all publications and the two unpublished manuscripts, except for 'Auditing an ICU recycling program' where there was equal contribution with Dr. Kubicki. I devised all studies, completed literature reviews, proposed the research questions and methods, obtained results, wrote the manuscripts and prepared the publications.

In addition, there were several publications that are relevant to the PhD that I undertook prior to enrolment. The most important of these publications were an assessment of plastics used in hospitals, two audits of waste pre-recycling, and a life cycle assessment of plastic drug trays:

1. McGain F, Clark M, Williams T, Wardlaw T. Recycling plastics from the operating suite. Anaesthesia and Intensive Care. 2008 Nov;36(6):913-4.
2. McGain F, Story D, Hendel SA. An audit of Intensive Care Unit Recyclable Waste. Anaesthesia 2009; 64 (12): 1299-1302.
3. McGain F, Hendel SA, Story D. An audit of potentially recyclable waste from anaesthetic practice. Anaesthesia and Intensive Care 2009; 820-823.
4. McGain F, McAlister S, McGavin A, Story D. The financial and environmental costs of reusable and single-use plastic anaesthetic drug trays. Anaesthesia and Intensive Care 2010; 38: 538-544.

ACKNOWLEDGEMENTS

Many people have contributed directly and indirectly to this thesis. I thank Associate Professor Jim Black for his wonderful supervisory role. Jim’s incisive questioning honed my ongoing interest in asking precise questions and broadened my curiosity in all things scientific and beyond. Co-supervisor Professor David Story was fantastic, encouraging me to undertake a PhD in a nascent field of healthcare, and providing advice about study design and how to maximise publication opportunities. Associate Professor Grant Blashki encouraged me to proceed with a PhD and was forever optimistic about where I was heading. Associate Professor Graham Moore provided expert engineering and technical assistance and was integral to broadening the studies undertaken.

I am grateful for the love and support I’ve received from my wife Kirsty, and children Ruby and Flynn. This PhD would be lessened without them. My parents, Allan and Diane and brother Sturt buoyed my love of learning.

Thanks be to Scott McAlister who showed me the world of life cycle assessment and how it can be used well to begin to understand the complexities of environmental footprints. Scott collaborated particularly in Chapters 2 and 5, but also elsewhere throughout the thesis.

Mr. Chris Naylor co-wrote the major literature review on hospital sustainability with me. Dr. Eugenie Kayak, Professor Yoshihisa Kashima, (with me, Scott McAlister and David Story) co-wrote the publication ‘Workplace sustainability: the “cradle to grave” view of what we do.’ Dr. Nicholas Cox, Ms. Serina Cecchin and Dr. Paul Barach (with me, and Scott McAlister) co-wrote ‘Sustainable cardiac services - From the catheterization laboratory to the operating room and beyond.’

For the anaesthetic breathing circuits study (Chapter 3): Dr.Tony Lim and Dr. Kate Algie obtained results with me, whilst Dr. Jo O’Toole and Associate Professor Karin Leder imparted expert microbiological (and other) opinion. Associate Professor Mohammadreza Mohebbi gave statistical advice for the circuits’ project.

For Chapter 4 (‘What makes metalware single use?’): Dr. Jo O’Toole imparted microbiological knowledge and Mr. Graham Sussex contributed expert metallurgical opinion and equipment.

Mr. Andrew McGavin and other members of Western Health’s Engineering Department showed me the basics of hospital engineering, salutary especially for Chapters 5 to 7. Andrew McGavin also contributed to our life cycle assessment (Chapter 5).

Chapters 6 and 7 would have been impossible without members of Western Health’s Central Sterile and Supply Department. Karen Tricker, Carlos Paciocco, Rowena Wilmette, Nancy Trujillo, and others kindly answered my many queries about steam sterilisation. Dr. Rachel Sore of the University of Melbourne Statistical Consulting Service provided expert statistical advice for the study of steriliser energy and water use (Chapter 6).

Dr. Eugenie Kayak, Dr. Simone Mossenson and Dr. Stuart White co-wrote and edited the survey of anaesthetists’ views of hospital recycling. Ms. Catherine O’Shea, Ms. Sam Bates, Dr. Martin Nguyen and Dr. Katherine Jarosz all gave their time and fortitude to assist in the recycling audits (Chapter 9). The staff of Western Health’s operating theatres and intensive care unit were instrumental in undertaking recycling and added useful advice about commencing such recycling. The staff of Atherton (particularly Sean Boston and Martin Harrison) as well as Scancare (Nathaniel Vann) provided expert advice about steam sterilisers and operating theatre quality assurance.

My hospital workplace superiors were very kind in affording me time and advice to complete this PhD. Associate Professor Craig French, Dr. Andrew Jeffreys, Dr. Richard Horton and Dr. Elizabeth Hessian of Western Health’s Departments of Anaesthesia and Intensive Care (Melbourne, Australia) brought counsel and encouragement.

ABBREVIATIONS

°C	degree Celsius
GB£	Pounds (Great Britain)
3R's	Reduce, Reuse, Recycle
AC	Aerobic Count
ANZ	Australia and New Zealand
AS/NZS	Australian Standards/New Zealand Standards
AUD$	Australian Dollars
cfu	colony forming unit
CI	Confidence Interval
CO_2	Carbon Dioxide
CSSD	Central Sterile and Supply Department
CT	Computerised Tomogram
CVC	Central Venous Catheter
DPU	Day Procedure Unit
EIO	Economic Input Output
GWP	Global Warming Potential
ICU	Intensive Care Unit
IQR	Inter Quartile Range
ISO	International Organization for Standardization
kWh	Kilowatt hour
LCA	Life Cycle Assessment
LEED	Leadership in Energy and Environmental Design
MRI	Magnetic Resonance Imaging
OR	Operating Room
PE	Polyethylene
PP	Polypropylene
PVC	Polyvinyl Chloride
RCoA	Royal College of Anaesthetists
SDU	Sustainable Development Unit
UK	United Kingdom
USA$	United States of America
USD$	United States Dollars
VAP	Ventilator Associated Pneumonia
VRE	Vancomycin Resistant Enterococcus

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CHAPTER 1: INTRODUCTION

"Simply claiming that something is green, without demonstrating empirical benefits for human health and well-being, the environment, and economics, is not enough."(1)

Howard Frumkin
Green Healthcare Institutions
Institute of Medicine of the National Academies (USA).

1.1 BACKGROUND

In the setting of climate change and resource depletion there is increasing interest in environmentally sustainable health care. Hospitals are highly energy intensive, consume large amounts of resources and produce much waste(2). It has been calculated that healthcare; in the USA contributes to 8% of that country's entire 'carbon footprint' (CO_2 emissions)(3), whilst in England this is a more modest 3% of that country's CO_2 emissions(4). In Australia, no such national 'carbon footprint' study has been performed, but it is known that the CO_2 emissions from individual hospitals are large(5).

Hospital environmental sustainability is important for other, more prosaic reasons. It is often (though not always) the case that a more environmentally sustainable approach to healthcare is also more financially sustainable, equitable, efficacious and efficient(6). Despite this, knowledge of much of healthcare's environmental effects is unknown(7).

Environmental considerations of healthcare were thought novel until recently, so research related to most aspects of hospital sustainability has infrequently occurred. Further, unsustainable environmental behaviour has routinely been an uncosted externality (i.e. a factor whose costs are not reflected in the market price of goods and services). CO_2 emissions are a good example of an uncosted externality unless a 'carbon price' is attached.

Efforts to quantify the 'carbon footprint' of hospitals using life cycle assessment (LCA)(8) have been promulgated by the UK's Sustainable Development Unit (SDU). LCA is a scientific method to analyse an item's or process' entire 'cradle to grave' environmental effects, whether these be CO_2 emissions, water use, aquatic toxicity(9). LCA's role in analysing healthcare's environmental footprint is evolving rapidly, but a nuanced understanding of where to act first and what to do to improve hospitals' environmental sustainability is lacking(10). There are uncertainties regarding the foundations for LCA within healthcare. For example, it is uncertain what the actual energy (and thus CO_2 emissions) requirements are for many devices used by hospital staff in the Operating Room (OR), Intensive Care Unit (ICU), Radiology Department and beyond, thus it is difficult to assign CO_2 emissions per procedure performed.

It is useful to consider that the ongoing carbon footprint of hospitals stems from three main areas in descending importance: procurement, direct energy use and travel to/from hospitals(4). Procurement and waste have a greater carbon footprint (and much larger financial impost) than both direct energy use and travel combined. Moreover, if efforts are to be made to improve hospital sustainability one needs to consider the areas likely to have the highest impact, such as the OR and ICU(10). Thus, OR and ICU procurement is the focus of this thesis.

The environmental sustainability of the hospital built environment has been studied in greater detail than other aspects of hospital sustainability(11, 12) and is discussed only briefly in this thesis. Further, this thesis focuses solely upon studies of equipment, activities and behaviours that may *directly* improve hospital environmental (and financial) sustainability. There are many public health examples which *indirectly* improve healthcare's and a hospital's sustainability. For example, smoking cessation or prevention of obesity and diabetes have self-evident benefits for the individual patient, but also reduce requirements for hospitalisation and thus improve healthcare's overall sustainability. Such preventative approaches thus indirectly and significantly improve hospital sustainability, but are beyond the scope of this thesis.

First heard in the early 1970's, the mantra *Reduce, Reuse, Recycle*(13) has become a household term. *The 3Rs* have also been influential in developing a research based 'waste hierarchy', i.e. it is better to; reduce, then reuse, recycle, incinerate, and finally send to landfill(14). There is ongoing debate surrounding how recycling may/may not curtail overall reductions in the use of materials and the relative importance of each of the *R's*(15). Nevertheless the mantra is well known, simple and testable, particularly with the evolution of LCA methods(14). This thesis has thus used the Reduce, Reuse, Recycle waste hierarchy to classify hospital sustainability research and investigations within each of the three fields.

Within the Reduce, Reuse, Recycle framework there are a myriad of possible research topics, and if there is to be widespread progress improved knowledge in each of these areas is required. This thesis has examined the; required frequency of cleaning an OR device; life cycles of several equipment; staff use of hospital sterilisers; and opportunities to recycle. At least one example within each of the fields of reducing, reusing and recycling within the OR and ICU has been examined. Commonly used devices and equipment have been chosen, increasing the utility and generalizability of the thesis' results. Examples are given detailing financial and environmental savings from research findings and opportunities for the future. There is much scope for improving hospital sustainability. This thesis significantly adds to hospital sustainability research and gives examples of real improvements that can be readily achieved.

1.2 AIMS

This thesis aims to explore environmental sustainability within the OR and ICU. Reducing, reusing and recycling within the OR and ICU are examined and comparisons made between single use and reusable equipment. The important role that hospital steam sterilisation plays in the environmental footprint of all sterilised reusable, equipment is quantified. This thesis contributes to our knowledge of, and guides future research and advocacy in the field of hospital sustainability.

1.3 OBJECTIVES

1. Reduce: Consider where possibilities exist for reducing the amount of equipment used per patient within the OR and ICU.
    i. Examine in detail the reduction in use of one common item, without compromising patient care.

2. Reuse: Contrast reusable versus single use items.
    i. Critically assess the rationale and significance of medical equipment labelling as single use versus reusable.

    ii. Using a life cycle assessment (LCA) approach compare the environmental effects of single-use and reusable versions of a common item.
    iii. Examine in more detail the most important components of the ‘footprint’ of reusable surgical equipment: in particular steam sterilisation's energy and water requirements.
    iv. Explore energy efficiency: observe how hospital staff use steam sterilisers.

3. Recycle: Examine recycling’s potential within the OR and ICU.
    i. The psychology of recycling: survey anaesthetists' views of OR recycling
    ii. Audit OR and ICU waste, pre- and post-recycling.

1.4 RESEARCH QUESTIONS

1. Reduce: Focus upon one common reusable item in the OR, i.e. anaesthetic breathing circuits, to determine if it is safe to reduce the thermal disinfection (washing) frequency.
    i. For anaesthetic circuits, what are the differences in the circuits’ aerobic bacterial load with changes in the frequency of thermal disinfection? How do three washing regimes at 24, 48- hourly and weekly intervals affect bacterial load?

2. Reuse: Contrast reusable versus single use items and how reusable items are sterilised.
    i. For reusable and single use surgical metalware what are the physico-chemical differences between these items? Are both reusable and single use items stainless steel? Are there differences in the polishing/roughness of the two types of metalware?
    ii. Using LCA methods: for reusable and single use central venous catheter insertion kits what are the differences in the financial and environmental costs?
    iii. Steam sterilisers 1: What are the electricity and water requirements of hospital steriliser usage? Over a prolonged time period what are the relative amounts of electricity and water consumption by a steam steriliser during cleaning cycles, accessory cycles and idle modes? What is the

relationship between the mass and type of items sterilised and the electricity and water used?

    iv. Steam sterilisers 2: What is the efficiency of patterns of steriliser use by hospital staff? What is the relative proportion of times spent active, idle and off? Is it possible to safely switch off idle sterilisers?

3. Recycle:
    1. Is operating suite recycling standard practice in Australia, New Zealand and the United Kingdom? Are anaesthetists willing to increase recycling within the operating suite? In the opinion of anaesthetists what factors enable and impede the introduction of operating room recycling in an operating suite?
    2. What are the masses of different waste streams exiting the OR and ICU before and after the introduction of recycling programs? Does the introduction of recycling programs increase infectious contamination rates? Are OR and ICU recycling programs financially viable?

1.5 RESEARCH STRATEGIES

A number of research strategies are used in this thesis.

1. *For the study of reducing the washing frequency of anaesthetic breathing circuits:* Microbiological techniques to plate out circuit washings are used as guided by a microbiologist.
2. *For comparison between reusable and single use items:*

   Assistance from a metallurgist was sought as to how to measure the roughness of common metal ware devices and their physico-chemical composition (spectrophotometry).
3. *For life cycle assessment (LCA) study of common OR and ICU equipment:*

   Collaboration with an LCA expert and the use of LCA software (SimaPro®) and data inventories (Ecoinvent®).
4. *For studies of electricity and water use by sterilisers and how these sterilisers are used by staff:*

Collaboration with engineering staff. The use of Excel® and Access® databases with computer programming input from my supervisor and co-supervisors.

5. *For audits of OR and ICU waste and recycling:*

   Measurements of the masses of waste/recyclables are performed.

1.6 PUBLICATIONS ARISING

(a) Literature reviews

1. Overview of hospital sustainability.

   McGain F, Naylor C. Environmental sustainability in hospitals – a systematic review and research agenda. Journal of Health Services Research and Policy. 2014;19(4):245-252.

2. Review of sustainability within the cardiology and critical care areas.

   McGain F, Cox NR, Cecchin SR, McAlister S, Barach PB. Sustainable cardiac services - From the catheterization laboratory to the operating room and beyond. Progress in Pediatric Cardiology. 2012; 33: 81–84.

3. Review of life cycle assessment and sustainability as it applies particularly to anaesthetists.

   McGain F, Story D, Kayak E, Kashima Y, McAlister S. Workplace sustainability: the "cradle to grave" view of what we do. Anesthesia and Analgesia. 2012 May;114(5):1134-9.

(b) Chapters 3 to 9.

1. An examination of the microbiological effects of washing anaesthetic breathing circuits at different time intervals.
   McGain F, Algie CM, O'Toole J, Lim TF, Mohebbi M, Story DA, Leder K. The microbiological and sustainability effects of washing anaesthesia breathing circuits less frequently. Anaesthesia. 2014;69(4):337-4.

2. An analysis of the composition of medical instruments and what makes metal items single use.

McGain F, Sussex G, O’Toole J, Story D. What makes metalware single use? Anaesthesia and Intensive Care. 2011; 39(5):972-973.

3. A life cycle assessment of CVC insertion kits.
   McGain F, McAlister S, McGavin A, Story D. A life cycle assessment of reusable and single-use central venous catheter insertion kits. Anesthesia and Analgesia. 2012 May;114(5):1073-80.

4. Steam sterilisation’s energy and water footprint.
   McGain F, Moore G, Black J. Steam sterilisation’s energy and water footprint. Australian Healthcare Review. 2016 (in press).

5. How hospital staff use steam sterilisers.
   McGain F, Moore G, Black J. Hospital Steam Steriliser Usage: Could we switch off to save electricity and water? Journal of Health Service Research and Policy. 2016 Jan 13 (epub ahead of print).

6. A survey of anaesthetists’ views of OR recycling.
   McGain F, White S, Mossenson S, Kayak E, Story D. A survey of anesthesiologists’ views of operating room recycling. Anesthesia and Analgesia. 2012 May;114(5):1049-5.

7. OR waste post-recycling.
   McGain F, Jarosz KM, Nguyen M, Bates S, O’Shea K. Auditing Operating Room Recycling: A Management Case Report. Anesthesia and Analgesia Case Reports. 2015 Aug 1;5(3):47-50.

8. ICU waste post-recycling.
   Kubicki M, McGain F, O’Shea K, Bates S. Auditing an ICU recycling program. Critical Care and Resuscitation. 2015 Jun;17(2):135-40.

(c) Associated publications

1. McGain F. Why anaesthetists should no longer use nitrous oxide. Anaesthesia and Intensive Care 2007; 35: 808-9.
2. McGain F, Blashki GA, Moon KP, Armstrong FM. Mandating sustainability in Australian hospitals. The Medical Journal of Australia. 2009 Feb 15;190(12):719-20.

3. McGain F, Clark M, Williams T, Wardlaw T. Recycling plastics from the operating suite. Anaesthesia and Intensive Care. 2008 Nov;36(6):913-4.
4. McGain F, Story D, Hendel SA. An audit of Intensive Care Unit Recyclable Waste. Anaesthesia 2009; 64 (12): 1299-1302.
5. McGain F, Hendel SA, Story D. An audit of potentially recyclable waste from anaesthetic practice. Anaesthesia and Intensive Care 2009; 820-823.
6. McGain F, Kayak E. Where are hospital “green” committees and officers? Australian Health Review. 2010;34:523–524.
7. McGain F. Sustainable hospitals? An Australian perspective. Perspectives in Public Health. 2010;130(1):19-20.
8. McGain F, McAlister S, McGavin A, Story D. The financial and environmental costs of reusable and single-use plastic anaesthetic drug trays. Anaesthesia and Intensive Care 2010; 38: 538-544.

1.7 OVERVIEW

Chapter 2 is the literature review of hospital sustainability and more particularly, OR and ICU environmental sustainability research. Chapter 3 is about Reducing. Although we could reduce the use of many items, packaging and procedures within the OR and ICU it is necessary to consider a device that could feasibly be used less frequently or at least cleaned less frequently. We examine whether the frequency of washing anaesthetic breathing circuits influences the bacterial load count of such circuits.

Chapter 4 introduces Reusing. The seemingly inexorable increase in the use of single use devices is discussed first, with a focus upon why metalware in particular could be considered single use. Life cycle assessment is used in Chapter 5 to examine one commonly used OR and ICU device, the central venous catheter (CVC) insertion kit. Comparison is made with a device (studied prior to the commencement of the PhD) that was not sterilised (a drug tray). Differences in the environmental effects of the reusable and single use variants of the CVC insertion kits are compared and contrasted. Steam sterilisation of the reusable items in particular appears very energy and water intensive. In Chapter 6 it becomes apparent that the energy and water requirements of steam sterilisers as they are used in hospitals is incomplete. Chapter 7 thus is an examination of the electricity and water requirements of a hospital steam steriliser. Chapter 8 explores how hospital staff actually use steam sterilisers and the sterilisers' subsequent efficiency.

Chapters 8 and 9 are about Recycling. Chapter 8 defines what anaesthetists consider to be the most important enablers and barriers to OR recycling. OR and ICU waste audits pre- and post-recycling form the basis for Chapter 9. Chapter 10 ends the thesis with a discussion about what this thesis has achieved, the research significance, the resultant changes to staff behaviour and activity, and the improvements in hospital sustainability, and the future research agenda.

1.8 CONCLUSION

The research studies within this thesis give greater understanding to, and add to dialogue about, the environmental effects of hospital activities. Moreover, examples are given of improvements in OR and ICU sustainability already occurring as a result of this research. The methods used in this study are generalizable to many hospitals in most parts of the world. For example; comparisons between reusable and single use items can be researched with life cycle assessment, steriliser activity and energy/water use can be obtained with relatively straightforward software and waste audits are simple to achieve. Such research will guide future policy makers, clinicians, engineers and others to make rational, informed decisions to improve hospital sustainability, improve efficiency and reduce energy, water and pollution in an increasingly resource constrained world.

CHAPTER 2: LITERATURE REVIEW

2.1 INTRODUCTION

This chapter begins with the definition of sustainability, briefly traces the history of the sustainability movement, and provides an overview of sustainability in general. Thereafter, environmental sustainability within hospitals becomes the focus of this chapter and the entire thesis. The separation of environmental sustainability from financial and social sustainability is somewhat artificial since all subsets of sustainability are inter-related. Nevertheless, researching all aspects of sustainability was beyond the scope of this PhD.

Some elements of financial sustainability are examined, though the analyses chosen are relatively simple. A complementary approach would be to examine economic sustainability via return on investment and net present value. Another approach is to examine both economic and environmental sustainability via marginal abatement (of CO_2) cost curves. The Sustainable Development Unit of the UK has used such marginal abatement curves to examine how different sustainability strategies could lead to potential CO_2 emissions reductions and the associated financial costs needed to do so (16).

The relevance to sustainability of the mantra ‘Reduce, Reuse, Recycle’ is appraised. Life Cycle Assessment (LCA) as a method to examine sustainability is introduced and caveats to this method mentioned. The chapter then centres upon a literature review of sustainability within healthcare and more particularly within the hospital OR and ICU. The factors that are relevant to hospital sustainability compared with other aspects of sustainability more generally are examined. The current understanding and research base of hospital sustainability are explored and knowledge deficits emphasized. Finally, the aims, objectives and research questions as given at the end of Chapter 1 are discussed and justified.

A detailed history of sustainability is beyond the scope of this thesis. *Sustainability, A History* by J. Carodonna(17) provides a detailed account of the history of sustainability as a concept and way of thinking and is drawn upon in the following sentences. ‘Sustainable’ and the verb ‘to sustain’ derive from the Latin, *sustinere* meaning to ‘maintain, support, endure’ and stems from *sub* ‘up, from below’ and *tenire*, ‘to hold’. Various prominent figures in the 18th and 19th Centuries such as Adam Smith (*The Wealth of Nations*), Thomas Malthus (*On Population*) and John Stuart Mill (*Principles of Political Economy*) referred to economic, social and environmental sustainability, warning against the excesses of the industrial revolution and exponential growth on a finite planet. Environmentalism gathered pace gradually after the turn of the 20th Century. John Muir (founder of the Sierra Club), and later Rachel Carson (*Silent Spring*) were among several prominent environmentalists.

It was not until the early 1970’s however, that the noun ‘sustainability’ entered the English language(17). At the United Nations World Commission on the Environment and Development the Norwegian Prime Minister, Gro Harlem Brundtland defined sustainable development as “…development that meets the needs of the present without compromising the ability of future generations to meet their own needs."(18) Stimulated particularly by concerns such as climate change, ‘peak oil’, inequality and dwindling taxation revenue sustainability became a mainstream word and topic. By the end of the 20th Century sustainability; had evolved from a vague concept to one with solid foundations; taken on economic, environmental and social meanings; and become a research area in its own right, complete with University Sustainability Institutes(19).

2.2 REDUCE, REUSE, RECYCLE

‘Reduce, Reuse, Recycle’(13) was first heard in the early 1970’s, and although the exact origin is unclear it was certainly promulgated at the First World Earth Day with its associated publications(20). Although the ‘3Rs’ mantra has become ubiquitous in many societies its scientific foundation is more recent. Whilst there is certainty that ‘reducing’ will by definition decrease requirements for energy, water, and chemicals and reduce pollution it is unclear whether which of reusing or recycling has lower environmental effects and how this will vary with each item or process. Life Cycle Assessment (LCA) has developed as a method to examine such effects and is discussed in the next section of this chapter.

LCA has been used to develop a research based ‘waste hierarchy’, i.e. the environmental effects are lessened if our practice is to; firstly reduce the use of materials, then reuse, recycle, incinerate, and finally send to landfill(14). There is ongoing debate surrounding how recycling may/may not curtail the overall use of material resources and the relative importance of each of the ‘3R’s’(15). In certain circumstances some environmental effects may be greater when reusing rather than recycling or even disposing to landfill(15). Nevertheless the ‘3R’s’ mantra is well known, simple and testable, particularly with the evolution of LCA methods(14).

The Reduce, Reuse (reprocess), Recycle (and segregate) waste hierarchy provides a useful framework to consider hospitals’ environmental effects. Methods for reducing resource consumption, CO_2 emissions and waste amounts (including toxic by-products) range from minimizing hospital admissions (improvements in primary health care and increasing out-patient procedures) to reducing the use of drugs and equipment in daily practices. Reducing not just the *amount*, but also the *variety* and *diversity* of equipment may well lead to improved healthcare financial and environmental sustainability, though this area of research is not examined.

2.3 AN INTRODUCTION TO LIFE CYCLE ASSESSMENT (LCA)

Life cycle assessment (LCA) is a scientific method to determine the entire ‘cradle to grave’ environmental and financial effects of processes and products(9, 21). In 1991, the Society for Environmental Toxicology and Chemistry defined the components of an LCA of an item to be analysed; 1. raw material acquisition, 2. processing and manufacturing, 3. distribution and transportation, 4. use, reuse and maintenance, 5. recycling, and 6. waste management(9). Everything we use and do has a footprint, whether this be for any product or service (e.g. admission to hospital). LCA allows for rational product and medical practice choices that reflect true environmental and financial costs beyond short-term effects. LCAs have a ‘system boundary’, i.e. a limit to which one examines the environmental effects of a product or process. This system boundary is defined by local Australian and international standards (22, 23). For example, if we are examining a plastic syringe the system boundary could be defined to include the manufacture of the plastic and ongoing maintenance of installed infrastructure, but not the actual manufacture of such installed infrastructure used in turn to make the syringe.

Environmental factors beyond CO_2 ('carbon') emissions, including water consumption, petrochemical use, eutrophication (excessive nutrient enrichment of watercourses) and release of toxic by-products can be accounted for in an LCA. Comparisons between items may indicate relative advantages for one outcome (e.g. CO_2 emissions), which may be contrary to other outcomes (e.g. water use and contamination). In the late 1990s, standardization of how LCAs should be conducted was achieved when the International Organization for Standardization (ISO) released the ISO 14000 series(22).

LCAs make use of life cycle inventories (LCIs). An LCI is a catalogue of flows to and from nature; with inputs such as energy, water and raw materials, and outputs (releases) to air, land and water. There can be a large number of inventory flows numbering in the hundreds; for example even a simple plastic syringe's LCI requires flows of petrochemical resource extraction, manufacture, transport and use. To examine all of these details de novo every time an LCA was undertaken would be exhaustive and expensive. So, whilst it is ideal to obtain as much primary data as possible (e.g. measurement of a hospital steriliser's direct energy and water use) secondary sources of information are usually required for LCAs (e.g. details of plastic manufacture). Large, national and international databases are the routine sources for such information, such as Gabi®(24) and EcoInvent®(25) which incorporate geographically specific average industry data. For example, the estimated CO_2 emission from burning coal from a defined region is obtained from such environmental databases. Such average industry data can have greater associated uncertainty than directly measured (primary) data(26, 27). Care must then be taken to ensure that the secondary data indicates the local conditions of the LCA in question (e.g. local coal fired electricity versus gas fired electricity used for the secondary data). It is important to be aware that the CO_2 emissions per kWh of electricity produced in Victoria, Australia, are very high by world standards as the electricity is sourced from CO_2 emissions intensive brown coal(25).

Re-iterating, the LCI has inputs (such as electricity from coal) that are combined to form an output (e.g. a plastic syringe). Every input from secondary databases has a degree of uncertainty associated with it. This uncertainty routinely cannot be derived directly from the available information, so a standard procedure was developed to derive uncertainty factors from a qualitative assessment of the data, known as the

Pedigree Matrix(27). The Pedigree Matrix is a commonly used qualitative scoring system derived from the secondary data's reliability, completeness, temporal and geographical proximity to the process or item being assessed, and further technological factors(26, 27), with a score from 1 (good) to 5 (poor) for each factor.

The Pedigree Matrix relies upon expert judgement. For example, if the secondary data for CO_2 emissions per kWh of electricity produced was obtained recently from all local coal fired power stations this would have better reliability, completeness, and temporal and geographical proximity than secondary data from an overseas derived database which sampled one coal fired power station a decade ago. As the Pedigree Matrix is based upon expert opinion it is open to a perception of irregularities. The Pedigree Matrix has been updated to incorporate some of these concerns with greater emphasis upon direct empirical values for each of the factors (28).

Similarly, there are also uncertainties associated with all LCA primary inputs that are directly measured. For example, our prior LCA study of plastic drug trays required transport of such trays from China to Australia. There is little uncertainty associated with the CO_2 emissions from such shipping as the distance travelled is well known and the variability in fuel consumption of container ships is small. On the other hand, for the reprocessing of the reusable plastic drug trays, if we had measured just once the electricity use of the washer rather than over several days with different load types, the CO_2 emissions from such electricity use would have a greater associated uncertainty. As for secondary data from LCI databases, the Pedigree Matrix for primary input data is a qualitative scoring system.

For every LCA potentially hundreds of mostly secondary inputs contribute to output data, each with associated uncertainty distributions. The Pedigree Matrix for each of these inputs determines the degree of uncertainty. How does one then combine the values and frequency distributions of these hundreds of inputs to obtain outputs such as CO_2 emissions and water use? Monte Carlo methods are a broad class of computational algorithms that rely on repeated random sampling to obtain numerical results. Monte Carlo methods are useful when there are large numbers of inputs and where it is not pragmatic to obtain data for each of these inputs de novo and are used routinely in LCA.

When there is a range of possible values for a result there are a number of approaches to how to determine the best estimate and the frequency distribution around this result. Monte Carlo methods take data points from within the frequency distributions for all inputs to develop a final output result, frequency distribution and the plausible range including the central tendency of the frequency distribution(27) . The greater the number of ‘runs’ by Monte Carlo analysis the better the estimate of the most likely value and the associated frequency distribution.

Starting with Coca-Cola bottles in 1969(29), a multitude of LCAs from a diverse range of industries have been undertaken. In industry LCAs are common as they identify high energy and water use as well as waste production, e.g. in the steel industry(30). In architecture and building construction LCAs have guided knowledge about ‘green buildings’ for the Leadership in Energy and Environmental Design (LEED). In government there has been less emphasis upon LCAs although in some countries with CO_2 emission reduction plans this is beginning to change. For example, the UK plans to reduce the entire country’s CO_2 emissions by 34% by 2020 from 1990 levels(31). LCA such as that performed by the UK Sustainable Development Unit (SDU) will guide future CO_2 emission reductions within the UK’s healthcare system(4). Nevertheless, comparatively few LCAs have involved medical items and practices(32) (detailed later in this chapter, Sections 2.5.5 and 2.6.1).

There are several types of LCA of which two are particularly relevant to healthcare sustainability; Economic Input-Output LCAs and process based LCAs. Economic Input-Output LCAs assign an environmental effect to an item, process or service via knowledge of a monetary value. National economies are divided into many sectors (e.g. pharmaceuticals) with at least 100 sectors in developed countries (33). Each sector receives inputs from many other sectors and conversely has outputs to many sectors. Each sector has a different ‘intensity’ of environmental effect per financial cost. Such intensities are developed by government departments, e.g. by the Department of Commerce in the USA.(34). Briefly, for each sector, data are obtained of the monetary inputs from each financial sector, and likewise the monetary outputs (i.e. dollars produced) to each financial sector. Through calculations an environmental cost/$ for each sector can be developed.

Different sectors of the economy have different environmental impacts. Pharmaceutical production will have a different carbon intensity (CO_2 emissions) for every dollar spent on producing a drug compared with the CO_2 emissions of producing one dollar of foodstuffs or manufacturing plastics. For example, if a plastic syringe costs $0.10 there is a carbon, water etc. footprint associated with that syringe based upon the $0.10 that will be different to the environmental footprint of producing drugs.

When attributing an environmental cost to a sector, e.g. pharmaceuticals, areas such as research and development, lawyer fees and fees and travel for drug representatives are all included. The advantages of Economic Input-Output (EIO) LCAs are that they are all encompassing (‘broad brush’) and relatively inexpensive to perform once the initial expensive data gathering has occurred. Thereafter one only has to find the financial cost of any item or process in order to arrive at an environmental cost.

Process based LCAs arrive at an environmental cost for an item or activity based upon measured inputs. Process based LCAs thus examine the immediate inputs, but not more distant inputs, i.e. they have a smaller ‘system boundary’ than input output LCAs. For example, the aforementioned $0.10 plastic syringe has a weight and petrochemical composition that would be linked to environmental effects, but all of the associated effects resultant from petrochemical industry activity such research and development and the manufacture of machinery for drilling and exploration are not included. The environmental effects of process based LCAs are thus routinely less than EIO LCAs.

Process based LCAs do not encompass all of the effects of an item or process and are more expensive to perform than EIO LCAs. They do, however provide a detailed analysis of an individual item or activity and are useful when comparing two similar items/activities. Further, EIO LCAs are less precise for many products and processes in healthcare. Consider a drug, medical device or operation that costs twice as much as another: an EIO LCA would consider that the more expensive process has double the environmental effects, which could be unrealistic. On the contrary, it may be impossible to obtain details of pharmaceutical manufacturing for a process based LCA, leaving a questionable EIO LCA as the only manner in which to assess a drug’s environmental effects. Hybrid LCAs; (combinations of EIO LCAs and process LCAs) are used infrequently to attempt to overcome any knowledge gaps(35), but should be used with care when comparing two products or processes as input-output data will overestimate environmental effects in distinction to process based data.

2.4 LITERATURE REVIEW METHODS

This literature review is based upon a publication by McGain and Naylor(36). The aim of the literature review was to identify all articles that added new findings to the evidence base of environmental sustainability within hospitals. The bibliographic databases PubMed and Engineering Village were searched for articles published in English between 1/1/1990 and 1/6/2015. The Cochrane library, the King's Fund (UK) library database, and the websites of the Sustainable Development Unit (SDU) and the Sustainability for Health and Evidence Base for Action were also examined for the same period.

A search of PubMed for 'sustainability' alone revealed more than 12,000 references. Assessing the title and/or abstract of the first 200 of these, the majority were found not to pertain to environmental sustainability. To improve the search specificity a search algorithm was developed based on: 1. the main themes related to environmental sustainability found in the first 200 references, and 2. an existing conceptual framework developed by the SDU(4) Evidence relating to the following themes was identified: Hospital design, Energy, Water, Travel, Procured goods, Waste, and Staff Behaviour.

The search algorithm required that articles include the term 'sustainability' AND at least ONE of the following: 'hospital', 'green', 'environment', 'architecture', 'energy', 'water', 'travel', 'life cycle assessment', 'waste', 'recycling', 'reusing', 'reprocessing', 'psychology' and 'behaviour' and 'behavior'. Further studies were found by review of other publications' references, in particular recent related reviews(37, 38) and books(1, 7, 11) To avoid missing important studies in this review the first 200 (of >12,000) references found using 'sustainability' alone as a search term were rechecked. The more focussed search algorithm included the same studies as those found in the broader search.

The inclusion criteria were that studies had to be relevant to environmental sustainability within hospitals (as defined by the previous search algorithm) and either introduce new data or provide the latest review of a topic. There are a number of advocacy groups in several countries promulgating more sustainable approaches to healthcare, particularly within hospitals. These groups tend not to produce new research, but are mentioned here as they are influential in suggesting novel approaches to more sustainable healthcare. Examples include: 1. in the USA- Healthcare Without Harm(39) and the Green Guide to Healthcare(40), 2. in the UK- the Centre for Sustainable Healthcare(41), 3. in France, le Comité pour le Développement Durable en Santé (the Committee for Sustainable Healthcare Development)(42), and 4. in Australia- the Climate and Health Alliance(43) and the Doctors for the Environment Australia(44).

Novel approaches or trends to the study of sustainability within hospitals (such as life cycle assessment, reprocessing and behavior change) were included. Comment or advocacy pieces were excluded unless they introduced new themes or topics. Studies that were older or very specific and covered by more general or newer reviews were also excluded. A formal quality appraisal tool was not used, as the objective was to assess the breadth of the evidence base, including all methodologies and study designs. Web searching and review of reference lists did not identify significant numbers of additional articles, indicating that the database search had been sufficiently comprehensive.

The articles were analysed using the same thematic framework that formed the basis of the search algorithm (see above). For each article, there was a summary of: 1. research findings which provided an assessment of the scale of the environmental impacts of hospital care; and 2. findings which provided an evaluation of the effectiveness of interventions to mitigate these impacts.

The findings of this literature review are presented as the research foundation for: 1. sustainability within healthcare and hospitals in general, and 2. sustainability within the OR and ICU with a particular focus upon life cycle assessment (LCA) and procurement. Many areas of research can contribute *indirectly* towards improving sustainability, but this review focuses upon research that has at its primary aim improvements in hospital sustainability. Many public health measures will indirectly improve hospital sustainability, e.g. demand for health services can be reduced through measures that confer health and environmental co-benefits (smoking cessation)(45). This review is primarily of hospitals in high income countries, but there is a large potential for research about hospital sustainability in other income settings, where the effects of unsustainable practices such as climate change will be particularly large.

2.5 SUSTAINABILITY WITHIN HEALTHCARE AND HOSPITALS

Evidence relating to healthcare and hospital sustainability is given following the themes identified in the Methods section above: i.e. hospital design, energy, water, travel, procured goods, waste, and staff behaviour. Evidence relating to OR and ICU sustainability is detailed in Section 2.6 and primarily details procurement, waste and life cycle assessments of specific products or procedures.

While healthcare is likely to use a significant proportion of the world's total natural resources (including oil, food, water and minerals) precise estimates are unavailable. The delivery of healthcare contributes substantially to total CO_2 emissions(3, 8), adding to the health effects of climate change(46). Further, healthcare systems are at risk of the effects of climate change on building infrastructure, human health, supply chains and resource security(47).

The focus of healthcare sustainability research is often on direct energy consumption and the related but not identical focus of reducing CO_2 emissions. The National Health Service (NHS) in England accounts for 3% of the nation's CO_2 emissions(4) while healthcare in the USA (with higher health expenditure per unit of GDP) is responsible for 8% of total CO_2 emissions(3). In England, 19% of NHS CO_2 emissions in 2010 were related to direct energy use in healthcare facilities, with 16% related to staff and patient travel, and 65% resulting from the production of procured goods (e.g. pharmaceuticals, food and medical equipment)(48). In Australia, a national analysis of healthcare's 'carbon footprint' has not been performed, but the calculation of CO_2 emissions from metropolitan hospitals in Melbourne(5) had similar results to CO2 emissions for hospitals in England(48).

Despite the evolution of sustainability as a field of interest and research more broadly, within healthcare the issue has lagged as hospitals in particular are focussed upon immediate patient needs and there has not routinely been a culture of sustainably(37, 49). There are numerous voluntary organisations supportive of sustainability within healthcare and hospitals(39, 41, 42, 44). As of mid-2015, however, the United Kingdom (UK) was the only nation that has a government institution within healthcare specifically devoted to improving environmental sustainability, the Sustainable Development Unit (SDU). In 2008 the UK Government introduced the Climate Change Act, mandating a nationwide reduction in CO_2 emissions by 80% by

2050 compared with 1990. As a direct result of this mandate, the SDU has been measuring the National Health Service’s (N.H.S.’s) carbon emissions(4) and identified carbon hotspots(8). Differences in opportunities to improve healthcare sustainability between a country with mandated carbon emission targets (the UK) and those without (Australia) have been examined(50).

Sustainability may not be considered within healthcare for other reasons. Specifically, healthcare sustainability is not solely about the environment, and could be reframed(2). Being more sustainable means; improving patient care, avoiding ineffective treatments, increasing healthcare equity, raising efficiency and thus saving money, and improving environmental outcomes(6, 37, 51).

This literature review did not provide a detailed examination of general attempts to improve the sustainability of any building unless they were specific to hospitals (e.g. the energy efficiency of operating room ventilation). Thus, ongoing general improvements in wall cladding or air conditioner energy efficiencies are not examined.

2.5.1 Hospital design

Sustainable architecture has an extensive research base, including textbooks with hundreds of references and standards focussed specifically on healthcare(11, 12) For example, the Green Guide for Health Care details methods to improve hospital design, construction, operation and maintenance and provides a toolkit for self-assessment towards best environmental practice(40). Such guidelines and textbooks specific to healthcare design arose from earlier efforts to improve the environmental standings of all buildings such as the Leadership in Energy and Environmental Design (LEED), developed by the US Green Building Council(52). The work of the group ‘The Design & Delivery of Robust Hospital Environments in a Changing Climate’ (led by Short et al) at the University of Cambridge (UK), is also acknowledged(53).

Incorporating energy efficiency at the planning and design stage is important for securing longer-term efficiencies(54). Energy usage per unit area (m^2) for hospitals is the second highest for all building types(55), but varies considerably between hospitals depending on design(56). Most modern hospitals are built on a deep-plan design (with a large distance from the centre to the periphery), requiring high electricity consumption for ventilation of the building’s core(56).

There have been some encouraging research findings regarding the benefits of ‘healthy’ buildings to staff and patients. For example, Ulrich(57, 58) found that having a ‘room with a view’ (i.e. a view of a tree versus a brick wall) reduced hospital length of stay and analgesia requirements post-operatively but as the sample size was small further research is needed. On the contrary, Wunsch et al found that the presence of a window room for ICU patients with subarachnoid haemorrhage had no effect upon patient outcomes(59). The purported benefits of healthy buildings remain somewhat contentious and require further research.

Absenteeism appears to be less in sustainable work environments, though this has been rarely studied in healthcare environments(58). There are potential areas of conflict between greater upfront capital costs and reduced recurrent costs. Single patient rooms may be associated with reduced infection rates, but have greater initial costs and energy requirements compared with multi-use patient rooms(11, 58). Two reviews(60, 61) suggested that the benefits of single patient rooms are not yet proven and that further research is needed to investigate the balance of costs and benefits, as indicated by ongoing controversy about the clinical and social advantages of single patient hospital rooms(62).

2.5.2 Energy

Direct energy use by healthcare accounts for approximately 20% of all public sector energy consumption in Victoria, Australia(63) and is likely to be similar in other developed countries. Heating, ventilation and air conditioning typically account for at least half of direct hospital energy usage, with lighting and equipment accounting for most of the remainder(64) How much energy use arises from individual hospital areas such as the operating suite is not well established. Further, there is incomplete information on the energy consumption of many common machines as they are actually used within hospitals rather than being determined by the manufacturers’ specifications(65).

A large body of architectural and engineering research focuses on reducing direct energy consumption in buildings of all types. There are several instances in which the large and continuous energy requirements of hospitals have stimulated research into specific technologies and energy sources, such as gas-fired co-generation, solar thermal cooling and ground-sourced heat pumps(64). Co-generation (combined heat and power) is ideal for hospitals which require continuous electricity and heat, provides added energy security, and can have reasonable payback times(55).

There has been a limited amount of hospital-specific research examining energy usage for heating, ventilation and air conditioning. Tensions can exist between protecting the patient and the environment, often due to infection control concerns(66). A one degree Celsius rise in room temperature in summer or reduction in winter can reduce annual cooling and heating costs by 5%(7). Methods to reduce hospital energy consumption by widening the permitted temperature range, particularly during extreme weather events, without compromising safety or alienating patients or staff are largely unexplored.

Ventilation within most buildings is routinely mixed ventilation (supply air mixes with room air) or, less commonly, displacement ventilation (supply air spreads from the floor and rises as it warms)(67). Displacement ventilation can produce equivalent air quality with lower energy consumption, but quantification of savings is unclear within hospitals(67). Hospital ventilation is routinely left running continuously, including within operating rooms (ORs) that are unoccupied overnight. There is, however, evidence of no difference in the microbiological load of air samples from ORs where the ventilators are turned off in idle ORs overnight compared with ORs with continuous ventilator usage(68).

Several models estimating healthcare energy use occurring with inpatient and outpatient admissions and different types of surgeries have been developed by Pollard et al(69, 70). The aim of such modelling is to improve the financial and environmental sustainability of healthcare without impeding patient care. Work occurring at the UK SDU (48) will assist in guiding hospital staff to reduce energy use and carbon footprints.

2.5.3 Water

Hospitals use considerable amounts of water – e.g. 1% of a city’s total water consumption(71). Within a hospital the majority of water use occurs in four areas; wash basins, sinks and showers (20 to 40% of total); toilets (15 to 30%), laboratories, cooling towers, macerators and sterilisers (15 to 40%); and food preparation (5 to 25%)(71).

Water savings of 10 to 25% can be achieved through simple means which do not require further innovations or research: auditing usage including installing data-logging meters and sub-metering; checking for leaks; applying flow restrictors on hand basins and showers; installing dual-flush toilets; and reclaiming water from dialysis units and sterilisers(71). Areas of ongoing research have focussed upon the operating suite and the dialysis unit. Significant water savings are possible (hundreds of litres/tap/day) from altering the surgical hand scrub whether through water-saving devices such as automatic tap timers or replacing water with disinfectants(72). Water savings of several thousand litres/day are also possible from dialysis units(73-75).

2.5.4 Travel

Hospital travel incorporates ambulance, private and public transport. Car travel in particular is a major contributor to CO_2 emissions as well as being an inactive, unhealthy form of transport. The UK SDU estimates that 16 percent of carbon emissions related to healthcare are attributable to staff and patient travel(4). Improving the sustainability of hospital travel can be subdivided into technical, financial and social changes. Technical changes include any incremental improvements to vehicle technologies and service transformation to reduce travel. Financial interventions include incentives to increase active and public transport or increasing car parking fees to reduce car travel. Social and cultural factors shape the forms of transport used by hospital patients and staff.

Technical changes may lead a transformation of hospital travel. Improved teleconferencing or telemedicine can reduce travel demand for business, patient and staff leading to financial, environmental and time savings(76, 77) Other clinical innovations, however may increase patient travel. Replacing thrombolysis in local hospitals with interventional cardiological procedures in more distant, larger hospitals will increase ambulance CO_2 emissions(78) highlighting conflicts that can arise between protecting the patient and the environment(66).

Whether altered financial or tax incentives can change travel pathways to hospitals is an important topic for future research. Perverse incentives may mean that the pecuniary interests of hospitals are at odds with sustainability; e.g. rent from car parking vs. lower fees for pooled cars, or tax reimbursements for inter-hospital travel(79).

Social factors are also likely to be important in altering hospital transport. Large reductions in car transport to hospitals are possible with improved public transport services, car-pooling and encouraging cycling. For example, at Addenbrooke's hospital, Cambridge, UK, by doubling the number of bus services and greatly improving hospital bicycle facilities the proportion of journeys made by car was reduced from 60% in 1999 to 38% in 2006(80). Social norms and peer influence within the hospital workforce may shape staff decisions regarding how to travel to work. Research regarding the most important determinants of travel behaviours is limited.

2.5.5 Procurement

Several studies have found that procured goods represent by far the largest contributor to healthcare's carbon footprint(8). Research on haemodialysis, for example, has shown that dialysis consumables are responsible for similar CO_2 emissions to total dialysis transport and dialyser energy use combined(81). Over the past 30 years many reusable products have been replaced by disposable ones across most specialties, such that "…hospitals are now awash in throwaway supplies"(12). The research base of the environmental effects of hospital procurement is far less developed than for hospital architecture and engineering.

There is a natural tension between the potential environmental and financial benefits of reusable medical devices and their possible infection control concerns(66). The move to single use items has not been well studied and appears to be driven by other factors beyond infection control practices, such as cost, ease of use, difficulty making some reusable items patient ready again, individual (doctor) preferences and marketing(12).

Efforts to understand the entire 'cradle to grave' environmental and financial costs of items or processes are based upon the method of life cycle assessment (LCA), introduced previously in Section 2.3 in this chapter. Despite being common in other fields, LCAs are relatively new to healthcare. Most medical LCAs have occurred in the fields of anaesthesia, surgery and dialysis units. LCAs within the OR and ICU are examined in Section 2.6.1 of this chapter.

Within nephrology there have been several recent LCA studies. Connor compared the carbon footprint of UK home and hospital dialysis finding that home dialysis had a greater footprint, and disposable dialysis items have a considerably larger footprint than other components to dialysis such as electricity use or transport to and from hospital(81). A similar Australian study found comparable results, noting further that regional variation in the source of energy (e.g. coal, gas, hydroelectric) dramatically altered the relative importance of the carbon footprint of the electricity used for dialysis(82). One study of the life cycle of receiving a CT scan in Kansas, USA found that the electricity used when the CT scanner was idle was an order of magnitude greater than the energy used for an actual scan received by the patient(83). Follow up studies examining the ability in a busy hospital to turn CT scanners off rather than leave them in standby are required. LCAs are rare in other fields of medicine (e.g. general practice, physician subspecialties).

Pharmaceuticals appear to have high environmental and financial costs as they appear to be energy intensive to manufacture(8). Openly available LCAs of pharmaceuticals will become increasingly important due to their high costs and large carbon footprints(84). Pharmaceutical companies have rarely engaged with LCA researchers and published in peer-reviewed journals, perhaps due to concerns regarding commercial confidentiality. In December 2012, however, a UK guideline *Carbon footprinting pharmaceuticals and medical devices* was promulgated by a collaboration of pharmaceutical representatives, health services employees, clinicians and LCA experts(85).

Chemists and chemical engineers, responding to concerns regarding the environmental footprint of their products and processes, have established a scientific foundation to ‘green chemistry’ which could be emulated in medicine(86). There has been some engagement of manufacturers of healthcare products and organisations such as Healthcare Without Harm to reduce the effects of packaging and waste(87). There is also renewed interest in return of unused medicines, one study finding that one quarter of all returned medicines were suitable for reuse(88).

Interest in the environmental effects of treating dialysis patients has been stimulated by funding from the UK Green Nephrology Scholarship. The frequency of dialysis has a greater effect upon CO_2 emissions than dialysis duration(89) With the rise of home dialysis delivered more frequently, innovative approaches will be required to prevent the predicted doubling of CO_2 emissions per dialysis patient, including methods to reduce consumables and waste disposal(89). Embedding sustainability into overall hospital procurement is still in its infancy and faces financial (real or perceived) and attitudinal barriers(90).

2.5.6 Waste

Hospitals in the USA alone generate an average of 5,500 tonnes of waste every day(91), indicating considerable opportunity to reduce hospital waste leading to financial and environmental improvements. The environmental and financial benefits of improving waste management processes are generally greater when moving progressively through the ‘waste hierarchy’ from discarding, through recycling, reuse, reduction and finally to avoidance of creating waste materials in the first place(14).

Avoidance of unnecessary or unproven hospital procedures is likely to have a greater effect than all current hospital recycling initiatives. There are many examples within medicine of unnecessary procedures, e.g. routine preoperative chest-x-rays(92) or coagulation tests(93).

Hospital recycling does, however, have an established research base. Examination of waste disposal shows financial and environmental benefits stemming from treating infectious waste by microwaving rather than autoclaving, lime or incineration(94). Approximately 30% of all hospital waste is paper and cardboard and a similar proportion is plastic, indicating high recycling potentials(95). Infection control concerns regarding hospital waste recycling can be managed provided there is appropriate education and action(96).

2.5.6 Behaviour

The psychological and social factors that shape hospital staff and patient behaviours is an important research topic(49). While an interest in the environment in their personal lives has been found to increase the likelihood that individuals would recycle at the hospital, often environmentally sustainable personal behaviours are not carried into the workplace(96).

Topf examined staff indifference to unsustainable hospital practices such as excessive lighting, consumption and waste(97). This research suggested that hospital environments encourage environmental ‘numbness’, and elicit a range of coping mechanisms including denial that unsustainable behaviour is occurring; overly critical thinking that may prevent change; myths that green practices and buildings are prohibitively expensive; temporal justification (i.e. staff being too busy dealing with short term goals to become involved in enduring concerns); and the so-called ‘moral offset’ - “I’m doing enough good just being a doctor.”(97).

Group coping mechanisms include diffusion of responsibility (someone else will solve the problem) and ‘groupthink’ (the illusion of unanimity due to the leader’s influence)(97). By supporting employees to make ethical decisions that align with their own values, employees are more likely to take action to address these concerns(98). There has been minimal research within healthcare about which of these psychological factors (e.g. the moral offset or groupthink) are the most important to address in order to encourage sustainable practice amongst hospital staff. Further, there is minimal understanding of patients’ views of healthcare sustainability(97).

OR and ICU sustainability research has occurred particularly within the fields of procurement and life cycle assessments of specific products or procedures, in addition to waste management (including reduce, reuse, recycle and reprocess). Themes such as the built environment, energy and water have been discussed previously as part of the more general topic of hospital sustainability. Although there are OR and ICU-specific energy saving areas such as reducing theatre ventilation when not in use(68) the majority of energy saving possibilities are likely to stem from more generalized improvements in overall heating, ventilation, air conditioning and lighting(99).

The Association of Anaesthetists of Great Britain and Ireland(100), the Association of Surgeons of Great Britain and Ireland(101) and the American Association of Anesthesiologists(102) have all separately issued policy documents to promote consideration of, and research about, the sustainability of anaesthesia and cost-effective and sustainable surgery. General reviews of sustainability efforts to reduce energy and water use and waste indicate the potential financial and environmental cost savings(32, 103-105).

2.6 SUSTAINABILITY WITHIN THE OR AND ICU

Operating room (OR) and intensive care unit (ICU) sustainability research has occurred particularly within the fields of procurement and life cycle assessments of specific products or procedures, in addition to waste management (including Reduce, Reuse, Recycle and reprocess). Themes such as the built environment, energy and water have been discussed previously as part of the more general topic of hospital sustainability. Although there are OR and ICU-specific energy saving areas such as reducing theatre ventilation when not in use(68) the majority of energy saving possibilities are likely to stem from more generalized improvements in overall heating, ventilation, air conditioning and lighting(99).

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2.6.1 Procurement and Life Cycle Assessment (LCA) in the OR and ICU

Procurement is the purchase of goods and services. Within the OR and ICU large numbers of single use devices are procured(32) and in addition, the OR particularly makes use of reusable steam sterilised items. The LCA method is being used increasingly to determine the environmental effects of these products and processes within the OR and ICU, particularly when comparing reusable and single use variants of a product and to examine entire surgical operations.

The environmental effects of procurement include the device or product itself, whether it be single use, reused, recycled or reprocessed and the effects of the packaging associated with that device. There is little information regarding the environmental effects of the significant packaging used to transport medical devices and which may have larger effects than the product itself. Further, despite the increasing interest in sustainability, the majority (70%) of OR suppliers do not promote sustainability practices(106).

Operating theatre LCAs have primarily been comparisons between reusable and single use variants of medical devices: surgical drapes(107), gowns(108), suction canisters(109), laparoscopic ports(110), and laryngeal masks(111), and dental burs(112). In the majority of these cases the reusable versions were found to be less financially expensive and had lower environmental effects (CO_2 emissions, water use, and land and water pollution) than the single use variants. Such environmental effects varied greatly according to the energy source used (e.g. coal has far higher CO_2 emissions than renewable energy sources)(112). Further, the environmental effects of the reusable items varied considerably with the relative efficiency at which the steam steriliser was loaded(112).

Input-Output LCAs attach an environmental effect to a financial value (as noted in Section 2.3) and have now been performed for entire operations. The carbon footprint of one cataract operation was found to be approximately 180 kg(113) (i.e. similar to burning 80 litres of petrol)(114). A process based LCA of the environmental effects of vaginal childbirth deliveries versus caesareans found that the former had approximately 40% of the carbon footprint of a caesarean operation(115). A recent hybrid model of input-output and process based LCA compared different types of hysterectomies, finding that robotic surgery had higher environmental effects than standard hysterectomies(35) and that the anaesthetic gases used during the operations contributed to approximately 30% of the total CO_2 emissions for the entire operation. Such LCAs of whole procedures complement studies of individual devices.

Despite the ubiquity of pharmaceuticals there have been few openly available LCAs examining their environmental effects(105). It is often easier to perform LCAs of medical equipment rather than pharmaceuticals because there is usually open access to the manufacturing methods for the former (e.g. plastic and steel production). The fundamental barriers to performing process based LCAs of pharmaceuticals appear to be primarily industry resistance (i.e. the commercial implications of comparing processes or items) and the costs of performing the study. Process based LCAs are expensive to perform (usually greater than AUD$10,000) primarily because of the labour costs of data gathering and validation. Sherman et al examined the environmental life cycles of several general anaesthetic drugs, finding that the carbon footprint of the intravenous drug propofol was less than one hundredth of desflurane’s(116). Nevertheless, this LCA relied upon generic data as no pharmaceutical companies were involved in the study despite invitations(116).

With collaborators I completed a process based LCA of plastic drug trays prior to PhD enrolment which is detailed further in Section 2.6.8 of this chapter(65).

2.6.2 Waste

The Reduce, Reuse (reprocess), Recycle (and segregate) waste hierarchy(14), in tandem with life cycle assessment, provides a useful framework to consider the environmental effects of work within the OR and ICU(32). ORs and ICUs are highly active parts of the hospital and correspondingly generate large amounts of waste. As examples of this intensity, the daily landfill waste from all operating rooms in the USA is more than 1,000 tonnes of rubbish(91). Beyond physical waste there are also the consumption of gases (e.g. inhalational anaesthetics) and pharmaceuticals.

Approximately 20% of all hospital waste stems from the operating room(95). Plastics form approximately 30% of operating room waste(95, 117). It has been known for more than 20 years that the recycling potential of the OR is large and that reducing the incorrect labelling of infectious waste can have significant financial benefits(118).

The recycling of waste is discussed further in this chapter under ‘Recycling’ (Section 2.6.6). With collaborators, I completed several waste audits of OR and ICU waste(119, 120) prior to PhD enrolment which are detailed further in Section 2.6.8 of this chapter.

2.6.3 Waste-Anaesthetic Gases and their Global Warming Potential

A special case of healthcare ‘waste’ relates to anaesthetic gases, divided into volatile gases (desflurane, sevoflurane, isoflurane and halothane) and non-volatile (nitrous oxide). These gases can be used in both the OR and ICU, but in Australia tend to be used only in the OR. Such gases provide general anaesthesia, are metabolised and degraded in only minimal amounts, and are subsequently vented via hospital scavenging systems to the atmosphere where they have a direct Global Warming Potential (GWP)(121, 122). GWP is defined as the relative potential of a gas to absorb energy in the infrared spectrum and thus warm the planet, compared with the baseline gas CO_2(122). Worldwide, anaesthetic gas use is estimated to have the same carbon footprint as one million average passenger cars(122). Nitrous oxide, for example has a GWP 300 times that of CO_2 and providing anaesthesia with it for one hour at a standard rate is comparable to driving an average car several hundred kilometres(123).

Volatile anaesthetic gases with similar chemical structures may have GWPs which are an order of magnitude different; e.g. sevoflurane has a GWP of 130 whilst desflurane's GWP is 2,540(122). Such volatile anaesthetics may be used interchangeably with no clinically different outcomes(32) indicating that the individual anaesthetist has an ability to significantly alter their carbon footprint according to their work practices(32).

Using anaesthetic gases at the lowest flow is the most obvious method to reduce the global warming effects of anaesthetic gases(124). Alternatively, for some operations, one could use intravenous anaesthetic drugs which have no direct GWP in lieu of anaesthetic gases(116). Further, there are technologies available that absorb the volatile anaesthetic gases and avoid their release to the atmosphere(125, 126). Despite these promising technologies used primarily in North America, they are not available in Australia as of mid-2015.

Other gases are also 'wasted' in the OR and ICU, e.g. oxygen and 'medical air' (i.e. filtered air). In the ICU high flows of oxygen and air are used, whilst lesser amounts are used in the OR due to the low gas flows and resorption of CO_2. There has been little focus upon these gases, including an examination of the energy required to compress them (e.g. conversion of oxygen to the liquid state for storage) and their environmental footprint is unknown or unpublished.

2.6.4 Reduce

It is very likely that to reduce the use of products and processes will decrease financial and environmental costs, yet such 'reductions' must avoid reduced patient care. Methods for reducing resource consumption and environmental effects in the OR and ICU range from; minimizing hospital admissions (improvements in public health care to reducing trauma rates and increasing out-patient procedures), and reducing the use of drugs and equipment for each procedure(32).

There are a number of behaviours in the OR and ICU that reduce the environmental footprint without impeding effectiveness: opening equipment only when needed, removing cotton gauze from pre-packed anaesthetic trays(65) turning off anaesthesia monitors between cases(127), using low flow anaesthesia(124), switching off lights and air conditioning or ventilation (including ICU isolation rooms) when not in use(104). Despite these and other possibilities to Reduce there is an ongoing increase in the amounts of waste stemming from ORs and ICUs(105).

2.6.5 Reuse

Comparisons between the life cycles of reusable and single use devices used in the OR and ICU have been discussed previously in this chapter (Section 2.6.1). Comparing reusable versus single use medical devices, the limited literature suggests that it is both an environmental and financial advantage to consider reusable devices where these exist (surgical scrub gowns, metal instruments, plastic trays), although caveats exist. Methods used to re-sterilise reusable equipment have rarely been subject to environmental assessment. Greater scrutiny of and comparisons between different methods of sterilisation (e.g. steam, gamma radiation, hydrogen peroxide) would add significantly to knowledge about the environmental footprint of reusable items.

There appears to be much opportunity to increase the research foundation for ‘Reuse’ in the OR and ICU. In the ICU in particular, but also in the OR in many developed nations there are very few remaining items that are actually reused. Anecdotally, for example, in the USA it is routine in many places that each patient in the ICU and OR has a single use; blood pressure cuff, heating blanket, pulse oximeter and anaesthetic/ICU breathing circuit. In Australia it would be unusual to have single use; pulse oximeters, breathing circuits and blood pressure cuffs. Studies regarding the infection control concerns and legislative requirements for the use of common medical equipment of different jurisdictions are warranted.

2.6.6 Recycle

An important first step in recycling hospital waste is to separate infectious from non-infectious waste as infectious waste is costly in both financial and environmental terms and cross-contamination of infectious waste into recycling streams can cease such recycling(117). Recyclable, non-infectious waste should then be further separated (at least one-third of all OR waste)(117, 119). There are still many ORs and ICUs where separating infectious and general waste occurs to a limited degree and there are inadequate recycling arrangements(103, 117, 119). Efforts to recycle have been promulgated by many organisations mentioned previously (e.g. Healthcare Without Harm). Manufacturing products from recycled rather than raw materials is often environmentally attractive when the entire life cycle is considered, particularly for metals and plastics, although this will depend closely upon the proximity of the recycling facility(128).

Recycling of metals is potentially easier than other recycling streams as they are easily identifiable and valuable. Paper and cardboard products can be correctly recycled due to their readily identifiable composition and kerbside home recycling programs. Recycling of glass(129) does occur although glass generally has low financial value and glass ampoules which have contained pharmaceuticals can be challenging to recycle.

There are multiple varieties of medical plastics which may be inadequately labelled, though guidelines exist to aid recycling which have been mentioned in Section 2.6.2 (130). It can be important to separate some plastic types, such as polyvinylchloride (PVC), that are processed differently. PVC is used for items including intravenous fluid bags and oxygen tubing and can comprise approximately 20% of a hospital’s plastic waste(95). Anecdotally, in Australia and elsewhere plastic recycling of polyethylene and polypropylene has been occurring for several decades in some hospitals.

There is evidence from psychological studies that there may not be a strong positive correlation between those who recycle and those who also reduce and reuse(131). Recycling is a very obvious activity that is often observed by other staff members; whilst reducing or reusing may be inconspicuous (e.g. one may be unaware that a drug tray is reused after thermal disinfection rather than single use). Such differences may explain why recycling is avidly approached by groups of staff, whilst reducing or reusing is less enthusiastically welcomed(131).

2.6.7 Reprocessing

Medical devices can be divided into three groups according to their usage: 1. single use, i.e. one use only (disposable), 2. reusable, i.e. able to be washed and sterilized for patient reuse generally within the hospital and 3. reprocessed devices, i.e. undergo assessment, repair, sharpening, smoothing, cleaning and sterilizing before being reused. Typically reprocessing is performed external to a hospital by a third party, with the device returned to the hospital for less than half the financial cost of the original ‘single use’ purchase price(132). Reprocessing of medical devices is a multi-billion dollar industry in the USA(132), although as of mid-2015 it does not exist in Australia.

Currently, manufacturers determine whether their product is single use and lodge this information with the relevant regulatory body(133). Further research on the validity of labelling devices as single use may have significant environmental and financial advantages. It is unclear if reprocessing is more environmentally sustainable than purchasing new items, although reprocessing is less expensive and appears to decrease landfill waste(132).

2.6.8 Related work by the author prior to the beginning of the PhD

(i) An LCA of anaesthetic, plastic drug trays

I completed a process based LCA of drug trays in early 2010 with the collaboration in particular of an LCA expert at our six-operating room hospital in Melbourne, Australia(65). We compared the financial and environmental life cycles of reusable and single use plastic anaesthetic drug trays. We were particularly interested in the global warming potential (CO_2 emissions) and water use. The reusable drug trays are washed (decontaminated), but are not required to be sterilised. Further, we examined the effects of adding cotton and paper to the drug trays, which is routine for all single use tray packages at our hospital. Cotton gauze and a paper napkin are added for fluid or blood spills, although anecdotally these are required by anaesthetists for less than half of operations. Our LCA included measurement of the labour costs to process a reusable tray to be patient ready again.

We found that the financial cost of single use drug trays with cotton and paper included was considerably greater than the reusable trays such that a conversion to the reusable trays would have saved the hospital approximately AUD$5,000 in 2010. We factored in the cost of requiring the cotton and paper to accompany the reusable trays half of all cases (likely to be an over-estimate).

The CO_2 emissions for one reusable and single use drug tray was110g CO_2 and 126 g CO_2 respectively (similar to driving an average Australian car one kilometre(114)) . The CO_2 emissions from the reusable and the single use plastic trays alone was similar primarily because the source of electricity for our hospital was brown coal, an energy source with very high CO_2 emissions, whereas the electricity source for the single use drug tray was a combination predominantly of black coal and nuclear.

The effect of adding just 3g of cotton gauze and 6g of paper added another 80g of CO_2 emissions. Further, the water use for growing cotton was an order of magnitude larger per gram than for plastics manufacture. Thus, although reusable drug trays processed in Melbourne's hospitals rather than single use trays resulted in similar CO_2 emissions, if cotton and paper were added routinely to trays (as is the case for all single use trays) the CO_2 emissions appreciably increase and the water use is greatly augmented. Our study gave the worst case scenario for reusable trays due to the brown coal based energy mix in Melbourne, Australia. As a result of our LCA in late 2010 the hospital anaesthesia department changed from routinely using single use to using reusable drug trays, saving money and reducing the environmental footprint of drug trays. This LCA of (unsterilised) drug trays formed the basis for a second LCA examining the life cycle of a common sterilised ICU and OR item and which becomes a thesis chapter.

(ii) OR and ICU waste audits prior to recycling.

In 2009, with the assistance of hospital collaborators (at Footscray, Melbourne, Australia) I completed waste audits of OR and ICU waste, prior to formally commencing this PhD (119, 120). Prior to 2010 there was no recycling occurring within the hospital's OR and ICU beyond paper and cardboard recycling in administrative areas. In order to perform the waste audits correctly we firstly obtained further details about the common medical items used in the OR and ICU and subsequently discarded as waste. Further, as recycling of such OR and ICU 'waste' was being considered post-2009, we needed to discover what types and amounts of recyclables were present.

Recycling plastic, cardboard, metals and household plastics could be straightforward as they were readily identifiable. Recycling medical plastics, however, could be problematic as there was limited information regarding different plastic types. We thus developed a simple guideline prior to the OR and ICU waste audits that enabled us to distinguish the plastic types that comprise common medical equipment such as intravenous fluid bags, oxygen masks and theatre wraps(130).

We then audited the waste exiting the OR and ICU for 5 and 7 days, respectively weighing 357 kg of OR waste and 540 kg of ICU waste. For the OR waste we examined in detail only the anaesthesia waste (i.e. stemming from anaesthesia waste bags contained on anaesthesia trolleys) which formed approximately one-quarter of all OR waste. The major findings from both the OR and ICU waste audits were:

1. Approximately 35-40% of the total waste could have been recycled
2. At least 40% of the recyclables were plastics
3. There was incomplete separation of infectious (clinical) waste from general waste leading to unnecessary hospital expenditure. This finding is similar to prior studies of hospital waste segregation(96, 117) (infectious waste costs at least four times as much per kg to dispose of compared with general waste)
4. Contamination of infectious waste in the general waste stream was minimal (less than 1%).

With these findings from our waste audits recycling programs were commenced within the OR and ICU. Audits of these post-recycling programs form ‘Chapter 9: Recycling. Waste audits in the OR and ICU post-recycling’.

Summary

This chapter briefly reviewed the history of sustainability as a concept and movement. The ‘3R’s mantra: Reduce, Reuse, Recycle and life cycle assessment (LCA) were introduced respectively as an approach and a method to begin to be able to quantify the environmental effects of products and processes. Thereafter followed a review of hospital sustainability for which common research themes were identified: hospital design, energy, water, travel, procurement, waste, and behaviour. Finally, the literature review focussed upon the evidence base for sustainability within the OR and ICU. A particular emphasis was placed upon OR and ICU procurement, waste and ‘the 3Rs’ as other themes had been reviewed previously.

Research regarding hospital design is at a relatively mature stage. Similarly, there is a developed research base regarding generic devices and technologies used within hospitals (such as air conditioners) to reduce the environmental effects of direct hospital energy and water use. Less well developed are analyses of how hospital staff use such devices, particularly those integral to the OR and ICU such as steam sterilisers. Less is known also about the clinical, psychological and social factors that influence how healthcare professionals use resources, travel to and from hospital, and interact with the buildings and technologies available.

This systematic review of hospital environmental sustainability and in particular OR and ICU sustainability was focused on particular themes, thus potentially overlooking other relevant literature. Studies that were covered more broadly or recently elsewhere were also excluded. Nevertheless, the themes were based on existing frameworks as well as the initial examination of the literature, and are likely to capture the most important ways in which hospital activities affect the natural environment.

Most research on hospital sustainability (e.g. architecture and engineering features) has been performed by specialists in isolation, with minimal clinician participation. Due to the broad nature of hospital sustainability, collaboration will be needed to improve research outcomes. This collaboration includes; clinicians, engineers, architects, chemists and pharmacists, life cycle assessors, and social scientists. Joint work between different specialties is now occurring, e.g. LCAs of medical devices. Collaboration between engineers and clinicians to achieve energy and water efficiencies while also improving or at least not adversely affecting patient outcomes would be valuable. Clarifying barriers to change, particularly behavioural, will be the domain of social scientists working with clinicians.

In this review relevant research findings of environmental impacts and natural resource use within a variety of academic disciplines were found, yet there remain substantial knowledge gaps. In particular, sustainability research in the OR and ICU is at a nascent, but expanding stage. At each level of reduce, reuse and recycle there are substantial opportunities for research.

CHAPTER 3: REDUCE

THE FREQUENCY OF WASHING ANAESTHETIC BREATHING CIRCUITS.

3.1 BACKGROUND

Following the ‘Reduce, Reuse, Recycle’ paradigm, Chapter 3 examines one example of ‘reducing’ to improve hospital environmental sustainability. Within the Operating Room and Intensive Care Unit one could reduce the use of many items, packaging and procedures. It is reasonable to consider however, a device that could feasibly be used less frequently or at least cleaned less frequently. Further, there are many devices/procedures where it would be impractical to reduce the use of without protracted discussions with multiple clinicians (e.g. surgical equipment). Finally, researching the environmental effects of an item in the field of the researcher’s specialty (i.e. the OR and ICU) may be influential if one then wishes to research environmental sustainability in related fields with other clinicians.

Within the ICU of many developed countries most devices beyond the machines used to provide invasive physiological support are single use. For example, all drugs and drug syringes, airway equipment, ventilator circuits, humidifiers, invasive venous access catheters and the kits used to insert these catheters are single use. Although it is possible to reduce the use of expensive pharmaceuticals by choosing less expensive variants or simply to use less of each drug, such studies are more within the domain of audits rather than new research. There was thus thought to be limited research opportunity to reduce the use of what were primarily single use items in the ICU.

Within the OR in Australia, many common anaesthetic items could be either reusable or disposable: e.g. face masks, breathing circuits and various airway devices. Anaesthetic breathing circuits are either reusable or disposable (i.e. used for a variable number of patients prior to disposal). There is variation between hospitals as to how frequently breathing circuits are changed. At our hospitals reusable circuits are used and changed daily. A study was undertaken to determine whether it would be possible to reduce the frequency of washing anaesthetic breathing circuits without increasing potential risks to the patient leading potentially to reduced usage of equipment, energy and water.

This chapter is mostly based upon the following publication: McGain F, Algie CM, O'Toole J, Lim TF, Mohebbi M, Story DA, Leder K. The microbiological and sustainability effects of washing anaesthesia breathing circuits less frequently. Anaesthesia. 2014; 69(4):337-4.

3.2 INTRODUCTION

A natural tension exists between protecting the patient and protecting the environment(66). For example, re-using clinical equipment can lead to financial and environmental savings, but is tempered by possible patient safety concerns. When single-use filters are used, anaesthetic breathing circuits are changed at different frequencies according to jurisdiction (134) – between patients in the United States (135), from daily in the United Kingdom (136), and weekly in Germany (137). In Australia, there are guidelines recommending single-use filters and how to clean anaesthetic circuit(138, 139), but the frequency of circuit cleaning is unspecified. Anecdotally, anaesthetic circuits are changed most often on a daily basis, but often more and occasionally less frequently.

Two previous studies have examined extended use of anaesthetic breathing circuits (140, 141). Hartmann et al studied the microbiological effects of extending the duration of use of breathing circuits prior to decontamination from 24 hours to up to 72 hours(140). Hartmann found no evidence of a clinically important change in circuit contamination rates with extended use up to 72 hours (140). Hartmann’s study was useful as it indicated that there was unlikely to be harm when reducing circuit decontamination to every 72 hours. Our aim was to study circuits for up to 7 days between decontamination. Hubner et al studied prolonging the use of breathing circuits prior to decontamination to up to 7 days and also found no change in circuit contamination(141). In Hubner’s study only 55 patients had circuit changes of 7 days and there was no statistical analysis included making it difficult to draw conclusions from the data(141).

3.3 AIMS

1. To examine circuit use for up to seven days, to investigate whether extending the use of reusable breathing circuits from 24 hours (standard interval between decontamination at our hospital) to 7 days resulted in a significant deterioration in the hygienic quality of breathing circuits.

2. To quantify any equipment, electricity and water cost savings resulting from extended circuit use.

3.4 METHODS

This study was a prospective microbiological examination of reusable anaesthetic circuits (Parker Healthcare, Victoria, Australia) at the Western Hospital, a 6-theatre, 300-bed, University-affiliated hospital in Melbourne, Australia. All surgical subspecialties except for cardiac surgery, obstetrics and cranial neurosurgery are represented at the Western Hospital. The Western Hospital Low Risk Ethics Committee approved this study (Approval Number: HREC/2011/WH/52). In accordance with local guidelines(138), a new, single-use airway filter was used (DAR electrostatic filter-350 U5879, Covidien, Boulder, Colorado, USA) for each operation.

Professional standards in Australia/New Zealand require that thermal disinfection of breathing circuits ‘destroy(s) non-spore bearing vegetative organisms’ (142). In line with this standard, we used aerobic heterotrophic plate counts (HPC) (143, 144) as a sensitive indicator of bacterial contamination by non-spore bearing organisms, and therefore circuit ‘cleanliness’ (145). The 3M Petrifilm™ plate used is an inexpensive thin-film version of the conventional Petri dish agar plate, and gives quantitatively comparable results (146, 147). Petrifilm™ plates are commonly used for hygiene testing (148), and their use is supported by the American Public Health Association and the Association Francais de Normalisation (149). They have also been used in operating theatres (150) and dentistry (151).

Decontamination (thermal disinfection) involves washing a device with water at either 80°C for 10 minutes, or 90°C for one minute, as per the Australian and New Zealand Standards-4187 (AS/NZS-4187)(139). The same Standards (AS/NZS-4187) require steam sterilisation to be performed for ‘critical devices’ (i.e. those which contact normally sterile places) at 134°C for 3 minutes(139). Routinely anaesthetic breathing circuits are not ‘critical’- i.e. they do not require sterilisation, but do require thermal disinfection. As per the AS/NZS-4187, Hospital Central Sterile Supply Department (CSSD) staff placed the reusable circuits in an industrial washing machine at 80 degrees for 10 minutes with appropriate detergent. A minimum of one anaesthetic load/day was required to wash all anaesthetic items.

Thermal disinfection of all reusable equipment (i.e. circuits, masks, laryngoscopes, laryngeal masks etc.) occurs in the same ‘anaesthetic load’. Initially, standard care was examined, i.e. 24-hourly circuit changes and decontamination/washing to verify baseline microbiological circuit loads. After a period of personnel education in how to drain circuit condensate appropriately, loads were examined after 48-hourly circuit changes and then after changes up to 7-days. Initially, when an extension to 48-hour circuit changes was piloted, there was an increase in visible fluid accumulation and a coincident increase in circuit contamination counts (results not shown). After holding one education forum to remind personnel of local hospital policy about emptying circuits of visible fluid, the study was recommenced and contamination counts fell.

There could be several reasons for circuit changes occurring more frequently than the proposed time interval. For example, if a patient was deemed infectious or if blood contaminated the circuit, the circuits would be changed. Patients identified with an infection requiring a change of circuit after use (Vancomycin Resistant Enterococcus, i.e. VRE) or infections reportable to the Victorian Health Department (Australia) were excluded from the study.

Microbiological samples were obtained at the end of each theatre list before thermal disinfection (washing), by one of three researchers according to an agreed sampling protocol(140). Under aseptic conditions, the breathing circuit and heat moisture exchanger were disconnected from the anaesthetic machine and a sterile plastic film (Tegaderm, 3M Health Care, St. Paul, Minnesota, USA) was applied to each end of the circuit tubing to prevent fluid escaping. Fifty mL of sterile 0.9% saline was poured into the inspiratory limb, followed separately by the expiratory limb, combining with any pre-existing circuit condensate. The tubing was shaken vigorously for 30 seconds to dislodge potential tubing biofilm. Solution from each limb of the circuit was decanted into a sterile bottle.

Microbiology samples were plated immediately. Five sets of 1mL sample solution for both the inspiratory and expiratory circuit limbs (i.e. 10mL total) were pipetted in a sterile fashion onto the surface of aerobic count (AC) Petrifilm™ (3M, St. Paul, USA) plates. These were incubated for 48 hours at 37°C, and then quantified for colony-forming units (cfu). We defined 'contamination' as one colony or more per 10mL of rinse water (expiratory and inspiratory lines).

The financial implications of moving from daily to weekly circuit decontamination, including requisitioning data for circuits, were examined. For one month each during the 24-hourly and 7-day decontamination periods the number of 'anaesthetic loads' for the disinfection of anaesthetic equipment were audited. Details of decontamination loads were not routinely kept by the hospital sterile supply department (unlike all sterilised loads). The costs for water, electricity, gas and detergent use for anaesthetic loads were based upon a previous study at the hospital(65). Records were obtained of the procurement of reusable anaesthetic circuits at the 24-hourly and 7-day time periods. Gas analyser tubing was attached to the anaesthetic machine side of the single use filter (i.e. away from the patient and protected by the filter). Gas analyser tubing is used to detect the concentrations of O_2, CO_2 and anaesthetic gases. The frequency of changing gas (CO_2 and volatile agent) sampling tubing was not altered, i.e. staff (conservatively) waited until the study's conclusion.

All six operating theatres were assumed to be used for 5 days per week for 48 weeks p.a., and that two operating theatres were used every day ('emergency theatres'). There were thus approximated savings for reduced procurement of gas sampling lines. A detailed labour time and motion analysis was not performed. A currency converter (152) on the 17/6/2015 to convert AUD$1 to USD$0.77.

Statistical analysis

STATA 12 software (StataCorp LP, Texas, USA) was used for statistical analysis. The sample size was calculated from pilot study data showing a 25-35% circuit contamination rate; assuming 80% power, we determined 100 circuits per group would demonstrate a clinically significant 7% effect size. The proportion of contaminated circuits was compared between study groups using Fisher's exact test. Circuit contamination was quantified as: the median bacterial cfu count, the 25%-75% Interquartile Range (IQR) and the lowest and highest count. Median bacterial counts at 48 hours and at up to 7 days were compared to 24 hour counts using the Mann-Whitney U-test. A significant difference was determined by $p<0.05$.

3.5 RESULTS

Over a 15-month study period between the 1st September, 2011 to the 22nd December, 2012, 305 breathing circuits used for 3,864 patients were analysed microbiologically (Table 1). Of the 100 circuits tested in the ‘up to 7 day’ category, 87 of 100 circuits were used for the entire 7 days. The remaining 13 of 100 circuits were changed due to patients with known infections, with 2 circuits sampled after 2 days, and 11 after 3-6 days.

There was no significant difference in the proportion of contaminated circuits when changed every 24 hours (57 of 105, 54%, 95% CI 45 to 64%) compared to 48-hours (43 of 100, 43%, 95% CI 33 to 53%, $p=0.12$) and up to 7 days (46 of 100, 46%, 95% CI 36 to 56%, $p=0.26$).

Table 1 Bacterial contamination of breathing circuits at intervals of 24 hours, 48 hours and up to 7 days. cfu= colony forming unit, IQR= Interquartile Range (25th-75th centile).

	Group 1: 24hrs		Group 2: 48 hrs		Group 3: up to 7 days	
Number of operations performed during the sampling period	557		998		2,309	
Complete circuits - any bacterial contamination (proportion of total) 95% CI	57/105 (54%)	44% - 64%	43/100 (43%)	33% - 53%	46/100 (46%)	36% - 56%
Complete circuits - Median bacterial count (cfu/10mL)	1		0		0	
Complete circuits - Bacterial count IQR (25th – 75th centile).	0-4		0-1		0-3	
Complete circuits -Range (lowest and highest counts)	0-2,610		0-12		0-671	
Inspiratory limb contamination (proportion and % of total)	28/105	(27%)	25/100	(25%)	22/100	(22%)
Expiratory limb contamination (proportion and % of total)	41/105	(39%)	25/100	(25%)	31/100	(31%)

Compared to the 24-hour circuit change group, there was a significant difference in the median bacterial counts/circuit for both the 48-hour (p=0.02) and 7 day (p=0.04) groups (Table 1). There was no significant difference in the median bacterial counts/circuit between the 48-hour and 7 day groups (p=0.70). At all time periods the proportion of contaminated expiratory limbs was equal to or greater than the contaminated proportion of inspiratory limbs of the anaesthetic circuits (Table 1). Each of the six individual operating theatres had circuits examined with similar frequency (range: 14% to 18% per theatre).

Table 2 details the non-labour costs of decontaminating circuits every 24 hours compared to circuits with up to 7 days between decontamination. Requisitioning data for the circuits was obtained: for the 12 months prior to the study, 90 circuits were purchased and for the 9 months from the time of commencement of ‘up to 7 days’ changes, 30 circuits were purchased. For the four weeks of auditing the number of anaesthetic thermal disinfection loads during the 24 hour and 7 day decontamination periods there were 68 loads and 28 loads, respectively (or 17 and 7 loads/week respectively). In Table 2 the electricity, water and detergent costs were based upon the aforementioned number of washer loads. That is, the financial and environmental costs of electricity and water were estimates. The annual number of gas sampling tubing used for the 24 hour and 7 day decontamination periods were also estimates based upon the findings of this study (Table 2).

Table 2 Annualised costs associated with decontamination of anaesthetic circuits (for 6-operating rooms). Financial costs are in AUD$ (with the totals in AUD$ and USD$).

	24 hour circuit decontamination	Up to 7 day circuit decontamination
No. circuits purchased p.a.	90	40
Cost of circuits p.a. (at AUD$20/circuit)	AUD$1,800	AUD$800
No. gas analyser tubings p.a.	4 (theatres) x 5 (days) x 48 (non-holiday weeks) + [2 (theatres) x 7 (days) x 52 (weeks)] =1,680	6 (theatres) x 52 (weeks) / 0.87 (% used for entire week) =360
Cost of tubing (at AUD$1.90/tubing)	AUD$3,200	AUD$690
Washer- no. of anaesthetic loads p.a.	17 loads/week x 48 (normal weeks) + [7 loads/week x 4 (holiday weeks)]= 844 loads	365 loads (1 load/day)
Washer- electricity p.a. (6 kWhr/load)	5,060 kWhrs	2,200 kWhrs
Cost of electricity p.a (AUD$0.11/kWhr)	AUD$560	AUD$240
Washer-water (100 litres/load)	84,400	36,500
Cost of water p.a. (at AUD$2.00/kilo Litre)	AUD$168	AUD$74
Cost of washer detergent p.a. (at AUD$2.70/anaesthetic washer load)	AUD$2,280	AUD$985
Total non-labour costs p.a. (to nearest AUD$10)	**AUD$8,000 (USD$6,160)**	**AUD$2,790 (USD$2,150)**

3.6 DISCUSSION

This study provides evidence that it is possible to reduce the frequency of anaesthesia breathing circuit decontaminations resulting in financial, energy and water savings without any increase in bacterial contamination, provided circuits were routinely emptied of visible condensate. It is likely that condensate accumulation may have occurred routinely in the 24-hour group, and that reinforcing standard protocols accounted for lower circuit contamination in the 48 hour and 7 day groups.

These results agree with earlier studies from other countries (134, 140, 141) that found extended use of breathing circuits beyond 24 hours does not increase the risk of circuit contamination, particularly as a more sensitive method of detecting microbial contamination has been used and there was analysis of a greater proportion of the rinse water volume (10mL/circuit) (which explains the higher proportion of contaminated circuits in our study (43%-54% vs less than 5%)). Furthermore, the sample size was correctly powered to detect any significant difference in contamination rates.

This study has limitations. With collaboration from the infection control staff a prospective, before and after cohort design was chosen as the most appropriate and pragmatic methods to minimize risks to patients and operating room productivity. Randomizing individual circuits, which would have eliminated selection bias, would have been desirable, but was considered impractical. The circuit exterior was not examined. In our hospital the circuit exterior is routinely cleaned between uses with chlorhexidine, reducing the risk of cross-contamination of circuits and patients(153). The microbial testing was limited to bacterial contamination count with no speciation.

It is possible that similar rates of bacterial contamination between groups could have resulted as much from personnel education as from prolonging the interval between decontamination. This study did not compare the environmental effects of using reusable and disposable anaesthetic circuits as this was primarily a microbiological study. Financial and environmental savings estimated by this study could be further validated by auditing of CSSD decontamination loads and requisitioning of anaesthesia circuits and gas sampling lines.

The presence of prions or viruses in the circuits was not tested for. Prion transmission occurs very rarely via oral, parenteral or direct intracerebral inoculation. Prions are not usually considered to be airborne, but prions can be efficiently transmitted to mice through aerosols(154). Although aerosol-transmitted prions have never been found under natural conditions(154), there will be ongoing interest in the perceived prion transmission risks of all medical equipment.

The ultimate aim of cleaning or disposing of anaesthetic circuits is to avoid cross-contamination of patients who may develop viral infections and/or ventilator associated pneumonia (VAP). Accordingly, testing for viruses of concern would be ideal, but specific testing for all possible respiratory viruses is not practical based on the availability and cost of suitable methods. Examining the rate of VAP in patients who receive breathing circuits with different periods of use, would be useful. Studying VAP rates is difficult because of the very low rates of VAP in patients presenting primarily for elective surgeries and thus the need for large numbers of patients to conduct such a study. A formal examination of the rates of VAP in patients over the 15 month study period was not performed although anecdotally at our hospital, such pneumonia is very rare beyond patients who develop VAP in the ICU. As noted previously, in lieu of speciating viruses and bacteria it was chosen to examine several hundred circuits, quantitating aerobic bacterial counts, as this was a feasible, practical method to indicate circuit ‘cleanliness’.

Due to the possibility of circuit cross infection with Hepatitis C virus(155-157), guidelines advocate that for each operation either single-use filters or single use or clean reusable circuits be used(136-139). In our hospital circuits are reused and single-use filters are discarded for each case. Each filter costs approximately AUD$2, while disposable circuits cost AUD$10.

Converting from circuit changes every 24 hours to every 7 days led to annual savings for our hospital (6 operating theatres) of: AUD$5,210 (USD$4,010). Requisitioning of reusable anaesthetic circuits fell from approximately 90/annum pre-study to 40/annum post-study, despite no significant change in the number of operations. Circuits are perhaps most likely to be damaged when they are hot post-washing. Since each reusable circuit costs approximately AUD$20 per circuit, savings of more than AUD$1,000 per annum have been achieved due to reduced circuit requisitioning. Further, significant financial savings of more than AUD$2,500 (USD$1,925) per annum are made possible by changing the gas sampling tubing once a week rather than once a day.

There was a 57% decrease in anaesthesia circuit steriliser loads associated with a yearly saving of 2,760kWh of electricity and 48,000 litres of water - i.e. similar to the consumption of a one-person Australian household(158). Financial savings would be much larger in institutions where circuits are changed with every patient, such as is required in the USA(159). If our 6 operating theatre hospital used disposable circuits (AUD$10 each), converting from daily to weekly disposable circuit changes would save AUD$5,200 (USD$4,840) for the reduction in circuit use alone. Converting from single-use circuits to weekly disposable circuit use would save more than AUD$25,000 (USD$23,200).

3.7 CONCLUSION

Extending the interval between anaesthetic circuit decontaminations from daily to weekly is not associated with increased bacterial contamination, results in reduced financial and environmental costs, and complies with Australian and New Zealand professional standards(142), provided daily emptying of circuit condensate is undertaken. This change in practice is commended, as is already routine in Germany, as a safe method of reducing the environmental effects of clinical anaesthesia. This study adds to calls for greater sustainability within the operating room and challenges current guidelines requiring anaesthesia circuit changes for each and every patient in some countries including the USA(159).

As a result of this study there was a change of policy at our hospital; from circuit changes every 24 hours to circuit changes every 7 days. Such a change led to an estimated annual financial saving of AUD$5,210 (USD$4,010), with associated water and energy savings. These study findings are generalizable: small financial and environmental savings from reduced circuit changes at one hospital could become much larger savings for an entire healthcare system. Research opportunities examining the potential for ‘reducing’ the use of other products and processes without compromising patient care or staff workflow patterns are likely to be significant.

CHAPTER 4: REUSE VERSUS SINGLE USE

WHAT MAKES SURGICAL METALWARE SINGLE USE?

4.1 BACKGROUND

Chapter 3 studied one example of ‘reducing’ the use of equipment without compromising patient care in the Operating Room (OR). It was found that prolonging the interval between anaesthesia breathing circuit decontaminations results in financial, energy and water savings, without any significant increase in bacterial contamination.

The focus of this chapter moves from Reduce to Reuse. Within the OR particularly and to a lesser extent in the Intensive Care Unit (ICU), there are many items that are reused such as surgical instruments, linen drapes and garments, and plastic containers. It is unclear in many instances what the environmental effects of OR and ICU reusable items are, or of the comparable single use variants(10). Prior to further chapters examining particular reusable items and comparing them with single use items it is important to consider what makes something single use in the first place.

Medical devices can be divided into three groups according to their usage: 1. single use, i.e. one use only, 2. reusable, i.e. able to be washed and sterilized for patient reuse generally within the hospital and 3. reprocessed devices, i.e. undergo assessment, repair, sharpening, smoothing, cleaning and sterilizing before being reused. Currently, manufacturers determine whether their product is single use. A minority of reusable devices are recommended to be used for a limited number of times due to wear and tear (e.g. reusable plastic laryngeal masks used in anaesthesia). Such devices are generally not made of metal and remain classified as reusable both by authorities and in this thesis.

A variety of different materials are used in the manufacture of medical items. Common items used in the OR and ICU could be considered to be made of linen, metal or plastic. Several different plastics are used for medical products, making comparisons between reusable and single use versions difficult. It is possible (though currently unclear) that single use linen may not be constructed for longevity beyond one use. On the contrary, single use metalware appears robust for more than one use.

Stainless steel is robust, can be repeatedly sterilised, and has a high carbon footprint (4.2 kg of carbon dioxide (CO_2) per kg steel)(160).

This chapter expands upon the following publication: McGain F, Sussex G, O'Toole J, Story D. What makes metalware single use? Anaesthesia and Intensive Care, 2011, 39; 5, 972-3.

4.2 INTRODUCTION

In the hospital setting, single use metal ware is found in suture sets, in vascular access insertion kits, and as individual items such as scissors. Anecdotally, in Australia and elsewhere the use of these items has rapidly increased over the past few decades. There is literature comparing the relative clinical merits of reusable versus single use devices(161, 162). There are few comparisons, however, of the financial and environmental costs of reusable and single use medical devices(109, 111, 163). It is less clear why some devices are single use and why these devices are replacing reusable variants.

As examples of national regulators of medical devices the USA Food and Drug Administration, the UK Medicines and Healthcare Products Regulatory Agency, and the Australian Therapeutic Goods Administration, all accept at face value the manufacturers' designation of an item as single use(133, 164, 165). Reported legitimate reasons for labelling medical devices as single use include: 1. device design precludes adequate decontamination, 2. malfunction is likely with reuse, or 3. reprocessing is difficult because of concerns such as material degradation(133).

The International Organisation for Standardization (ISO) details the requirements for stainless steel surgical instruments, including the chemical composition and corrosive resistance (ISO-7153-1 and ISO-13402(166, 167). Stainless steel must contain at least 10.5% chromium, although most surgical instruments should have at least 11.5-12% chromium and are generally of the Martensitic subtype, (i.e. relatively hard, with high carbon content and good machining characteristics(168, 169).

The aims of this study were to question if and why there had been a significant increase in the use of single use metalware and what were the physico-chemical differences between reusable and single use metalware?

4.4 RESEARCH QUESTIONS

1. Why are some craft groups of doctors using more single use rather than reusable surgical instruments?
2. Why are some simple surgical metal devices labelled as single use and how is their composition different from traditional reusable metalware?
3. What are the broader ecological and social issues that might influence a decision to purchase single use surgical metalware?

4.5 METHODS

The trend to single use surgical metal ware was investigated at Footscray and Sunshine Hospitals (total of 600 beds), Melbourne, Australia. The hospitals' Human Research Ethics Committee manager approved this observational study. Central Sterile and Supply Department (CSSD) staff noted that although expensive single use metal surgical devices, such as laparoscopic ports, had become more common, surgical preference and their cost had prevented a significant increase in use. Correspondingly procurement was obtained for the following surgical metalware: scissors, needle-holders, artery forceps, scalpel holders, chest tube clamps and 'sets' of metal instruments such as those used for basic surgical, anaesthetic, emergency department and ICU procedures.

Cost data were obtained in Australian dollars (AUD$) for single use metalware procurement examining all medical subdivisions (e.g. operating suite, ICU, surgical wards etc.). Data were reliable from 2007 (when a new dataset was installed) to 2010. Subsequently various packages of single use metalware were opened and the metal items weighed on digital scales precise to the nearest gram. Advice pertaining to single use metalware was sought from multiple hospital staff and from reference infection control material(170-172).

Single use and reusable scissors and needle holders available in our hospital were compared. Both were equally easy to decontaminate and appeared equally sturdy for routine use. Possible differences in composition and design that rendered the single use items unsuitable for repeated washing and sterilisation were sought, and whether such differences could be inexpensively eliminated by local processing.

The chemical composition of one each of a reusable and single use needle holder and scissors (i.e. 4 items) was determined by requesting such information of the manufacturers and then verifying this by independent spectrographic examination (Spectrometer Services Pty Ltd, 206 Newlands Rd, Coburg, Victoria, 3058, Australia).

The physical design of two each of the reusable and single use scissors and needle holders were examined, noting in particular the surface smoothness and corrosion resistance by naked eye examination. To further examine surface smoothness a stylus surface roughness meter (Accretech, Tokyo Seimitsu Co.) was used, taking the average of five readings from several locations on each of the metal items.

To reduce the roughness of the single use items two each of scissors and needle holders underwent successive reprocessing by phosphoric acid bathing, mechanical polishing and nitric acid bathing (Alimtype Pty Ltd, 65-67 Canterbury Rd., Montrose, Victoria, Australia). Reusable surgical metalware undergoes identical processing at our hospitals after every 100 uses or if there is evidence of rusting.

Subsequently, two each of the unprocessed and processed single use scissors and needle holders were each run through the hospital washer and sterilizer for five cycles. Experienced hospital sterile supply staff were involved in the washing, examining and comparison of the unprocessed and processed items.

A currency converter (152) on the 17/6/2015 to convert AUD$1 to USD$0.77.

4.6 RESULTS

At the two hospitals the value (rounded to the nearest AUD$10) and weight of single use metal surgical items purchased rose from AUD$6,030 (USD$4,640) and 65kg for the year 2007 to AUD$47,130 (USD$36,290) and 850 kg in 2010. For the operating suite alone the value and weight rose from AUD$2,820 (USD$2,170) (32kg) in 2007 to AUD$8,710 (USD$6,706) and 116 kg in 2010.

Hospital CSSD and infection control staff noted that the shift to single use medical items was not driven by any infection control concerns. While microbiological contamination of reusable metal devices can occur from processing failure, no episodes of contamination had occurred and quality assurance control by the hospital’s CSSD staff had remained unchanged. Instead the loss of relatively more expensive (AUD$10-15) simple reusable surgical metalware, combined with the greater availability of inexpensive (AUD$1) single use items was driving staff to purchase more single use items. Loss of metalware was particularly prominent when; instrument counts (by two nurses/doctors) did not occur at the end of procedures, e.g. when anaesthetists performed central line insertions in theatre; and in locations remote from the operating suite, such as the ICU, emergency department, outpatients and hospital wards.

Interestingly, as individualised hospital 'cost centres' (based on wards and medical units) became the norm, the CSSD moved from routinely compensating for the loss of reusable instruments, to charging other hospital cost centres for this loss. Due to this cost imposition from losses of reusable instruments on wards and medical units such wards/units converted from reusable metalware to less financially expensive single use metalware.

Table 3 presents the spectrographic analysis of the single use and reusable surgical metalware and shows that there was no functionally important difference in the stainless steel content. Most importantly, reusable and single use metalware were stainless steel (Chromium content greater than 11.5%), and had low levels of impurities (silicon and sulphur). There was some variability in the concentrations of other elements within the reusable and single use metalware, but such variation would not alter the steel's integrity. There was also minimal variation in the composition of the metalware between our results and the manufacturers' specifications.

Table 3 Average composition of stainless steel from one each of reusable and single-use scissors and needleholders.[1]

Element	% in reusable metalware	% in single use metalware
Carbon	0.14%	0.17%
Chromium	12.0%	11.9%
Copper	0.01%	0.11%
Manganese	0.25%	0.20%
Molybdenum	0.04%	0.08%
Nickel	0.15%	0.36%
Phosphorus	0.02%	0.03%
Silicon	0.37%	0.41%
Sulphur	0.02%	0.02%

[1] Data for Table 3 obtained from Spectrometer Services Pty Ltd, 206 Newlands Rd, Coburg, Victoria, 3058, Australia.

A naked eye examination indicated a rougher mechanical finish on the unprocessed single use surgical items when compared with the reusable variants which was confirmed with a stylus surface roughness meter (Table 4). Surface roughness is indicated by average roughness (Ra). Above an Ra of 0.5 micrometres there is a significant increase in the likelihood of corrosion and conversely there are minimal changes to corrosive resistance with lower levels of roughness(173, 174).

Table 4 Surface roughness of the single use surgical metal instruments pre- and post-processing.[1]

Surgical metal item	Average roughness (micrometres)	Detection of rust pits following 5 cycles of washing and sterilisation?
Reusable scissors	0.1	No
Reusable needle holders	0.4	No
Single use unprocessed scissors	0.9	Yes
Single use unprocessed needle holders	0.5	Yes
Single use processed scissors	0.2	No
Single use processed needle holders	0.2	No

[1] Data for Table 4 obtained using a stylus surface roughness meter (Accretech, Tokyo Seimitsu Co.).

After reprocessing (for AUD$5 per item) the surface roughness of the reprocessed single use items was less than 0.5 micrometres, as for the reusable items (Table 4). After washing and sterilisation fine rust pits were found in the unprocessed, single use items, but not the reprocessed ones. No visible difference was detected between the reprocessed single use and reusable metalware by CSSD staff (i.e. they were visually indistinguishable).

4.7 DISCUSSION

Single use surgical metalware rapidly replaced reusable variants at our hospitals. Infection control concerns had not led to the increase in single use metalware, the use of these being mandated in Australia only for those at high risk of prion disease(171, 172). The shift to single use metalware occurred primarily outside the operating suite due to staff misplacing more expensive reusable surgical instruments and the subsequent decision by individual cost centre staff to purchase cheaper, single use items.

The results showed that for two simple surgical instruments single use and reusable variants were composed of essentially the same stainless steel. Chromium imparts resistance to rust, while sulphur and phosphorus increase the risk of rusting. The higher nickel and copper levels (Table 2) in the single use items would not significantly alter the quality of the Martensitic steel(168), although the higher molybdenum content of the single use items would provide greater corrosion resistance. Whilst the single use items were found to have a rougher finish which precluded their reuse we found that with simple, inexpensive reprocessing, these single use items could withstand multiple cycles of washing and sterilisation without evidence of rust. Reprocessing (for AUD$5), and resterilising (considering CSSD labour costs etc.) is probably not, however, cost competitive with buying another AUD$1 single use item.

This study shows that it is inexpensive to reprocess single use stainless steel items. Particularly in the USA, companies do legally reprocess single use medical items, though this questions the entire concept of ‘single use’(175). In addition, it is likely that reprocessing external to the hospital is more energy consumptive than simply re-sterilising instruments. The increasing use of single use metalware leads to the discarding of tons of energy dense stainless steel (4.2 kg CO_2 per kg steel)(160) which does not assist national healthcare efforts to reduce CO_2 emissions(4).

An alternative approach could be to recycle single use items, although this also is likely to be more energy intensive than resterilising reusable metalware. Stainless steel has one of the highest recycling rates (70%) of any material(160), although the recycling rate from healthcare seems to be virtually zero. Unfortunately, in order to recycle the used metal items (or even donate them to less developed nations) first requires decontamination by washing, with the attendant hospital labour costs, negating the whole purpose of purchasing the bargain priced single use metalware.

The single use surgical metalware examined in this study originated in Pakistan. More than 85% of the world’s surgical instruments are made in Pakistan or Germany(176). Concerns regarding the ‘fair trade for surgical instruments’ have been raised previously(176, 177) to which we add the complexity of single use metalware. It is unclear whether it is beneficial to labourers in Pakistan to be producing as many inexpensive, single use instruments as possible. It is concerning that Pakistan, where 21% of the employed population survives on less than USD$1.25 per day(178) and many do not have adequate access to healthcare, produces a large proportion of the world's surgical metalware that the citizens of more affluent nations now discard after one use.

This study measured only simple, single use metalware as the use of more complex, expensive, single use metal surgical devices had not changed significantly. Due to altered electronic records reliable data were present for only a four-year period, although these indicated a significant increase in single use metalware. Further large procurement increases in single use metalware are not envisaged since at our hospitals very few reusable metal items are now used outside the operating suite and the ICU.

The findings of this study may not be applicable to all hospitals in developed nations, although at least in the UK, New Zealand and the USA there is similar anecdotal evidence of single use surgical metalware replacing reusable variants. A spectrographic analysis was performed of just one each of a single use and reusable scissors and needle-holder. Although many more spectrographic analyses could have been made this would be unlikely to reveal notable differences as worldwide, most reusable and single use surgical metalware is made from the same grade of stainless steel in relatively few countries(176).

Naked eye assessments of many other single use metalware suggested that performing further detailed surface roughness assessments would not be revealing. Unprocessed (i.e. 'rough') single use metalware rusts after even a few washes. Although the processed single use items could rust after more than five washes, this would be unlikely as they have the same chemical and physical composition as the reusable metalware.

This study is aims to draw the attention of health departments and all healthcare providers, but particularly anaesthetists, surgeons and ICU physicians, that there is no scientific merit behind the term 'single use stainless steel' and that similar concerns could exist for other single use items. Tonnes of stainless steel are being discarded to infectious waste because hospital staff in the more affluent nations do not consider it important to retain reusable surgical instruments and/or they see a short term 'bargain' in purchasing the single use items. This practice is wasteful of energy, water and stainless steel itself and may also be encouraging a ‘race to the bottom’ for labour costs in Pakistan.

Double counting of items outside operating theatres generally does not occur, emphasising that the count is performed to prevent loss within the patient, rather than any concern for tracking of the surgical metalware. Regardless of the location within the hospital, staff could emulate the operating theatre ritual of ‘count correct’ at completion of a procedure. Placing radiofrequency tags on surgical items to track their location or loss is possible, but has not been frequently explored in medicine(179).

Purchasing supply agencies could follow the lead of the UK Sustainable Development Unit in at least developing an ethical business approach that complies with international ethical standards(176, 180). National regulatory bodies of medical devices could also contribute to the transition towards improved environmental, social and financial sustainability in healthcare and at least ask of manufacturers why any stainless steel items are ‘single use’.

4.8 CONCLUSION

Within the past decade there has been a 10-fold increase of single use stainless steel surgical metalware in our hospitals, driven by losses of the alternative expensive reusable metalware, and occurring primarily where instruments were not ‘double counted’ such as in the ICU and emergency department (i.e. outside of the OR).

‘Single use metalware’ was found to have the same chemical composition as reusable metalware, i.e. both were stainless steel. Physically, the single use metalware had a rougher surface, leading to rusting when steam sterilised. When this single use metalware underwent simple reprocessing it became physically and visually indistinguishable from reusable metalware. It is, however, unlikely to be financially attractive and to reprocess such single use metalware is made challenging by current Australian regulations. There are broader ecological and social issues that might influence a decision to purchase single use surgical metalware such as the ‘fair trade for surgical instruments’(176), to which this study adds the complexity of single use metalware.

There is a profound disconnect between our reuse of stainless steel cutlery at home thousands of times and similar stainless steel for surgical instruments discarded after a single use. Prior to comparing common reusable and single use medical equipment in the following chapters this study questioned the foundation of what makes an item single use.

CHAPTER 5: REUSE

THE LIFE CYCLE OF REUSABLE AND SINGLE USE CENTRAL VENOUS CATHETER (CVC) INSERTION KITS

5.1 BACKGROUND

Prior to making any comparisons between reusable and single use items Chapter 4 examined what makes a subset of medical equipment single use in the first place. Single use stainless steel metal ware was compared with and found to have very similar physico-chemical composition to reusable metal ware(181). Retailers of medical products decide whether equipment is single use with perhaps unforeseen environmental, financial and social consequences.

This chapter examines Reuse and life cycle assessment (LCA) for a simple item used commonly in the operating room (OR) and intensive care unit (ICU). Introduced in Chapter 2, section 2.3, LCA is a useful method to examine the environmental effects from the ‘cradle to grave’ of a product or procedure. Process based LCAs arrive at an environmental cost for an item or activity based upon measured inputs - e.g. the amount of plastics and metalware contained within a surgical tray. Process based LCAs make comparisons possible between reusable and single use variants.

As noted in the thesis literature review (Chapter 2, section 2.6.8) an LCA was performed prior to PhD enrolment by the author and colleagues, examining the environmental and financial effects of reusable and single use anaesthetic, plastic drug trays(65). The reusable plastic trays required thermal disinfection (‘washing’), but not sterilisation, to be made patient ready again. The major findings of that LCA were that the reusable trays cost less money (inclusive of labour) and used less water, but had similar global warming potential (CO_2 emissions) when compared with the single use drug trays. Further, as the single use tray routinely had cotton gauze and a paper towel included (which were not required for the majority of patients requiring an operation), the combined CO_2 emissions for the single use tray with cotton and paper were almost twice as high as for the reusable tray alone. The CO_2 emissions for the reusable trays were high as a result of the state of Victoria’s (Australia) electricity mix which remains predominantly brown coal with a very high CO_2 emissions factor(114).

The LCA of plastic drug trays did not analyse the environmental effects of sterilisation. Steam sterilisation remains the most common method to sterilise most reusable surgical devices(182). Since: (i) sterilised items are ubiquitous in the OR (and to a lesser extent the ICU), and (ii) it was possible that sterilisation contributed materially to the CO_2 emissions and water use of reusable items, a comparison LCA was undertaken of a common OR and ICU reusable item and its single use counterpart.

Process based LCAs provide a detailed analysis of an individual item or activity and are useful when comparing two similar items or activities. Further, Economic Input-Output LCAs are less precise for many products and processes in healthcare. Consider a medical device that costs twice as much money as another: an Economic Input-Output LCA would consider that the more expensive process has double the environmental effects, which is probably unrealistic.

Process based LCA can be either attributional or consequential(22). Attributional LCA assigns (attribute) flows and potential environmental impacts to a specific product system typically as an account of the history of the product. Attributional LCA predates consequential LCA and is considered to be simpler as there are no assumptions about the environmental changes that occur as a result of a decision. Consequential LCAs study how environmental flows may change because of the possible decisions made in the LCA(22).

The system boundary of consequential LCA is broader than attributional LCA and includes the activities contributing to the potential future environmental consequence of the change. As an example, for this LCA comparison of reusable versus single use CVC insertion kits a consequentialist approach would be to examine what would be the changes to CO_2 emissions from moving completely from single use to reusable kits. In Victoria, Australia, the main source of electricity generation is brown coal. Nevertheless, because of certain government policies to increase natural gas and renewable electricity generation, each *new* kWh of electricity would not be primarily sourced from brown coal. The CO_2 emissions from moving to reusable kits would be less than predicted from an attributional LCA which would model any CO_2 emissions arising from reusable kits upon the current electricity mix of Victoria.

Life Cycle Inventory databases usually include information about the marginal producers of electricity, resources, and many products and processes to allow for consequential LCAs to be performed. There is, however, always more uncertainty surrounding consequential than attributional studies as assumptions are made about future sources of materials. This LCA study of CVC insertion kits is attributional as the study is relatively simple in nature, and the focus was upon examining the most important contributors to the environmental effects of the reusable and single use kits.

This chapter expands upon the publication: McGain F, McAlister S, McGavin A, Story D. A life cycle assessment of reusable and single use central venous catheter insertion kits. Anesthesia and Analgesia 2012 May;114(5):1073-80.

5.2 INTRODUCTION

The manufacture, purchase, and acquisition of equipment and drugs contributes more to healthcare CO_2 emissions than direct hospital energy consumption and transport to and from hospitals combined(4). Life cycle assessment (LCA) is a ‘cradle-to-grave’ approach for determining the financial and environmental costs of a product over its entire life(9, 21) There are few published life cycle assessment studies of medical items and processes (35, 65, 108, 109, 111, 113, 116, 163), although there is expanding interest in the field(32).

To recapitulate Chapter 2, section 2.3: there are two common types of LCAs; process based and Economic Input-Output. Process based LCAs arrive at an environmental cost for an item or activity based upon measured inputs (e.g. amount of electricity, gas and water required to wash a plastic tray as well as the mass and type of plastic used to make that tray). Process based LCAs thus examine the immediate inputs, but not more distant inputs, i.e. they have a smaller ‘system boundary’ than input output LCAs (and thus routinely smaller environmental effects).

Our prior LCA of plastic drug trays did not include the environmental effects of sterilisation as this was not required for such items. This study examined a common medical item that was sterilised since it was unclear if there were financial and environmental benefits in using reusable instead of disposable versions. Both reusable and single use central venous catheter insertion kits are commonly used in anaesthesia and other critical care areas. These kits are used to assist insertion of single use plastic central venous catheters. The insertion kits are typically composed of metal ware (scissors, needle holders and tissue forceps) and plastic (bowls and wrap). The disposable central venous catheter sets themselves, which included the catheters as well as various other plastic items, were not examined as they were common to both reusable and single use approaches to central line insertion.

5.3 RESEARCH QUESTIONS

1. What are the complete financial costs of the reusable and single use CVC insertion kits when used in hospitals?
2. What are the environmental effects (CO_2 emissions, water use, metal use, toxicity) of the life cycles of the reusable and single use kits?
3. What effect does the source of electricity have upon CO_2 emissions?

5.4 METHODS

This observational study of central venous catheter (CVC) insertion kits was performed at Western Health in Melbourne, Victoria and at Atherton's' Sterilisers Factory, also in Melbourne, Victoria. Ethical approval was granted by the Western Health Ethics Committee (Quality Assurance Number 2010.27). Using SimaPro life cycle assessment (LCA) software (Pre Consultants, The Netherlands) we modeled the financial and environmental life cycles of reusable and single use central venous catheter kits that are used to aid insertion of disposable central venous catheters.

An LCA uses different types of data for modelling. Some data are directly collected. Most LCA data, however, are not directly measured, but obtained from life cycle inventories calculated as a weighted average from a number of production sites. One example is the average amount of CO_2 emitted/kWhr of electricity produced from coal burning power stations. Average industry data are often used in LCA modelling because collecting all such data would make most LCAs unviable. Average industry data, however, have greater associated uncertainty than directly measured data. Other data are collected from international data bases. Where local data were not available we used an internationally recognized LCA database (Ecoinvent v3.1, Swiss Centre for Life Cycle Inventories, Zurich, Switzerland)(25) using transparent methodologies(183) . These data were used in accordance with The International Organization for Standardization standards for LCAs(22).

We analysed the environmental effects of the CVC insertion kits including CO_2 emissions, water use, mineral use, aquatic and terrestrial Eco toxicity, and solid waste. A sensitivity analysis examines how changes in the inputs affect the outputs (results). For example, we could examine the effects of altering an input (electricity source) on an output (CO_2 emissions). We performed sensitivity analyses of altering the source of electricity for the reusable CVC insertion kits: brown coal, gas co-generation, and the American (USA) and European standard electricity supply. We did not perform such sensitivity analyses for the single use CVC insertion kits as cogeneration is an unusual source of electricity for plastic and metal manufacture, and the single use plastic and metal items are almost exclusively sourced from China and Pakistan.

Both single use and reusable CVC kits contained a plastic kidney dish, two plastic gallipots, three surgical metal items (needle holder, scissors and artery forceps) and plastic wraps (one for the kit cover and one to provide a sterile field). For the reusable central venous catheter kit the two plastic wraps were single use, while for the single use CVC kit all items were single use. All items were weighed with an electronic balance accurate to +/- 0.5g (Satrue KA-1000, Shang Chuen Co., Taiwan). Other items such as cotton gauze and antiseptic were not examined as they were common to the insertion of all central venous catheters.

The International Organization for Standardization-14040 series are standards for conducting LCAs(22). An attributional LCA (see section 5.2 of this chapter for further detail) was performed based on currently available sources of electricity. As per standard protocol, items such as washers and sterilisers that were already in place were not included in this LCA (22). Data for life cycle assessments were either directly collected or obtained from life cycle inventories; i.e. local industry or internationally recognized databases(25, 26). Direct data for the washer and steriliser electricity and water use were obtained, but most other inputs were acquired from databases. Processes included in this study (the System Boundary) were raw material extraction, manufacture, packaging, transport, washing, sterilization, and disposal (Figure 1).

The metal components of both of the reusable and single use CVC insertion kits were fabricated from stainless steel(181). Details of the types of plastics used for the central venous catheter kits were provided by the manufacturer, which we confirmed with the 'burn test'- i.e. the colour and odour of the burnt plastic(184). The reusable CVC insertion kit's metal components were made in Germany and the plastic items in Australia. The single use CVC insertion kit's metal components were made in Pakistan and the plastics were fabricated in China. No life cycle inventory data were available from Pakistan and there were only minimal Chinese data available. Local Australian inventory data for the manufacture of the reusable and single use plastic items were thus used(185) and European data for the reusable and single use metal components(25). Direct life cycle inventory data have not been collected in China or Pakistan. It is likely that electricity sourced from China and Pakistan has a higher CO_2 emissions per kWh produced than electricity sourced from the European grid (due to the high coal use), thus the results will tend to under-estimate the CO_2 emissions for the single use items.

A Pedigree Matrix(26, 27) was developed, a qualitative scoring system that allowed LCA input uncertainty to be quantified based upon the data's temporal and geographical proximity to the study site, as well as reliability and completeness. For example, as the steriliser's electricity consumption was directly measured on multiple occasions the data's temporal and geographical proximity was high.

An LCA has inputs (such as the CO_2 emissions for electricity from brown coal), which are combined to form a process (such as the CO_2 emissions for making plastic trays). Every input has a degree of uncertainty associated with it, which is expressed as a probability distribution and is derived from a qualitative scoring system. A final 95% confidence interval (95% CI) for a process is achieved based upon the repeated random sampling anywhere within the 95% CIs for all inputs (Monte Carlo analysis)(26, 27).

Monte Carlo analysis is the random sampling of data, repeated thousands of times, to obtain a probability distribution(26, 27). Monte Carlo analysis is used when examining large amounts of stochastic (random) data where it is infeasible to obtain an exact result. For example, the CO_2 emissions emanating from just the manufacture of stainless steel (an output) requires many hundreds of inputs, such as the production and transport of iron, chromium, and other metals, each with their own variations in

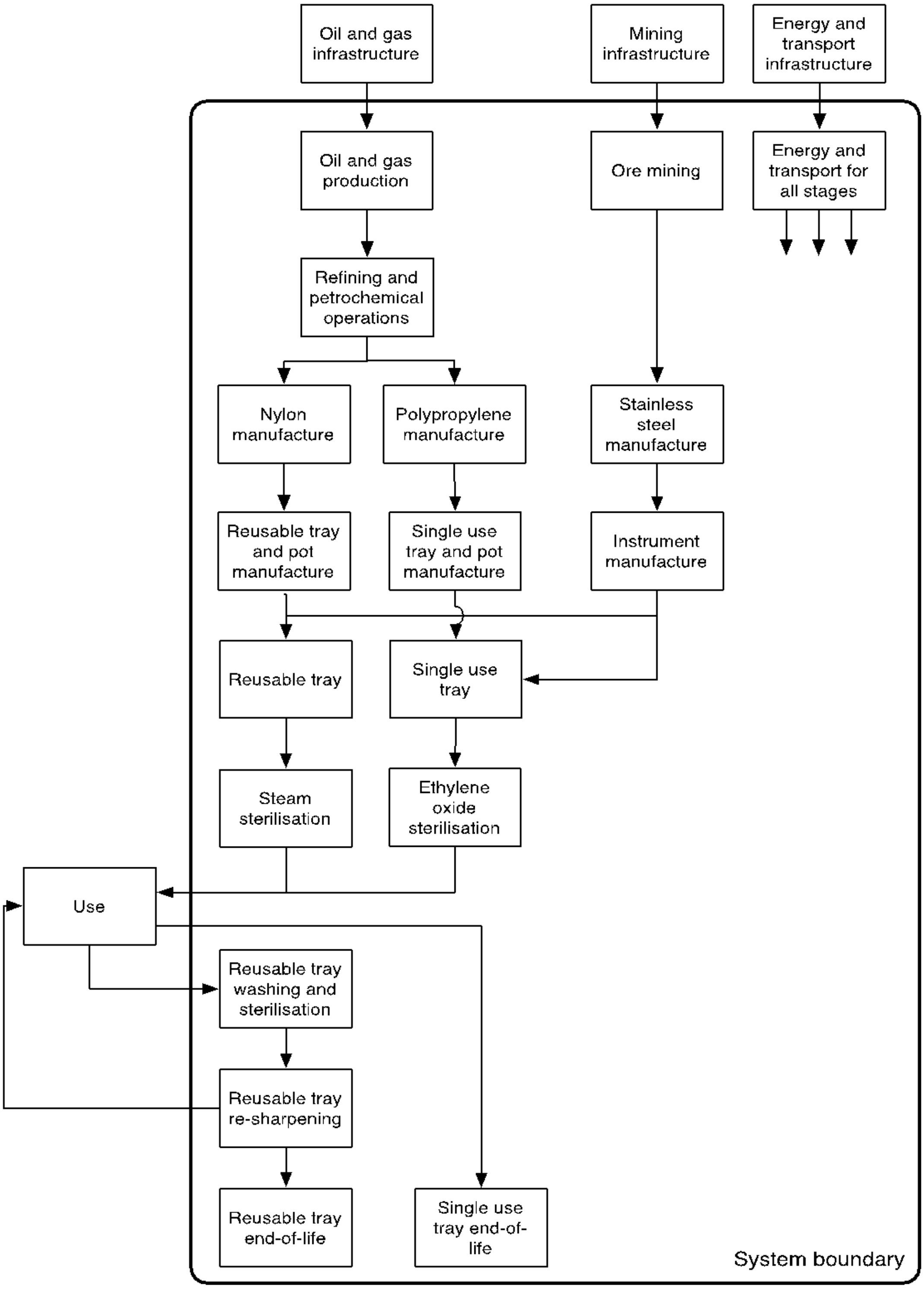
CO_2 emissions. It would be infeasible to obtain direct data from the source for each and every one of these inputs for each new LCA study.

A Monte Carlo assessment will randomly assign the data from each input based on its individual distribution to create a probability distribution that describes the aggregate data. The Monte Carlo SimaPro software analysis involves at least 1,000 ‘runs’ of random sampling to reduce the likelihood of unusual results which can be a lengthy process requiring hours of computer work.

The purchase costs for the single use and reusable central venous catheter kits for our hospitals (Table 5) were obtained. These prices were similar to central venous catheter kits obtained by other local hospitals. For the single use central venous catheter (CVC) insertion kit costs were also determined for storage, logistics, and metal components disposal into sharps bins. An assumption was made that all other waste from both the reusable and single use CVC insertion kits was placed into infectious (clinical) bins.

For the reusable CVC insertion kits the following were included: electricity, water, gas for hot water, chemical and biological indicators, and maintenance costs for the washer and steriliser, as well as washer detergents and packaging. Steriliser accessory loads (warm ups and infection control cycles) were also included. Washing and sterilisation was assumed to conform to the Australian and New Zealand Standards(139). On a conservative estimate the reusable metal components and plastic items were known to have a lifespan of 300 uses by Central Sterile Supply Department staff, with the metal components requiring reprocessing (sharpening) every 100 uses. No assumption of loss of reusable items was made, although investigation was separately made of the effects of loss of reusable CVC insertion kits at our hospitals.

Figure 1 System Boundary. Processes examined for the reusable and single use CVC insertion kits lie within the system boundary (i.e. within the large rectangle).[1]



[1] Only data for the washing of the reusable tray are directly measured, while all other data are average industry inputs.

The entire financial costs of making the reusable CVC insertion kits ‘patient ready’ again were examined. With Central Sterile and Supply Department (CSSD) staff a time and motion study that compartmentalized labor costs was developed. The following time periods were included: carriage of the reusable CVC insertion kits from the intensive care unit to CSSD, decontamination, loading and unloading the washer, inspection, barcoding and scanning, second checking, loading and unloading the steriliser, and packaging. CSSD staff used stop clocks to time the duration of each segment of the processing of the reusable central venous catheter kits and entered these times onto sheets. Staff entered their estimate of how full (as a percentage) the washer and steriliser were with each load. For the time-in-motion study to be representative all staff were encouraged to complete the study, but no more than twice per staff member.

The hospital washer used was a Steris Reliance synergy disinfector (Steris Corporation, Mentor, Ohio, USA) while the steriliser was an Atherton’s Gorilla (Atherton, Melbourne, Australia). The volumes of hot (gas heated) and cold water used by both devices and the kilowatt hours of electricity were measured. The steriliser has three sources of water use for: 1. steam generation, 2. the vessel jacket to keep the steriliser warm and 3. the liquid ring vacuum pump to ‘pull a vacuum’ for efficient sterilisation. Sterilisers can either have an internal electric element to heat water to steam or rely upon an external steam source such as a gas boiler. Since gas boiler dependent steam heating within hospitals in Australia is becoming less common the hospital electric steriliser was examined.

The electricity consumption of the washer and steriliser was measured with a ‘power clamp’- a Hioki 3197 Power Quality Analyser, accurate to +/- 3% (Hioki Corporation, Japan). Electricity consumption calculations were verified both with external consultant engineers (Aquaklar, Melbourne, Australia) and by measurements at the Atherton’s steriliser manufacturing facility in Melbourne. On each of these three occasions the steriliser’s electricity consumption over a 48 hour period was measured, including routine and accessory cycles. Steriliser water consumption was measured by direct flow meters at the Atherton’s factory. Water consumption of the hospital washer was measured with flow meters with an error rate of +/-5%, (S-100 and V-100 water meters, Elster, Essen, Germany).

The details of the sterilisation of the single use CVC insertion kit with ethylene oxide (by Steritech, Melbourne, Australia) were examined. Sharps bins waste and infectious waste was treated with sodium hypochlorite or incinerated. Despite requests to the infectious waste company contracted to our hospitals it was impossible to examine directly the environmental effects of such waste disposal processes, instead relying upon industry data(25).

As is routine for modelling(27), where it was not feasible to obtain first order data for a process the most conservative (lowest) estimate for CO_2 and water consumption was used. Since considerably more first order data were available for the reusable CVC insertion kits than for the single use kits, this study likely under-estimates the environmental effects of the single use kits. All financial costs and the energy and water consumption of the washer and dryer for reusable plastic trays were directly measured. External industry data were used for all environmental costs for the single-use tray, and all other environmental data except energy and water consumption of the washer and dryer for the reusable trays. A currency converter (152) on the 17/6/2015 was used to convert AUD$1 to USD$0.77.

5.5 RESULTS

The cost of the reusable CVC insertion kit to the hospital was AUD$6.35 (95% CI 5.89 to 6.86), (Table 5), while the single use CVC insertion kit cost AUD$8.65 (Table 6). There was little variation in the cost of the single use CVC insertion kits in other hospitals in Melbourne, Australia (thus no 95% CIs are given). CO_2 emissions and water usage for the reusable and single use CVC insertion kits are given in Tables 7 and 8. Energy and water use based on brown coal electricity generation were three and ten times greater respectively for the reusable kits compared with the single use CVC insertion kits. Other environmental effects (such as terrestrial and aquatic pollution) were either similar or of minor difference for the two approaches.

Steam sterilisation was almost 70% of the total CO_2 emissions for the reusable CVC insertion kit (Table 7), while for the single use CVC insertion kit, manufacture of plastics contributed 70% and stainless steel metal components 25% (Table 8). The reusable kit weighed 627 g, including approximately 50 g of single use wrap, while the single use kit weighed 171 g including wrap.

At the time of this study there were 33 CSSD staff employed at various fractions at the Western Hospital, Melbourne, Australia. The time and motion study was completed on 29 occasions with no staff member completing the study more than thrice. The mean labour time to make one reusable CVC insertion kit patient ready again was rounded up to 9 minutes (range of 5 to 12 minutes, 80% between 6 to10 minutes). The mean hourly pay rate for CSSD staff in November 2011 was AUD$31.22 (including all on-costs such as sick leave and superannuation). Other financial costs (washer detergents and maintenance of the washer and steriliser) were relatively minor (Table 5). The washer and steriliser at full capacity were measured to take 32 and 48 reusable central venous catheter kits respectively. The CSSD staff estimated that on average the washer and steriliser were 90% full for the 29 occasions (Table 5).

Labour contributed 70% (AUD$4.45 of $6.35) of the financial costs for the reusable CVC insertion kits (Table 5). The cost of repackaging the reusable CVC insertion kit in single use plastic was the next most expensive component (AUD$1.20, 19% total). The financial costs of all detergents, gas, electricity and water were relatively minor.

Table 5 gives the financial costs for one single use CVC insertion kit. Of the total costs of AUD$8.65 (USD$6.65), more than 90% is due to the purchase cost of the kit. Waste disposal via the relatively expensive sharps and infectious waste routes was less than 10% of total financial cost.

Table 5 Itemised financial costs for one reusable CVC insertion kit

Item	Cost (AUD$)
Labour for an average of 9 minutes at AUD$31.40/hr to wash, sterilize, etc. for each reusable CVC kit.	$4.45
Single use packaging of the reusable CVC kit- plastic theatre wrap (AUD$0.83), chemical and biological indicators, barcode label, internal chemical indicator, plastic cover.	$1.20
Reusable plastic items (assuming 300 uses): 1 plastic kidney dish and 2 gallipots (200g)	$0.04 ($13.20/300)
Reusable metal ware (assuming 300 uses): 3 stainless steel surgical instruments (100g)	$0.07 ($22.00/300)
Reprocessing (sharpening etc.) of reusable metal ware every 100 uses (AUD$10 for each of the 3 metallic items)	$0.30 ($30/100)
Electricity-for washer and dryer- 4.1 kWh at AUD$0.11/kWh at a max. of 32 kits per cycle with an average of 90% capacity (i.e. 29 kits)	$0.02 ($0.45/29)
Gas-for washer hot water 25.2 MJ at AUD$0.004/MJ	$0.01 ($0.10/29)
Washer- water- 200 litres at AUD$1.30/kilolitre	$0.01 ($0.30/29)
Detergents for washer: Alkaline- 150ml at AUD$5.70/litre= AUD$0.85, Neutralizing agent- 150 ml at AUD$11.20/litre= AUD$1.70, Drying agent -8 ml at AUD$6/litre= AUD$0.05	$0.08 ($2.60/29)
Maintenance for washer AUD$1,600 for > 160,000 items/annum	$0.01
Electricity for steriliser-27.3 kWh at AUD$0.11/kWh at an average of 90% capacity (max. 48 kits/load, i.e. 44 kits)	$0.08
Maintenance and validation for steriliser AUD$6,000 for 3,350 loads/annum	$0.05
Entire reusable CVC kit Total	**$6.35 (AUD$) $4.90 (USD$)**

Table 6 Itemised financial costs for one single use CVC insertion kit

Item	Cost **(AUD$)**
Single use CVC kit	$8.00
Cost of logistics to store, transport etc. item from warehouse (4% of purchase price)	$0.30
Sharps disposal 60 g metal= 300ml. **22 litre sharps bin disposal costs AUD$20- i.e. AUD$0.91/litre**	$0.25
Infectious waste disposal (110g) at AUD$1/kg	$0.10
Entire single use CVC kit in AUD$	**$8.65 (AUD$)** **$6.66 (USD$)**

The water and electricity use of the washer was determined on 19 occasions over a 48-hour period. The mean washer electricity usage was 4.1 kilowatt hours/load, gas fired hot water (65 degrees) use was 79 litres/load and cold water use was 126 litres/load. The washer was assumed to be 85% efficient and thus use 25.2 MJ of gas to heat the 79 litres of water from 15 to 65 degrees.

The steriliser electricity and water usages were measured for two separate periods at the hospital (a total of 23 routine and 8 accessory cycles) and at the Atherton's factory. The Atherton's factory steriliser performed 6 routine and 5 accessory loads, using an average of: 22.3 kilowatt hours/routine load, 30 litres of steam, 72 litres of heat exchanger water and 434 litres of vacuum pump water. Since an average operating day consists of several accessory steriliser loads these were also included in the energy and water calculations, i.e. four accessory loads per 10 routine loads per 24-hour period. The final steriliser electrical consumption per load was thus 27.3 kWh. Due to difficulties in obtaining accurate steriliser heat exchanger water use at the hospital and because the electricity usage at the factory was by direct measurement these factory data were used in the final analysis. The electricity usage per cycle for the steriliser when measured at the factory when compared with the hospital was up to 10% greater.

Table 7 gives the effects on CO_2 emissions and water use for the reusable CVC insertion kit processed with electricity sourced from brown coal (the overwhelming source of electricity for the state of Victoria, Australia). Steam sterilisation contributes 830 of 1,211g (69% total) of CO_2 emissions, with the remainder arising from washing; 256 of 1,211g (21%) CO_2; and single use plastic wrap, 121 of 1,211 g

(10%) CO_2. The manufacture and production of the reusable plastic and metal ware as well as transport of such items and waste disposal together contributed to less than 2% of the CO_2 emissions. A similar pattern was seen for water use, although the washer contributed to relatively more of total water use, 11.2 of 27.7 (40%) litres of water.

Hospital procurement documents of CVC insertion kits showed that loss of items was very rare in the operating rooms, but that loss of scissors or needle holders occurred on average once per five uses in the intensive care unit (ICU). Loss of a single AUD$10 reusable scissors for every five kit uses would increase the overall cost of the central venous catheter kits to 5x AUD$6.35 + AUD$10= AUD$41.75 for 5 uses, approximately the same (AUD$8.35) as five single use kits at AUD$8.65 each. Adding new, reusable instruments to CVC insertion kits has little effect on carbon dioxide emissions and water use as such reusable items are used hundreds of times.

Table 7 Effects by life cycle stage for one reusable CVC insertion kit.

Process/Item	CO_2 produced (grams)	Water use (litres)
Washing (thermal disinfection)	256	11.2
Steam sterilisation	830	15.7
Single use packaging- **polypropylene plastic theatre wrap (32g)** **clear polypropylene plastic cover (15g)**	121	<0.05
Nylon plastic kidney dish (280g) **two plastic gallipots (100g each)** **(used 300 times)**	<5	<0.05
3 stainless steel surgical instruments (100g total) **(used 300 times)**	<5	<0.05
Trucking	<5	<0.05
Infectious waste disposal for plastic theatre wrap and clear plastic cover (50g) **90% hypochlorite treatment, 10% incineration**	<5	<0.05
Total for all items and processes	**1,211 g**	**27.7 L**

For the single use CVC insertion kit only 5% of the total environmental effects were due to processes other than manufacture of the plastic and metal components (Table 8). Such processes as international shipping transport, ethylene oxide sterilisation, infectious waste treatment, and discard to landfill were relatively insignificant from an environmental and toxicological perspective.

Other environmental effects of the CVC insertion kits examined included aquatic and terrestrial Eco toxicity, carcinogens, solid waste and mineral use. The reusable kit had greater environmental effects except for solid waste and mineral use, but these differences were minor.

Table 8 Effects by life cycle stage for one single use CVC insertion kit.

Process/Item	CO_2 produced (grams)	Water use (litres)
Polypropylene plastic kidney dish (25g), Two galley pots (8g each)	114	0.1
Polypropylene plastic sheet for sterile field (41 g), packaging wrap (25 g)	170	0.1
Three stainless steel surgical instruments (60g)	104	1.7
Rubber ends on sharp instruments (4g)	10	0.4
Shipping and trucking	8	<0.05
Ethylene oxide sterilisation	<2	<0.05
Sharps disposal (60g metal). 90% hypochlorite treatment, 10% incineration.	<2	<0.05
Infectious waste disposal (110g). 90% hypochlorite treatment, 10% incineration	<2	<0.05
Total	**407 g**	**2.4 L**

Table 9 compares the CO_2 emissions and water use for different sources of electricity for the reusable CVC insertion kit. As noted in 5.4 Methods, the European electricity mix was assumed for the single use CVC insertion kit as imprecise data were available for China’s and Pakistan’s electricity generation. Further, gas cogeneration is an unusual source of electricity for plastic and metal manufacture. Gas cogeneration is a more efficient form of electricity production since there is both electricity production and heat capture, both of which are useful for hospitals.

Table 9 CO_2 Emissions and water use for the single use and reusable CVC insertion kits, accounting for different energy sources for the reusable kits.

Type of CVC insertion kit (and energy source)	CO_2 emissions (grams) with 95% C.I.s	Water use (litres) with 95% C.I.s
Single use (European energy mix)	407 (379-442)	2.5 (2.1-2.9)
Reusable - brown coal	1,211 (1,099-1,323)	27.7 (27.0-28.6)
Reusable- hospital gas cogeneration	436 (410-473)	26.0 (25.8-26.2)
Reusable- USA electricity mix[1]	764 (509- 1,174)	46.3 (36.6-62.6)[3]
Reusable- European electricity mix[2]	572 (470-713)	40.5 (36.4-45.8)[3]

[1] In 2012 the USA electricity mix was: coal-49%, nuclear-20%, natural gas- 17%, hydro-7%, oil-3%, other renewables-<1%.(25)
[2] In 2012 the European electricity mix was: coal-43%, nuclear-21%, natural gas- 18%, hydro-9%, oil-5%, other renewables-4%.(25)
[3] The USA and European electricity mix use large volumes of water primarily, because nuclear power stations use large amounts of water for cooling(25).

5.6 DISCUSSION

The financial and environmental costs of a reusable and a single use central venous catheter (CVC) insertion kit were modelled using LCA. The reusable kit was less financially expensive, but had greater environmental effects except for solid waste and mineral use. In a hospital in Melbourne, Australia, to make the reusable CVC insertion kit patient ready again produced three times the CO_2 emissions and required ten times the water use of the single use CVC insertion kit. Sterilisation contributed to the majority of the environmental effects for the reusable kit, while for the single use kit, plastic and metal ware manufacture were the most prominent. A reusable CVC insertion kit made patient ready in a hospital on gas co-generation instead of brown coal would produce similar CO_2 emissions to a single use kit, although water use would be greater for the reusable CVC insertion kit.

Compared with using brown coal, using electricity from the current American and European mix would have resulted in approximately 33% and 50% less CO_2 emissions to process the reusable CVC insertion kit(25). Some hospitals have on site gas boilers for steam generation that would have less than 50% of the CO_2 emissions compared with brown coal sourced electrical sterilisation. Water use was greater for reusable CVC insertion kits with electricity sourced from the American and European mix because of the large amount of water required for nuclear energy.

There are limitations to this study. As for most LCAs the majority of data were not directly measured, but sourced from reputable databases(25). It is likely that the CO_2 emissions in particular have been underestimated for the single use CVC insertion kit as we used European data for metal components production as direct data measurements from China and Pakistan had not been performed. Source data were obtained for ethylene oxide sterilisation of the single use CVC insertion kit, but infectious waste processing data were incomplete.

Despite imprecise data many processes such as the manufacture of stainless steel and different plastics do not vary considerably between locations and the environmental effects of such processes are in the public domain. Further, because many processes were common to both CVC insertion kits (e.g. stainless steel and plastic manufacturing) not having source data available is unlikely to lead to significantly different conclusions. It is more important for LCAs to have as much direct data for processes that are different between two alternative products; in this case washing and sterilising the reusable CVC insertion kits.

A loss of reusable items was not accounted for, even though this contributes to the drive towards single use items(181). Loss of reusable items was found to be infrequent in the OR due to double counting and checking to prevent loss (or retention within patients) of items. Loss of metal items in the ICU was more frequent, because of the lack of double-checking and the presence of single use metal items creating confusion and increasing discard of reusable items into the sharps bins.

It is likely that there will be a large variation in the loss of reusable items both within and between hospitals and these losses can quickly negate any potential financial savings. The reusable CVC insertion kits (627g) weighed almost four times as much as the single use kits (171g), but unless large numbers of reusable kits were being lost the subsequent environmental effects due to this weight difference would be relatively insignificant compared with the carbon dioxide and water costs of sterilisation and washing. Recycling of infectious or sharps waste (from single use CVC insertion kits and the like) does not occur in Australia unless there is prior decontamination which is often prohibitively expensive.

It was beyond the scope of this study to examine CVC insertion kit reformulation (i.e. altering kit componentry). Considerable environmental and financial improvements could be made by reformulating these (and other) kits to routinely include or exclude cotton gauze, sutures and antiseptic. The reusable CVC insertion kits included a single use polypropylene wrap (‘blue wrap’ in many hospitals). Such a plastic wrap could be replaced by reusable steel cases, but the requirement for a sterile field to achieve central venous line access would still necessitate the use of either a single use plastic or a reusable linen wrap.

On multiple occasions the electricity and water use of the washer and steam steriliser to make the reusable CVC insertion kit patient-ready again were directly measured. This LCA was modelled upon the routine steam steriliser without alterations. Our findings that the reusable item had worse environmental effects for most parameters than the single use item is at odds with the few other medical life cycle assessments of steam sterilised items. LCAs of sterile gowns(107), laparoscopic instruments(110), laparotomy pads(163), surgical drapes(108),and laryngeal masks(111) found that the reusable items had lower CO_2 emissions and water use than single use variants. The three German studies(108, 110, 163) had reusable devices reliant to some degree upon nuclear powered electricity. LCI databases that contain information about electricity sourced from nuclear power routinely include the environmental effects of uranium mining, purification and nuclear power plant decommissioning(25). Nuclear power has significantly lower CO_2 emissions than the Australian brown coal used as the electricity source for the washer and steam steriliser for the reusable CVC insertion kit in this study.

The small size and relatively light CVC insertion kits compared with large surgical trays(110) and heavy linen packs(107) are also greatly contributory to the findings of this study. Although it is possible to load 48 reusable CVC insertion kits into the steriliser examined this represents 5kg of metal components, similar to just one major orthopaedic instrument tray. It may be possible to alter the design of the steriliser racks to accommodate more CVC insertion kits whilst conforming to local sterilisation standards.

It is not standard hospital practice to load only reusable CVC insertion kits into steam sterilisers, but rather to prepare a mixed load of such kits with larger surgical trays, linen and plastic ware. Thus, actual hospital steam steriliser loads have greater masses than a 5kg, 'fully loaded' CVC kit steriliser cycle. The energy efficiency of the steam steriliser (kWh per kg of mass sterilised) would likely be improved with the larger mixed loads of various heavier items, although this has not been well studied. Finally, this study does not account for the energy and water consumption during inactive periods of the washer and steriliser - i.e. when these machines are idle, or on, but not in an active cycle processing equipment.

In this study the reusable CVC insertion kits were found to have considerably greater electricity and water consumption, other environmental effects were similar, but the reusable kits were less expensive than the single use kits. These findings were primarily explained by the hospital's brown coal based electricity and steriliser energy and water inefficiencies. For similar hospitals that use about 500 CVC insertion kits yearly, using reusable CVC insertion kits would save AUD$1,000 (USD$770), but produce 400kg more CO_2 and use 12,500 more litres of water compared with the single use variant. This amount of extra CO_2 produced from using the reusable CVC insertion kit equates to driving an average Australian car approximately 2,000km(186) and a fortnight's water use for an average household in Melbourne, Australia(187).

It is relatively common for hospitals to use gas fired co-generation for electricity and heat production. For Australian hospitals using electricity from gas fired co-generation, using reusable CVC insertion kits compared with single use kits would result in similar CO_2 emissions (i.e. one-third that of the reusable kit dependent upon brown coal for steam sterilisation), and AUD$1,000 financial savings, but 12,500 litres increased water consumption. Although the environmental effects of the CVC insertion kits could be extrapolated to any hospital according to the energy source, financial costs would be region specific.

The large amounts of water use for the reusable CVC insertion kits are a concern: water used for sterilisation may preclude its use for other activities, which is particularly pertinent in the many areas of the world under water stress. Water increasingly has an energy ($ and CO_2) content also, as it may be sourced from desalination or pumped long distances from dams and rivers. Investigation of more water efficient washers and sterilisers and opportunities for water reuse or recycling could be fruitful.

The solid waste for the single use CVC insertion kits was greater than for the reusable variants. Most of the wastes were plastics or metals that are minimally toxic in landfill and have low environmental flows. As a result, these solid wastes are of minor importance despite the large numbers of CVC insertion kits used at our hospitals. Financial costs to dispose of infectious and sharps waste will vary greatly between countries. Further, although discard of single use stainless steel metal components appears wasteful, since the metals used are relatively abundant (iron, chromium) and inexpensive for small instruments, mineral use for the single use CVC insertion kits was minor. Other ecological effects such as carcinogens and aquatic and terrestrial toxicity for the two different kits, including the effects of ethylene oxide sterilisation, were either not statistically significant or of minimal difference. The environmental effects of the mode of waste disposal (incineration, steam autoclaving or chemical treatment) are likely to vary and require further research. The overall environmental effects of shipping from distant countries were minor.

5.7 CONCLUSION

Discarding a CVC insertion kit after but one use intuitively appears wasteful. This study however, found that for hospitals using electricity sourced from brown coal for washing and steam sterilisation the environmental effects (CO_2 emissions and water use) are greater if reusable kits are used instead of the single use variants. Efforts to reduce the environmental effects of reusable items should be directed towards the inefficiencies and energy sources of steam sterilisers in particular. Further investigations of different sized medical devices with different sources of electricity are required to clarify uncertainty surrounding the environmental and financial effects of most operating room and intensive care purchases.

CHAPTER 6: REUSE

STEAM STERILISATION’S ENERGY AND WATER FOOTPRINT

6.1 BACKGROUND

Chapters 2 and 5 described life cycle assessment (LCA). LCA or ‘cradle to grave’ analysis provides a method to examine the environmental and financial effects of a process or product(26, 183). LCAs of reusable and single use operating room items are increasingly being performed, including surgical gowns(107), laparoscopic instruments(110), laryngeal masks(111), and drug trays(65). LCAs of whole procedures have also been conducted including: cataract surgery(113), delivering a baby(115), different types of dialysis(81), hysterectomies(35), and laparoscopies and laparotomies (188).

Uncertainty is however, emerging regarding the differing results from healthcare LCAs. As an example, one input-output LCA found that the ‘carbon footprint’ of one cataract operation was approximately 180 kg CO_2 (113), similar to burning 80 litres of petrol (114). On the contrary, Woods et al performed a process based LCA, finding that a standard gynaecological laparoscopy had a carbon footprint of only 29 kg CO_2 (188). Such marked differences in an operation’s ‘carbon footprint’ indicate different LCA methods a paucity of baseline data and rarity of analyses.

Chapter 5 examined the life cycle of a reusable and a single use central venous catheter (CVC) insertion kit consisting of plastic pots, wrap and simple surgical metalware. Initially planned as part of this PhD were further LCAs of: (i) operating room and intensive care unit (ICU) equipment, (ii) an entire operation, and (iii) an ICU patient stay. It was considered however, that the environmental footprint of CVC insertion kits may have been unrealistic, i.e. an under or over-estimation. Steam sterilisation’s environmental effects were found to be the major contributor to the total carbon footprint and water use required to make a reusable CVC insertion kit patient ready again. The CVC study may have overestimated the true carbon footprint since the hospital steriliser routinely took much heavier loads than a steriliser modelled to be full of relatively light CVC insertion kits. That is, the LCA of CVC insertion kits was modelled with relatively ‘inefficient’ loads that may not represent standard hospital practice. On the contrary, the LCA of CVC insertion kits may have underestimated the steriliser's energy and water use due to inclusion of only steriliser loads and accessory cycles, but omission of the energy consumption when the steriliser was in standby mode.

In place of further life cycle assessments this PhD turned to closer study of hospital steam sterilisers. This chapter studies steam steriliser energy and water use and the following chapter investigates how sterilisers are used by hospital staff over a prolonged period.

'Steam sterilisation's energy and water footprint' by McGain F, Moore G and Black J, of which this chapter is an expansion, has been submitted for consideration of publication. This chapter is based upon the article 'Steam sterilisation's energy and water footprint' by McGain F, Moore G and Black J, Australian Health Review 2016, (in press).

6.2 INTRODUCTION

Worldwide, steam remains the most common form of sterilisation for reusable surgical items (182). A basic input for any life cycle of reusable surgical equipment should include steam sterilisation, yet there are few data for in-situ hospital steam steriliser energy and water usage (189). Prior studies of the electricity requirements of steam per unit of mass sterilised vary from 0.2 to 1.4 kWh/kg for external linen sterilisation facilities (107). Campion et al(115), (and later Thiel et al)(35), calculated from 'machine specifications' that to decontaminate and sterilise a caesarean section pack in a USA hospital required approximately 0.5 kWh/kg, but, Campion noted, this does not appear to account for the steam production (115).

Our previous study found that the electricity consumption for hospital sterilisation of central venous catheter (CVC) insertion kits was significantly greater, at 3.6 kWh per kg (189). Those estimates may be imprecise, since it was assumed that a small steriliser load, steriliser cycles were examined for only a few days, and idle (standby) steriliser electricity use was excluded. Prolonged measurements of a steam steriliser's energy and water use were undertaken to provide data that could serve as estimates for LCA of operations and potentially lead to a reduced financial and environmental 'footprint' of steam sterilisation.

The features of the sterilisers used by the Central Sterile Supply Department (CSSD) at our hospital were typical of many installations globally. A steriliser is either 'off' or 'on'. When 'off' the steriliser is totally off, or in a 'deep sleep', using minimal electricity and no water. When 'on', hospital steam sterilisers may be performing an active cycle or 'idle' (in standby). An idle steriliser still requires electricity and water, primarily to produce steam to keep the steriliser jacket warm. Active steriliser cycles are 'standard' 134 °C cycles for sterilisation of items, or 'accessory cycles' for quality assurance, in which no items are sterilised. Accessory cycles include Warm Ups (to prepare the steriliser for actual loads), Bowie Dicks (a test using chemical indicators to assure thermal penetration) and the Leak Test (to ensure an adequate vacuum) (142). Batch Monitoring System and Spore Test cycles (chemical and biological indicators of sterility) were deemed Standard 134 °C cycles as they were used to sterilise actual items and labelled secondarily as Standard 134 °C cycles.

There are three points of water use for a steam steriliser: steam production, water for the vacuum ring pump, and cooling water for the chiller/heat exchanger (see Figure 1). Steam produced in the generator will move to the jacket and into the chamber when the steriliser is in an active cycle. After leaving the chamber the steam is condensed to liquid water via a heat exchanger. When the steriliser is idle, steam moves from the generator to the jacket and thus via steam traps to the heat exchanger, thus bypassing the steriliser chamber. For the same time period the amount of steam required for the steriliser jacket is a fraction (approximately 10%) of the steam required for an active cycle for the steam chamber.

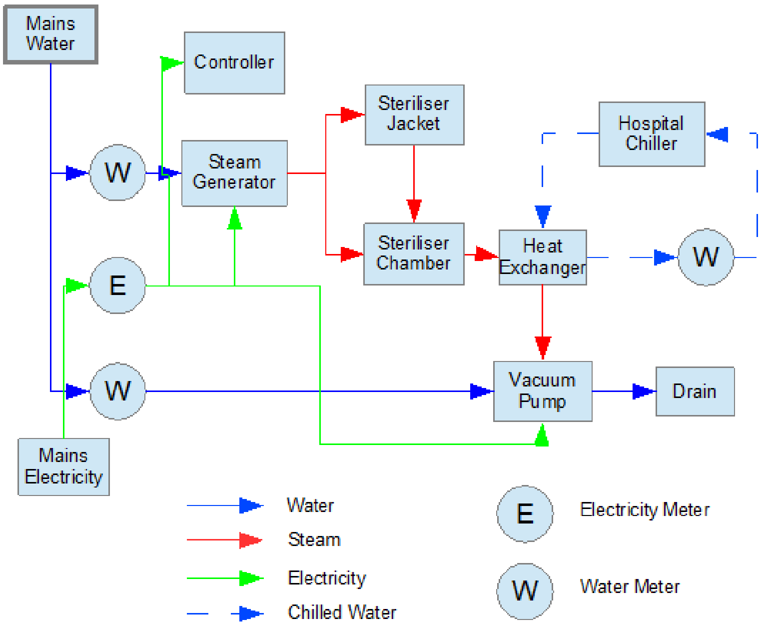
The vacuum pump evacuates the steriliser chamber prior the steam's entrance into the chamber to improve steam penetration. Smaller amounts of mains water are also used to cool steam exiting the steriliser jacket, e.g. during a Warm Up cycle, when the steriliser is idle, and when the steriliser is 'blown down' from idle to deep sleep every night (to prevent 'scale formation' in the steam generator). As the vacuum pump uses the majority of the mains water this second water stream has been labelled as vacuum pump water.

A third source of water is required by a heat exchanger to rapidly condense the steam after it has passed through the sterilising chamber during an active cycle (so that it is not hot enough to damage piping) and thus on to sewerage. There is no water transfer between the steriliser steam condensate and the heat exchanger water. Water use is an order of magnitude greater for the vacuum pump and chiller/heat exchanger than steam generation.

The standard 134 °C cycles were mostly mixed (linen, metal, plastic or mixed metal and plastic), although there were single type cycles – linen, metal or plastic. Open steriliser loads (no wrapping) of loan equipment were also performed, which have no sterile theatre wrap and no drying time. Such loan equipment has been used by the hospital theatre staff and is being sterilised prior to their non-sterile return for checking by the external loan company.

A routine day commences with the Warm Up whereby steam is piped into the steriliser jacket at 125 °C and 215 kPa. Although no vacuum is created within the steriliser chamber, water is used to cool the steam exiting the jacket. For a Bowie Dick cycle to test for sterility there are 7 vacuum pulls (with vacuum pump water) to achieve a chamber pressure of minus 85 kPa followed by steam entry into the chamber at 134 °C for 4 minutes. The Leak test detects a vacuum leak of anything beyond 1.3 kPa over 10 minutes. No chamber steam is used, although the background steam production to keep the jacket warm continues. The Leak test cycles are performed once a week to ensure that a vacuum can be ‘held’ without a noticeable steriliser leak. All accessory cycles are of approximately 20 minutes duration. For Standard 134 °C cycles there are also 7 vacuum pulls followed by steam entry at 134 °C for 4 minutes, but thereafter there is also a drying time of between approximately 10-25 minutes to ensure a dry load. These standard 134 °C cycles had a variety of different contents, mostly being mixed (linen, metal and plastic), although there are smaller numbers of single type cycles – linen, metal or plastic.

Figure 2 Location of instrumentation on the steam steriliser.



The aim of this study was to determine the contribution of steam sterilisation to the energy and water use required to make reusable surgical instruments patient-ready again. It was unclear what the patterns of electricity and water consumption of a standard hospital steriliser were over a prolonged period. After discussion with engineering staff it was considered that the electricity and water consumption of hospital sterilisers would: (i) increase linearly with greater load mass, whilst taking account of the different specific heats of the linen(190), metal and plastic (191), and (ii) also have a fixed component dependent purely upon steam occupying the steriliser chamber. The proportion of steriliser electricity and water use when idle was unknown.

6.3 RESEARCH QUESTIONS

1. What is the total electricity and water consumption of the steriliser over a representative period (up to one year) and what are the masses of items (linen, metal and plastic) sterilised for this period?
2. What are the absolute and relative amounts of steriliser electricity and water use for standard cycles, accessory cycles and idling?

3. What are the frequency distributions of the: (i) mass of items sterilised in standard cycles, (ii) electricity and water consumption for standard and accessory cycle sterilisations?
4. What are the averages of electricity and water consumption per kilogram of equipment for: (i) standard 134 °C cycles, and (ii) total steriliser use?
5. What is the relationship between the total mass of equipment in mixed steriliser cycles and electricity and water consumption?
6. What is the relationship between the individual masses of linen, metal and plastic in mixed steriliser cycles and electricity and water consumption?
7. What is the relationship between the mass of linen in linen-only steriliser cycles and electricity and water consumption?
8. What is the relationship between the mass of metal in metal-only steriliser loads and electricity and water consumption?
9. What is the relationship between the mass of plastic in plastic-only steriliser loads and electricity and water consumption?
10. What is the marginal cost (i.e. cost/unit= kWh/kg and litres/kg) of electricity and water per mass of items per steriliser run? How does this marginal cost vary with mass?

6.4 METHODS

The activity of one ‘Gorilla’® electric steam steriliser (Atherton, Thornbury, Australia) was examined at the 350-bed Sunshine Hospital, Melbourne, Australia. Only one of four sterilisers was metered since the sterilisers performed very similar numbers of cycles per annum and there were metering costs involved. The steriliser had a metered source of electricity applied (accuracy of +/-0.1 kWh). Three metered sources of water were also applied – steam, vacuum pump water and heat exchanger/chiller (accuracy of +/- 5 litres, Elster V-100, Essen, Germany) (Fig. 1). Sunshine hospital performs most surgery types (excluding cardiothoracic, vascular and neurosurgery) and has a significant obstetric and emergency service requiring 24-hour theatre cover.

Several hundred litres of water for both the heat exchanger and vacuum pump were used per sterilisation cycle. The heat exchanger water for the sterilisers had previously been replaced with continuously recirculating ‘chiller’ (air conditioning) water, achieving water savings of greater than one hundred litres per cycle. Since none of this measured chiller water was consumed it was of minimal further interest, although it was warmed by the condensing steam, leading to greater chiller energy cooling requirements. Previously (189) it was found that for a typical 20kWh sterilisation cycle the extra electricity requirements per cycle from the chiller were 7kWh. Those data were not re-examined in this study (i.e. this study is most likely under-estimating steriliser electricity consumption). Some hospitals also recirculate the vacuum pump water to achieve water savings, but this does not occur at Sunshine Hospital.

For quality assurance purposes at the study hospital all sterilised items were ‘scanned in’ to a database with a unique identifying code, using ScanCare software (ScanCare, Varsity Lakes, Queensland, Australia). The details of all sterilisation cycles from ScanCare were obtained. Before commencing data collection all sterilised items were weighed on electronic balance scales (+/- 1gram). An ‘item’ was defined as anything with a unique number, e.g. needle-holder (50g) or a large orthopaedic set (6kg). We neither recorded the volume of items sterilised nor the associated proportion of space occupied by items in the steriliser chamber. The manner in which items were stacked by CSSD staff could significantly alter the number of items occupying a steriliser load. For example, placing the smaller items singly would quickly fill a steriliser rack much more so than if they were placed side-by-side in a ‘toaster rack’ then placed onto the main rack.

‘Loan sets’ (i.e. items loaned to the hospital) varied in their composition even for the same unique identifying label (e.g. ‘Loan Shoulder Tray Set’). An approximation of the mass of these loan sets was made by Central Sterile Supply Department (CSSD) staff weighing and averaging several examples of each tray. There were four categories of items sterilised: linen, metal, plastic, and mixed metal and plastic. Most metal items were sterilised on plastic trays that were separately weighed to distinguish between ‘true’ metal and plastic masses (‘gross’ metal masses included the plastic tray’s mass, but ‘net’ metal masses subtracted the mass of the plastic tray, which was thus added to ‘gross’ plastic mass).

Electricity and water usage data were sampled five minutely to a wireless data logger (SoftLogic, Milnthorpe, Cumbria, UK) and thus to an associated website (http://www.softlogic.com.au). Each 5 minute datum point was correct to the nearest 0.1 kWh (electricity) and 5 litres (water). The utility data were downloaded onto a spreadsheet and database. The data were then summed into electricity and water use for each steriliser cycle (all standard 134 °C cycles and accessory cycles) and overall electricity and water usage. Visual Basic programming was used to link the data tallies of electricity and water use to the timing of the steriliser cycles, summing such data into utility use for each steriliser cycle. The meter data were synchronised with datum from the steriliser controller and scanned data of items in each load.

It was planned to obtain one year's data (April 2013 to April 2014). Since the heat exchanger water was recirculated, and the volume of steam water was less than 30 litres per cycle no statistical analyses of steam water use were made. 'Open' and failed steriliser loads were included in the total steriliser electricity and water use, but were excluded from further analyses of electricity and water use per mass sterilised as they had a very different (lower) usage pattern which would not be indicative of making a reusable, sterilised item patient ready again.

SPSS 22 (IBM, Armonk, NY, USA) statistical software was used to perform statistical analyses. Linear regression techniques were used to search for relationships between item mass and types (linen, metal and plastic) sterilised and electricity and water consumption. Common non-linear relationships ('transformations') were also searched for between steriliser mass and items – i.e. squared, cubed, square root, reciprocal (inverse), log10. Since the amount of steam water used per cycle was very small and the error rate was up to five litres no statistical analyses of steam water use were performed. Further, since the heat exchanger/chiller water was not actually consumed no statistical analyses of chiller usage were done. Analyses of water use thus focus upon vacuum pump water. A currency converter **(152)** on the 17/6/2015 was used to convert AUD$1 to USD$0.77.

6.5 RESULTS

Data were available for 304 out of 365 days (with gaps principally due to 6 weeks Wi - Fi outage over January-February 2014). Over the 304 days the hospital steriliser required 54.2 MWh of electricity, 1,576,370 litres of vacuum pump water and 65,430 litres of steam water to sterilise 28,282 kg (Table 1). Of the total mass of 28,282 kg, 11,427 kg (43%) was linen, 10,903 kg (41%) metal, 5,321 kg (14%) plastic and 631 kg (2%) mixed metal and plastic items. Of the 1,343 standard 134 °C cycles, there were 1,066 mixed cycles, 248 ‘single type of item’ cycles (196 linen, 30 metal and 22 plastic), 18 ‘open’ loads of loan equipment and 11 failed loads.

Table 10 shows that electricity usage during idling was 40% of the total, although 70% of the vacuum pump water was used during the 134 °C cycles. There is minimal usage of the vacuum pump water during idling time, although there is water used to cool the steam exiting the jacket and for when the steriliser is blown down to deep sleep. The mean (standard deviation) load mass of 134 °C cycles was 21.2 (+/-9.7) kg. The 10th centile was 10.9 kg, the 90th centile 36.0 kg, and 32% of cycles were less than 15kg. For the electricity consumption for 134 °C cycles, the 10th and 90th centiles were 16.4 kWh and 21.0 KWh.

Table 10 Steriliser Electricity and Water use for 134 °C and Accessory Cycles and Idling time.

	134 °C Cycles		Accessory Cycles[1]		Idling	
Number of cycles	1,343		830		N.A.	
Electricity (kWh) Total (% total)	24,870	(46%)	7,782	(14%)	21,457	(40%)
Electricity (kWh) Mean +/-S.D.	18.7	+/-1.9	9.4	+/- 4.1	N.A.	
Water[2] (litres). Vacuum Pump – Total (% total)	1,103,675	(70%)	143,495	(9%)	329,200	(21%)
Water (litres) Vacuum Pump – Mean, +/-S.D.	822	+/-135	173	+/- 79	N.A.	

[1] Accessory Cycles are: Warm Up, Bowie Dick and Leak Tests.

[2] Since steam use is small with a relatively high margin of error and the heat exchanger (chiller) water is recirculated continuously these have been excluded (see text).

Table 11 shows the steriliser energy and water consumption per kg of equipment sterilised and includes 134 °C cycles alone, followed by all usage. Twice as much electricity and almost 50% more water/kg items sterilised were used when including all steriliser use compared with 134 °C cycles alone.

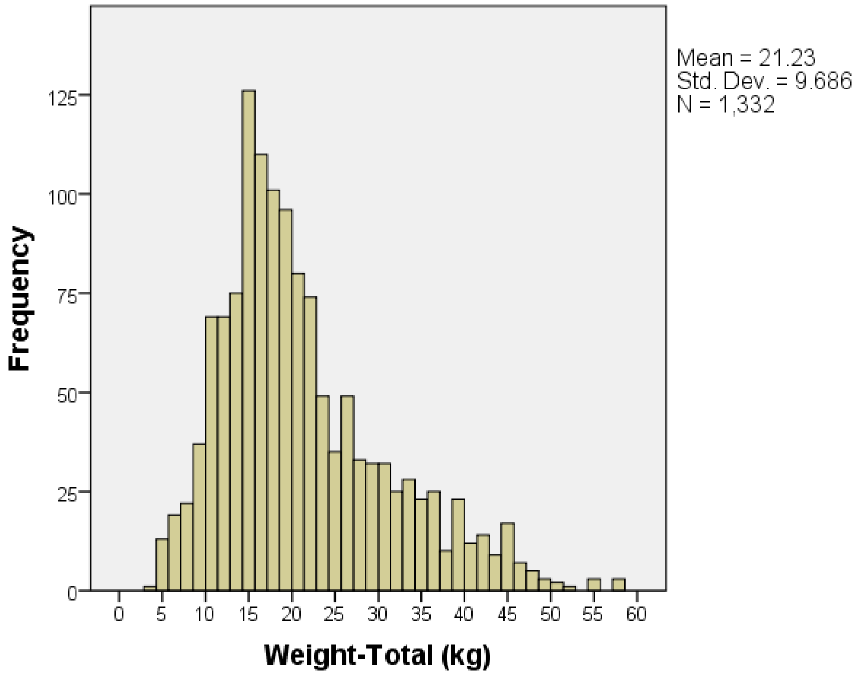
Table 11 Average masses of items for different types of 134 °C cycles

Cycle Type	Number[1]	Average mass (kg)	+/- S.D. (kg)
All cycles	1,332	21.2	+/- 9.7
Linen only	196	36.5	+/- 8.8
Metal only	30	19.6	+/-10.2
Plastic only	22	7.7	+/- 2.6

[1] The 11 failed cycles were excluded from the total 1,343 cycles.

Figure 2 shows the frequency distribution of the masses of items for all loads with the following centiles of note: 10th centile= 10.9 kg, 75th centile= 26.6 kg and 90th centile= 36.0 kg, whilst 56% of all steriliser cycles had 20kg or less and 32% were 15kg or less.

Figure 3 Frequency distribution of the total mass of steriliser items[1]



[1] The 11 failed cycles were excluded from the total 1,343 cycles.

Table 12 is derived from Tables 10 and 11 and shows the amount of electricity and water used per kg of equipment sterilised. Due in particular to the long idling times the total amount of electricity and water used by the steriliser per kg of sterilised items is appreciably greater than the amount used per kg when considering only the 134 °C cycles.

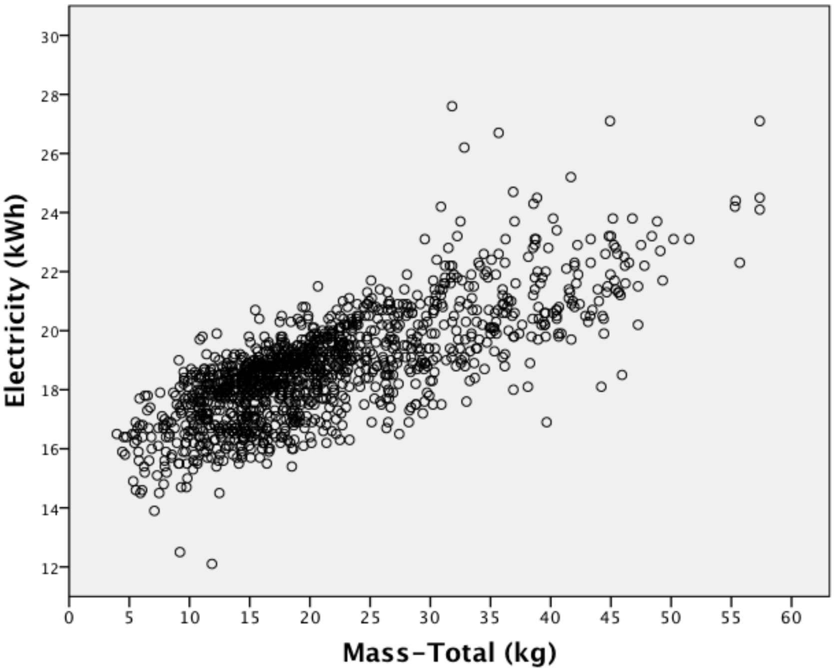
Table 12 Average electricity and water usage[1] per kg of equipment sterilised for all 134 °C Cycles (n= 1,343) and total steriliser use.

Steriliser Mode	Electricity (kWh)/kg	Water (litres)/kg
134 °C Cycles	24,870/28,282 **=0.9kWh/kg**	1,129,275/28,282 **=40 L/kg**
Total[2]	54,190/28,282 **=1.9 kWh/kg**	1,641,800/28,282 **=58 L/kg**

[1]Total water use/kg includes steam and vacuum pump water.
[2]Total electricity and water use includes all cycles and idling time.

For further analyses of 134 °C cycles, the 18 open load cycles were excluded due to their lower consumption patterns, as were the 11 failed cycles, leaving 1,343 – (18 + 11) = **1,314 cycles**. Fig. 3 graphs the relationship between total mass and electricity use for 134 °C cycles.

Figure 4 Mass-total versus Electricity for 134 °C cycles.[1]



[1](n=1,314). Note non-zero y-axis.

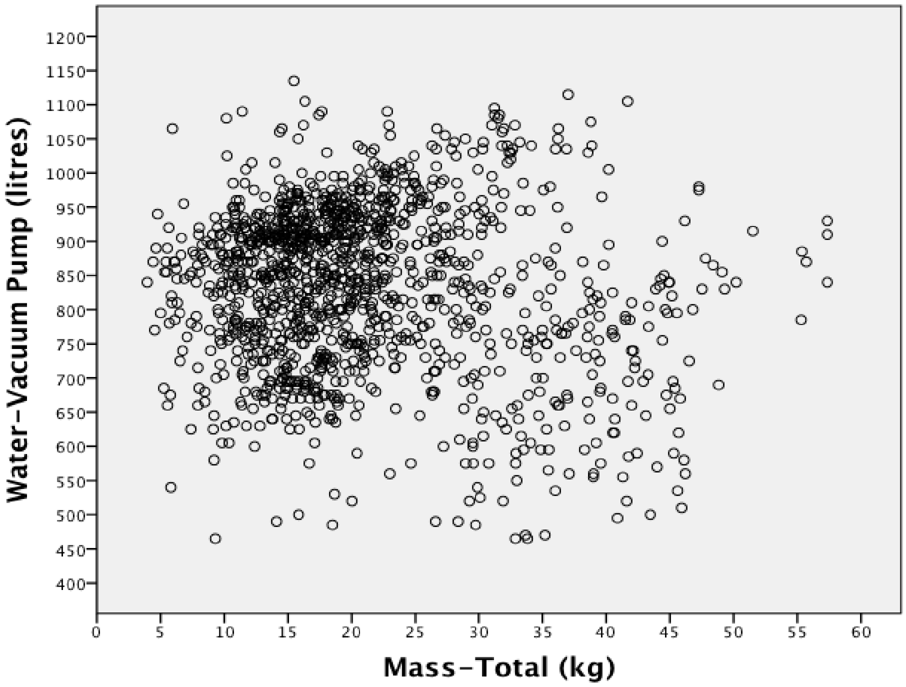
The general linear regression model is: $y = C + a x$, and here: y= electricity (kWh), C= Constant, a= co-efficient of x (mass) and x= mass. Visual inspection of Figure 4 shows that there is a relationship between total steriliser load mass and electricity use, but that any regression line may explain these data only moderately well and that the 'constant' (i.e. y-intercept) is likely to be more important than the total load mass for electricity use. Figure 4 explores the linear regression analysis of steriliser load mass with electricity use.

Linear regression of mass versus electricity gives a statistically significant ($p<0.01$) model of Electricity (kWh) = 15.7 + 0.14 (Mass in kg), though $R^2= 0.58$, indicating that the equation explains the data only moderately well. The major component to the prediction model is the constant (15.7 kWh), with a small mass coefficient (0.14 kWh/kg). Common transformations (see Methods) were used to investigate other relationships, but in all cases $R^2<0.5$, indicating a poor fit with the data.

Relationships between steriliser load mass and vacuum pump water use were also examined. Figure 5 does not show a clear relationship between the steriliser load mass and the vacuum pump water use. A large amount of water is used regardless of the load mass (i.e. a high y-intercept or constant). R= 0.02, indicating that although the relationship between water use and weight was statistically significant ($p<0.01$), the model did not explain the data at all well. Common transformations did not improve the fit of the model with the data of water use.

There was a weak relationship between the mass of steriliser cycles and water use by the heat exchanger (chiller) ($R^2<0.01$, model summary of the data not shown). Chiller water is used regardless of the load mass, as the chiller water is recirculated constantly. Further, steam water use was not modelled as such use is small (< 30 litres/cycle) compared with vacuum pump water and the limits of water meter accuracy (+/- 5 litres) precluded further modelling.

Figure 5 Mass-total versus Water-Vacuum Pump for 134 °C steriliser cycles.[1]



[1](n=1,314). Note non-zero y-axis.

The linear regression equation for electricity consumption of 134 °C cycles that takes account of different item composition and mass was: Electricity (kWh) = 15.6 + 0.15(kg of Linen) + 0.10(kg of Metal) + 0.22(kg of Plastic) + 0.28(kg of Mixed Metal and Plastic), $p<0.01$. Again the mass coefficients (0.10 - 0.28 kWh per kg) are small compared to the constant. The equation fits the data similarly well ($R^2 = 0.60$) to the mass-only model. Models of water use which took account of the types of loads did not explain the data well ($R^2=0.02$), as per models of total mass only. Such models were poor for all common transformations.

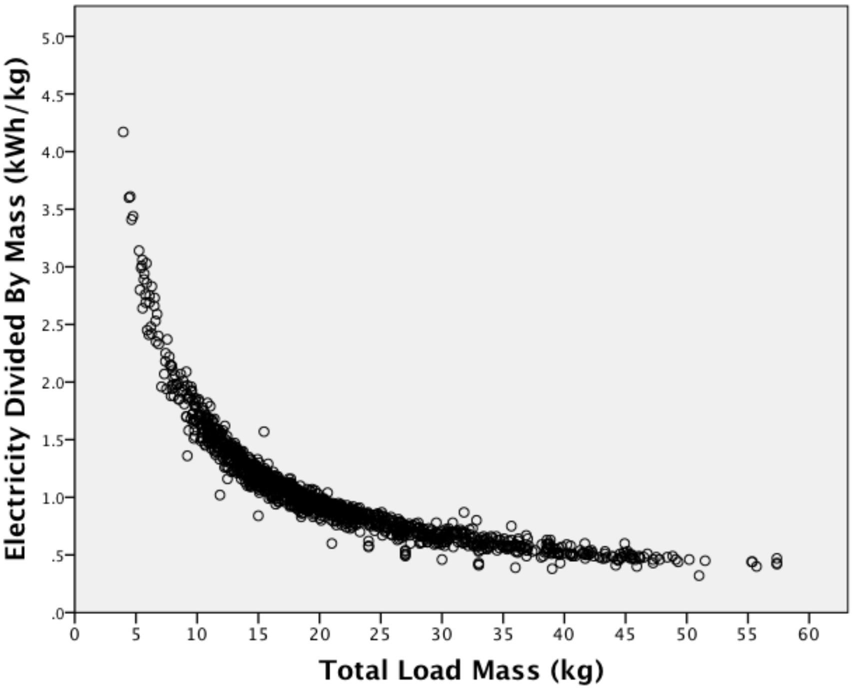
Linear regression models were also developed for the 248 ‘single type of item’ cycles (linen, metal or plastic only) comparing mass to electricity and water. Mixed metal and plastic item steriliser loads did not occur. As noted in the Methods, we took account of the masses of plastic trays that held metal ware.

For electricity, these statistically significant ($p<0.01$) models had R^2s of 0.57 for plastic, 0.70 for linen and 0.80 for metal, indicating a moderately good fit with the data for linen and metalware. The actual linear regression equations were: (i) Electricity (kWh) = 13 + 0.2 (kg Linen), (ii) Electricity (kWh) = 14.5 + 0.15 (kg metal) and (iii) Electricity (kWh) = 14.6 + 0.34 (kg plastic). As for the analyses of all 134 °C cycles the load mass coefficients were small. The constant for linen only cycles (13 kWh) was lower compared with all other cycles. The mean (+/- S.D.) duration of the linen only cycles was 43 (+/-6) minutes compared with 51 (+/-4) minutes for all other non-linen cycles. Linen only cycles had a 10 minute versus 25 minute drying time, perhaps because the water molecules bound to the linen fibres are released slowly. There were poor ($R^2<0.25$) fits between load mass and vacuum pump water use for all item types.

The constants for all models of mass versus electricity and water were more important than the load mass coefficients. That is, the extra electricity and water used per kilogram of added mass fell as we added more items. The following graphs give the cost/unit (kWh per kg and L per kg) of electricity and water per unit mass of items (Figures 6 and 7). From Fig. 5, the kWh cost/kg of mass for a steriliser cycle load of 5kg was approximately 3 kWh per kg (or 15 kWh total). The kWh cost per kg for a 15 kg load is 1.2 kWh per kg (18 kWh total) – adding another 10 kg to the steriliser load increased the electricity consumption by less than 3 kWh. The electricity consumption of a 50 kg steriliser load (25 kWh) was only 4kWh more than for a 30 kg load (21 kWh). Steriliser electricity use reached a minimum of 0.5 kWh per kg at the greatest load.

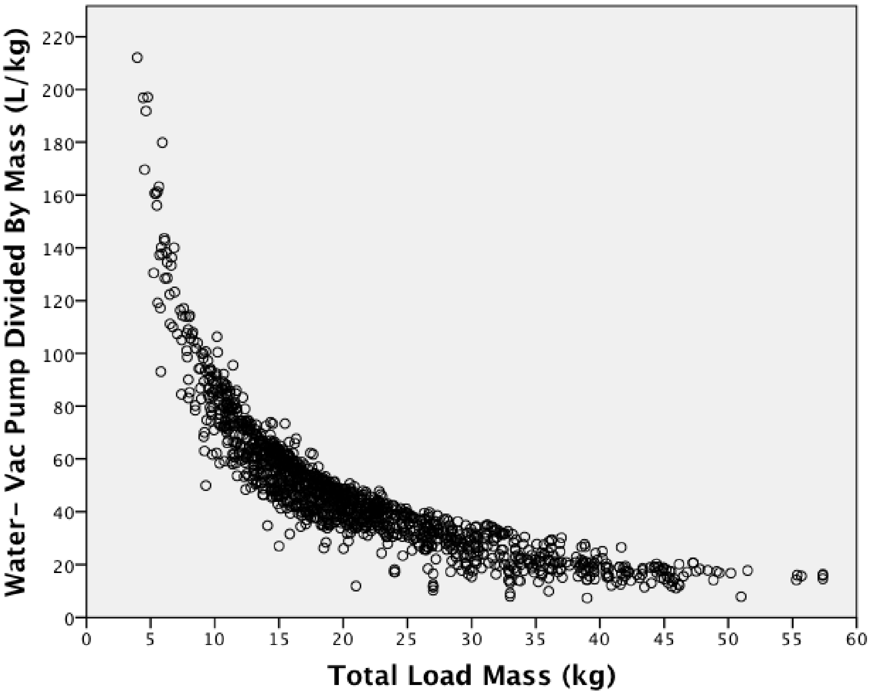
The cost curve for water-vacuum pump/mass versus mass (Fig. 6) showed a similar descending curve. The unit cost of vacuum pump water is large for small loads (150 litres per kg for a 5kg load). A steriliser load mass of 15kg was required to achieve <50 litres of vacuum pump water per kg. The extra water use for a 50kg load versus a 30kg load is small.

Figure 6 Electricity Cost Curve. Electricity divided by Mass versus Mass.[1]



[1] (n=1,314).

Figure 7 Water Cost Curve. Water-Vacuum Pump divided by Mass Versus Mass.[1]



[1] (n=1,314).

6.6 DISCUSSION

The electricity and water use of a hospital steam steriliser was measured over 304 days. A large proportion of electricity (40%) and water (20%) use occurred during idle (standby) times; heavier loads were more efficient; almost one in three steriliser loads were ‘light’ (less than 15kg), and thus inefficient; and linear regression analyses provided moderately predictive equations of electricity use/mass, but not water use. Per day the steriliser required approximately 178 kWh of electricity and 5,400 litres of water. The average 4-person household in Melbourne, Australia has a daily usage of 16 kWh of electricity (158) and 600 litres of water (187). One steriliser’s daily electricity and water use was thus equivalent to 10 households, whilst one standard 134 °C cycle used approximately one day’s worth of household electricity and water.

As a proportion of total steriliser electricity use, a surprising 40% of electricity was used when idle. Approximately 1.9 kWh of electricity and 61 litres of water were required per kilogram sterilised. The electricity/kg sterilised was approximately half of that calculated in the prior LCA study detailed in Chapter 5 (3.6 kWh/kg) (189), primarily because in this current study no assumptions were made about steriliser load mass. Prior studies gave more efficient steriliser electricity use (35, 107, 115) which could be due to using manufacturer specifications to calculate efficiency rather than measuring it; differences in steriliser mechanical efficiencies; different measurement methods (not including idle time); and operational differences such as having less idle time or shorter drying times or using large and perhaps more efficient sterilisers external to the hospital for linen sterilisation(107). It is difficult to compare our results with those of a recent LCA study of a much smaller autoclave used to sterilise small dental burs(112). Further, it is unclear in some published LCAs if the energy and water use of steam sterilisation is included. The following factors are important: (i) the large electricity use per kg compared with prior studies, (ii) the over-estimation in our prior study(189) from using small, inefficient steriliser load assumptions, and (iii) idle steriliser energy use can potentially double the total energy use/kg of items sterilised.

The vacuum pump used 96% of the water and only 4% was used to generate steam. There are large opportunities to reduce or recirculate steam steriliser water, though routinely these options incur financial installation costs. Discussions with the steriliser manufacturer indicate that vacuum ring pumps are by far the most common type of vacuum pump used in this type of application.

For standard 134 °C cycles, the electricity (kWh) used = 15.7 + 0.14(kg of mass), i.e. even for a 50kg load, less than one quarter of the electricity use is related to the sterilised items. The large constant and small coefficient in the equation indicates that most of the energy is used to heat the chamber, create the steam to fill the chamber volume and thermal losses, while relatively little is used to actually heat the items being sterilised. The majority of steriliser water use was also independent of the load mass for standard 134 °C cycles. Vacuum pump water forms the bulk of steam steriliser water use and appears to be dependent primarily on the sterilisation duration.

Linear regression equations were moderately useful for comparisons between item mass with electricity use, but did not improve with the addition of item type and were weak for water use. The linear regression equations for single type steriliser loads of linen and metal mass vs. electricity had higher R^2 values, probably because such cycles did not have a mixture of items with different packing arrangements. However, such single item type loads are relatively infrequent and perhaps of greater use to future calculations of operating room life cycle assessments is the average electricity and water cost/kg over 304 days for all standard 134 °C cycles (i.e. 0.9kWh and 40 L per kg). Further, as more load mass was added the extra cost of electricity and water fell. Almost one third of steriliser loads were less than 15kg, requiring on average 18 kWh, yet doubling these loads to 30kg would have required only 1.5 kWh more electricity per cycle.

It is possible that the five-minutely data were not precise enough to examine steriliser electricity and water use when cycles were close together, although this occurred rarely. The data were sent via Wi-Fi to a website. There was confirmation that the water data received electronically were identical to the water data directly measured by the steriliser meters and the Wi-Fi electricity data conformed closely to that directly measured by a ‘power clamp’: a Hioki 3197 Power Quality Analyzer, (Hioki Corporation, Nagano, Japan). Data were obtained for 304/365 days, and there were lacking data due to Wi-Fi difficulties during most of January/February 2014. Much of January in Australia is a summer holiday period of low elective surgical activity, i.e. this study probably underestimated idle steriliser time.

Dividing sterilised items into linen, metal, plastic and combined metal and plastic may seem crude, yet the vast majority of sterilised items fit clearly into these subtypes. The hospital's sterilisers have heat exchanger water cooled by recirculating chiller water, leading to hundreds of litres of water saving per cycle, but there is an energy cost through greater work required by the hospital chiller to cool the warmed heat exchanger water. Thus, a 20 kWh cycle would use approximately 27 kWh in total if the extra 7 kWh from the chiller was incorporated (189), with a corresponding one third increase in the electricity use per kilogram.

Our results may not be totally generalisable to other hospitals because of differences in steriliser design and usage, e.g. our sterilisers do not reuse vacuum pump water, although this occurs in some hospitals, with considerable water savings. Steam sterilisation, however, does not vary markedly between different hospitals in Australia, conforming to local (139) and international standards (22). It is likely that our results are broadly comparable with steriliser utility consumption in other countries. Steriliser idle time could vary significantly between hospitals due to local usage factors, particularly between purely elective and emergency hospitals (the latter requiring continuous steriliser functioning). Idle time could thus be much less for hospitals that cater for purely elective procedures. Greater inter-hospital variability for electricity and water used during idle time is likely than for differences between standard 134 °C cycles, although loading patterns remain important.

Steam sterilisation is nontoxic, inexpensive and rapidly microbicidal and sporicidal(182), thus remaining the most dependable method to sterilise most medical items. There is an increasing use of low temperature sterilisation systems (192), but these are mainly confined to sterilising malleable 'visual equipment' (e.g. colonoscopes). Future efforts to improve steriliser energy and water efficiencies could target two main areas: (i) how hospital staff use sterilisers, and (ii) steriliser hardware and software manufacture, although steriliser energy source/s remain important. Although the four sterilisers at our hospital consume less than 2% of the total hospital daily electricity use, their individual electricity usage remains considerable and can easily be reduced by changed work practices. Similar studies of other hospital equipment are now occurring, e.g. a USA study found that the electricity used when the CT scanner was idle was an order of magnitude greater than the energy used for an actual scan received by the patient (83). Further research is required to establish the safety of turning CT scanners off during periods of low demand, and the energy requirements to restart the CT scanner compared with leaving the scanner idle.

As a direct result of this study staff at Sunshine hospital have rotated off one of four sterilisers with no change to the number of 134 °C cycles, saving electricity, water, labour and reagent testing. An idle steriliser uses 5 kWh per hour, and routinely all four sterilisers were on for 22 of 24 hours, i.e. 110 kWh is now saved/day. Further, there are no morning accessory cycles (20 kWh) for that fourth ('off') steriliser, and the reduced chiller electricity use will be approximately 40 kWh (one third of 130kWh). It follows then that savings of 170 kWh electricity per day with a yearly financial value of AUD9,400 (USD$7,240)(152), equal to 10 average Australian houses per day (158) (with associated water savings) are occurring for the same number of sterilization cycles. Increasing steriliser load mass will also contribute similarly in future to environmental and financial savings.

Our study provides a baseline for future life cycle studies of reusable surgical instruments, and indicates the importance of measuring *how* hospital steam sterilisers are used during both active cycles and when idle. Measurement of how *groups* of hospital sterilisers are used will contribute further to energy and water efficiencies. Once such data are available, collaboration between CSSD hospital staff, engineers and others to develop novel ways to improve steriliser efficiencies is feasible. Our study indicates the importance of in-situ monitoring of hospital equipment and the integral role of real-time electronic data gathering and distribution. After a century of use the steam steriliser appears here to stay – and the opportunity to improve its significant electricity and water consumption worldwide grows in importance.

6.7 CONCLUSION

This study was performed to clarify whether the energy and water consumption used for steam sterilisation for the life cycle assessment detailed in Chapter 5 were realistic. The electricity and water use required for the steam sterilisation were quantified. A surprising amount of steriliser time was spent idle, consuming appreciable amounts of energy and water. The load mass had minor effects upon steriliser electricity and water use, whilst the type of load (linen, metal, plastic) had much smaller effects on such electricity and water use. The results of this study inform future life cycle assessments of operating room and ICU items and procedures. For example, future LCAs of reusable surgical items could use this study’s calculations of electricity and water use/kg load sterilised, whilst load type could be excluded. Further, considerable efficiency gains in steriliser use are possible through reducing idle periods as well as increasing steriliser load masses. Innovations in hospital steriliser usage and will become increasingly important in a financial, energy and carbon constrained society.

CHAPTER 7: REUSE

HOSPITAL STEAM STERILISER USAGE: COULD WE SWITCH OFF TO SAVE ELECTRICITY AND WATER?

7.1 BACKGROUND

Steam sterilisers are integral to the sterilisation of reusable medical equipment. Chapter 6 quantified the energy and water consumption of a hospital steam steriliser over a prolonged period. The results of Chapter 6 inform future life cycle assessments of operating room and ICU items and procedures. Further, it was noted that a surprising amount of steriliser time was spent idle and many steriliser loads were relatively light, consuming appreciable amounts of energy and water. Considerable efficiency gains in steriliser use could be possible at the hospital level through: (i) reducing idle periods, and (ii) increasing steriliser load masses, including changing the load stacking arrangement and stacking the steriliser with another layer of racking. An examination of the steriliser idle periods was thought more likely to lead to greater and more prompt efficiency gains than altering steriliser load masses.

This chapter is based upon the article 'Hospital Steam Sterilizer Usage: Could we switch off to save electricity and water?' by McGain F, Moore G and Black, J, Health Services Research and Policy 2016; Jan. (epub ahead of print).

7.2 INTRODUCTION

Steam sterilisation is an energy intensive process, each sterilising load of around 20 kg for a standard, medium to large sized hospital steriliser requiring about 20 kWh of electricity and 500 litres of water(189), equivalent to an Australian four-person household's electricity and water use for an entire day(158, 187). Despite the advent of new modes of sterilisation(192), steam remains the most common method of sterilising surgical items(182) Accordingly, a method was developed to examine how hospital steam sterilisers are used, to complement studies of steriliser utility consumption(107, 115, 189).

To reiterate Chapter 6.2 Introduction: a steriliser is either 'off' (i.e. in a 'deep sleep', using minimal electricity and no water) or 'on' (i.e. performing an active cycle or ‘idle’ in standby). Active cycles are ‘standard’ 134 °C cycles for item sterilisation, or ‘accessory cycles’ (such as Warm Ups and Bowie Dick tests for quality assurance) which do not contain items(139).

Efforts have been made to improve hospital steriliser efficiencies though there are few relevant publications. Unnecessary steriliser cycles can be avoided by standardisation of which items actually require sterilisation(193). One study found that steriliser efficiency (hours of active steriliser cycles/hours of available labour) was 63% for a 6-month period, although there were only monthly details of steriliser use(194). The use of hospital steam sterilisers was assessed and opportunities were sought to improve steriliser electricity and water efficiency.

An idle (i.e. in standby) steriliser still requires electricity, primarily to produce steam to keep the steriliser jacket warm, and water to condense the steam upon leaving the steriliser. The environmental ‘break-even point’ is the period at which potential electricity or water savings from switching off are balanced by the extra resources needed to warm up again before use.

In Chapter 6 one hospital steriliser was found to use approximately 25.8 of 63.9 MWh (40%) of its total electricity and 395,000 of 1,572,000 litres (21%) of its total water requirements for the year whilst idle. That is, each hour an idle steriliser used approximately 5.3 kWh of electricity for steam generation and 81 litres of water to cool this steam. Standard practice was for a Warm Up cycle to be performed prior to a Standard 134 °C cycle whenever the steriliser had been idle or off for two or more hours to avoid failed cycles. A warm up cycle for a steriliser that had been off (and was thus ‘cold’) used an extra 7 kWh and 60 litres of water compared with one that had been idle (‘tepid’). From such prior data the steriliser ‘break-even point’ was found to be less than two hours (a conservative approach to the break-even point).

At our hospital, due to lower demand for sterilisation overnight and labour capacity, it was routine practice to switch off: (i) one steriliser on all days between 10 p.m. and 6 a.m.; and the other three sterilisers (ii) between 4 a.m. and 6 a.m. every weekday, or (iii) between 2 a.m. and 6 a.m. on every weekend day. One could thus determine directly when a steriliser was active and indirectly when it was idle or off.

7.3 RESEARCH QUESTIONS

1. How were the four hospital sterilisers used during one full year, including details of periods spent in active use, idle or switched off?
2. Based upon data from Chapter 6, how much electricity and water were used by the sterilisers during these different periods (i.e. active, idle or off)?
3. What would have been the consequences for electricity and water use of two alternative usage policies based upon switching sterilisers off when not needed (either whenever idling, or at set times of the day)?

7.4 METHODS

For one year the activity of four ‘Gorilla’® electric steam sterilisers (Atherton, Thornbury, Australia) was studied in the Central Sterile and Supply Department (CSSD) at Sunshine Hospital, Melbourne, Australia. Ethics approval was obtained from the Western Health Low Risk Ethics Panel (approval no. 2012/165). At the end of each steriliser cycle the summary details of that cycle were routinely recorded by CSSD staff into the ScanCare® database (ScanCare, Varsity Lakes, Queensland, Australia).

All steriliser cycles were included in the analyses whether they were classified as ‘pass’, ‘fail’ or ‘maintenance/validation’ (using staff estimates for the duration of the last). Accessory and standard 134 °C cycles take about 20 and 50 minutes respectively. If a steriliser was in an active cycle at any point during a given hour that hour was categorized as ‘active’. With four sterilisers the maximum number of steriliser-hours available per day was 96.

Due to lower demand it was routine practice to switch off sterilisers overnight (see the final paragraph of 7.2 Introduction for precise timings). Exceptions to this practice were looked for by noting active steriliser cycles during these off hours and when two or three sterilisers were off. The steriliser ‘off’ hours could thus be calculated, and finally the idle hours (as total hours less active and off). Data were stored and analysed using Microsoft Excel® and Access® software (Microsoft, Washington, USA).

Chapter 6 (Steam sterilisation’s energy and water footprint) identified several potential areas for improved steriliser resource efficiency including reducing idle time and increasing the average mass of each steriliser load. This chapter explores reducing the idle steriliser time only. Two potential opportunities to reduce the hours of steriliser use with an unchanged number of active cycles were analysed: turning off sterilisers routinely instead of leaving them idling, and turning off one steriliser for certain periods if very few on-active cycles occurred in those hours. The potential reductions in electricity and water consumption that would result from such switch offs were modelled.

7.5 RESULTS

Data were obtained for 365 days (8,760 unique hours between 15/4/2013 and 14/4/2014) of all hospital sterilisation cycles. The amount and proportions of time spent by the four sterilisers when active, idle and off are given in Table 13. Of note: all four sterilisers were simultaneously active for only 9% of the hours, and two or more sterilisers were idle for 69% of the hours. For the 365 days there were 53 fewer occasions than predicted by CSSD policy when four sterilisers were off, indicating that some were left idle (such hours were not active). On 41 occasions sterilisers were off when policy indicated they would be idle. There were 57 failed cycles, including 14 standard 134 °C cycles, requiring maintenance work on the sterilisers on six occasions for an average (anecdotal) duration of 6 hours. Most failed cycles were due to ‘colourimetric uncertainty’ of Bowie Dick cycles. Validation of the sterilisers occurred for one day for each of the four sterilisers. Two sterilisers were cleaned for 20 minutes each on every Saturday and Sunday.

Table 13 Hours when the sterilisers were active, idle and off.[1]

No. active	No. idle	No. off	No. of hours (8,760 total)	Percentage of total
0	4	0	522	6.0 %
0	3	1	558	6.3%
0	0	4	897	10.2%
1	3	0	2022	23.1%
1	2	1	447	5.1%
1	0	3	37	0.4%
2	2	0	2546	29.1%
2	1	1	110	1.3%
2	0	2	4	0.0%
3	1	0	864	9.9%
4	0	0	753[2]	8.6%

[1] Routinely, 0, 1, or 4 sterilisers were off although there were 41/8,760 hours when either 2 or 3 sterilisers were off.

[2] 726/753 times there were 4 sterilisers on simultaneously during the hours of 6 a.m.-10 a.m. (i.e. 27 times outside these hours in a year).

The frequency distributions of the numbers of sterilisers in active use per hour for the 365 days are given in Figures 8 (week days) and 9 (weekend days). Figures 8 and 9 reveal greatest steriliser activity between 6 a.m. and 10 a.m., and rarely was there more than one active steriliser on from 11 p.m. to 6 a.m. There were four sterilisers active from 10 a.m. onwards on only 27 of 261 week days and on 1 of 104 weekend days. On weekends three sterilisers were active from 10 a.m. onwards on only 27 of 104 days. Finally, there were only 5 of 365 days when more than two sterilisers were active from midnight until the routine steriliser switch off at 4 a.m. on week days and 2 a.m. on weekend days.

For the four sterilisers together, the year 15/4/2013-14/4/2014 had 1,460 steriliser-days or 35,040 steriliser-hours. For these 35,040 steriliser-hours, the sterilisers were active for 13,430 (38%) steriliser-hours, off for 4,822 (14%) and idle for 16,788 (48%) (Table 13).

Figure 8 Pattern of active steriliser use on week days.

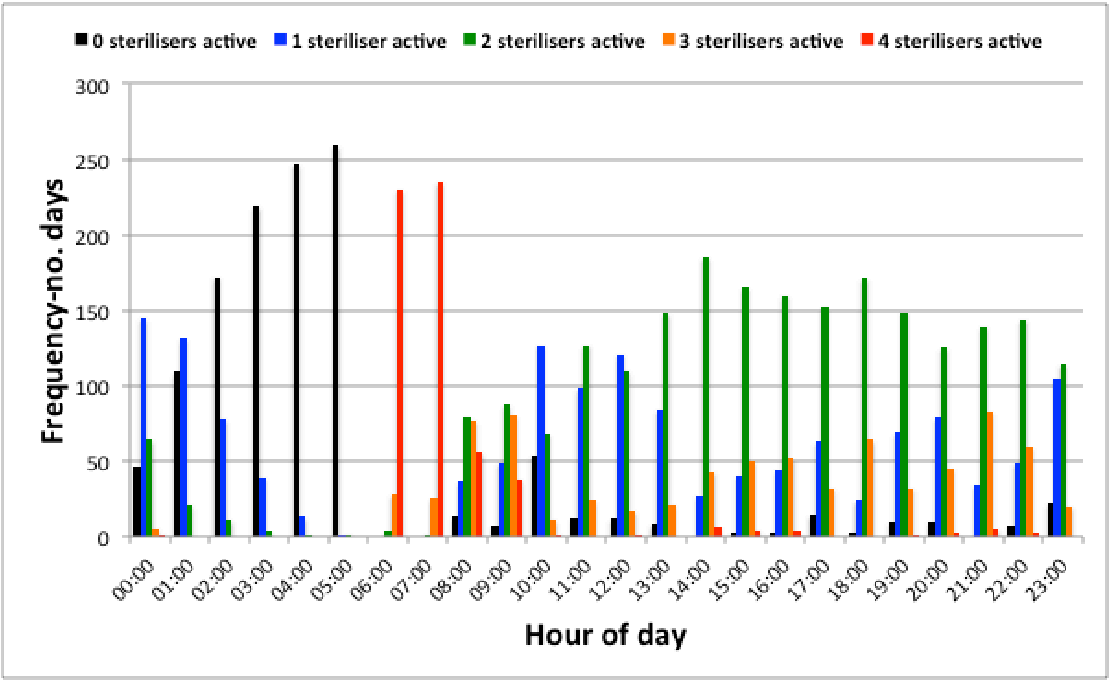


Figure 9 Pattern of active steriliser use on weekend days.

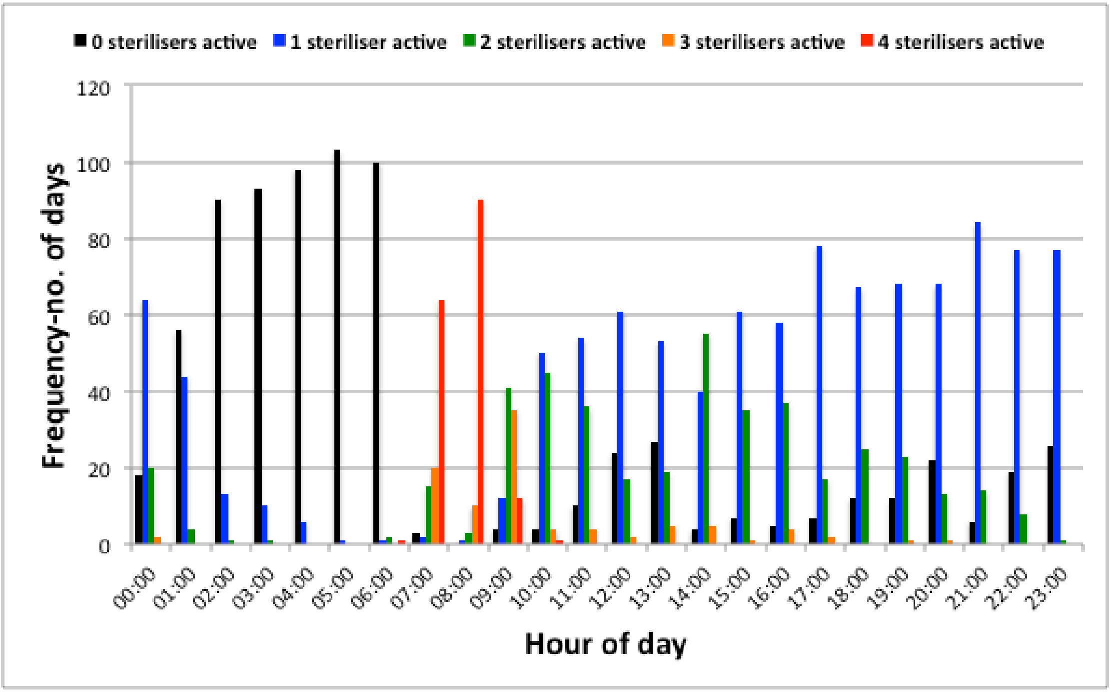
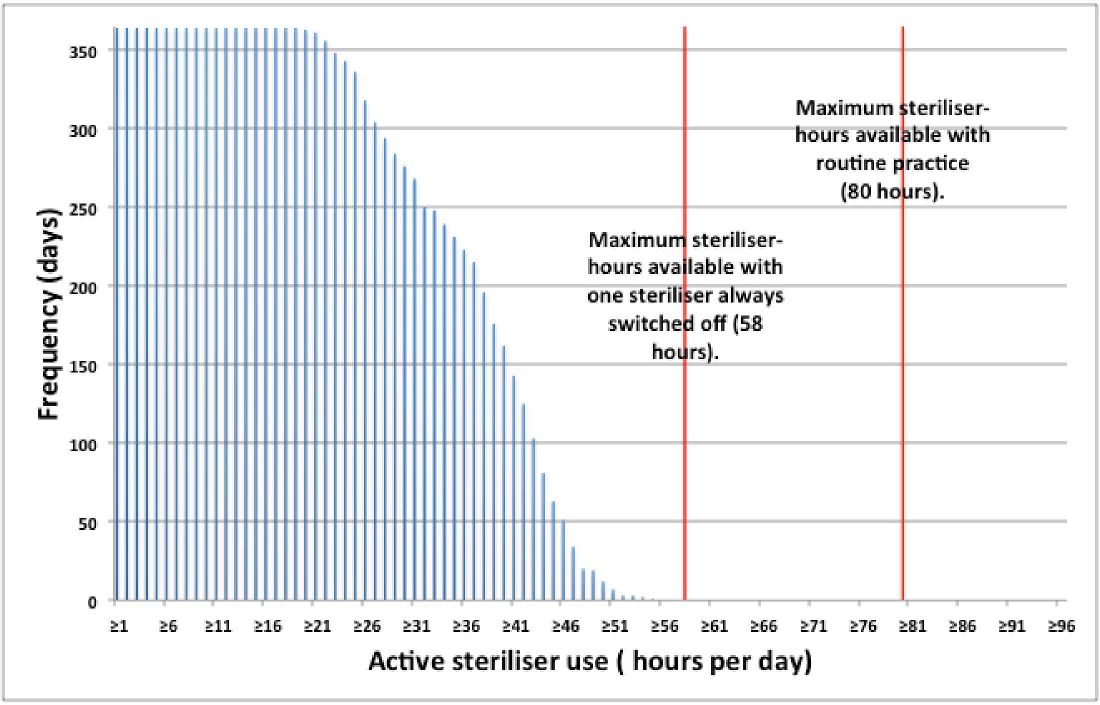


Figure 10 gives the spread of active steriliser time for 365 days, i.e. the 'demand', on a daily basis. In Figure 10 the x-axis represents the active steriliser-hours, whilst the y-axis indicates the number of days on which those hours of use occurred. Given that the four sterilisers have a maximum of 4x24=96 steriliser-hours of active use per day, active steriliser use for all hours for all days would be indicated by vertical lines reaching 365 days for all 96 hours. The maximum steriliser-hours per routine day prior is 80 hours due to routine steriliser switch offs, whilst a potential switch off of one steriliser permanently would reduce the maximum steriliser-hours to 58 (see Fig. 3). A minimum of 18 hours of active use occurred on every day, whilst the maximum usage on any day was 55 hours.

Figure 10 Frequency distribution of steriliser-hours of active use per day for one year for routine practice[1] and if one steriliser was to always be switched off.[2]



[1] The average sum of available steriliser-hours is <96 hours as there are routine periods when the steriliser is turned off, i.e. (1) one steriliser is off from 10 p.m. on all days, (2) 4 sterilisers are off from 4 a.m.-6 a.m. on weekdays, and (3) 4 sterilisers are of from 2 a.m.-6 a.m. on weekends. Thus, routinely there are a maximum of 80 steriliser-hours available per day averaged over weekdays and weekends.

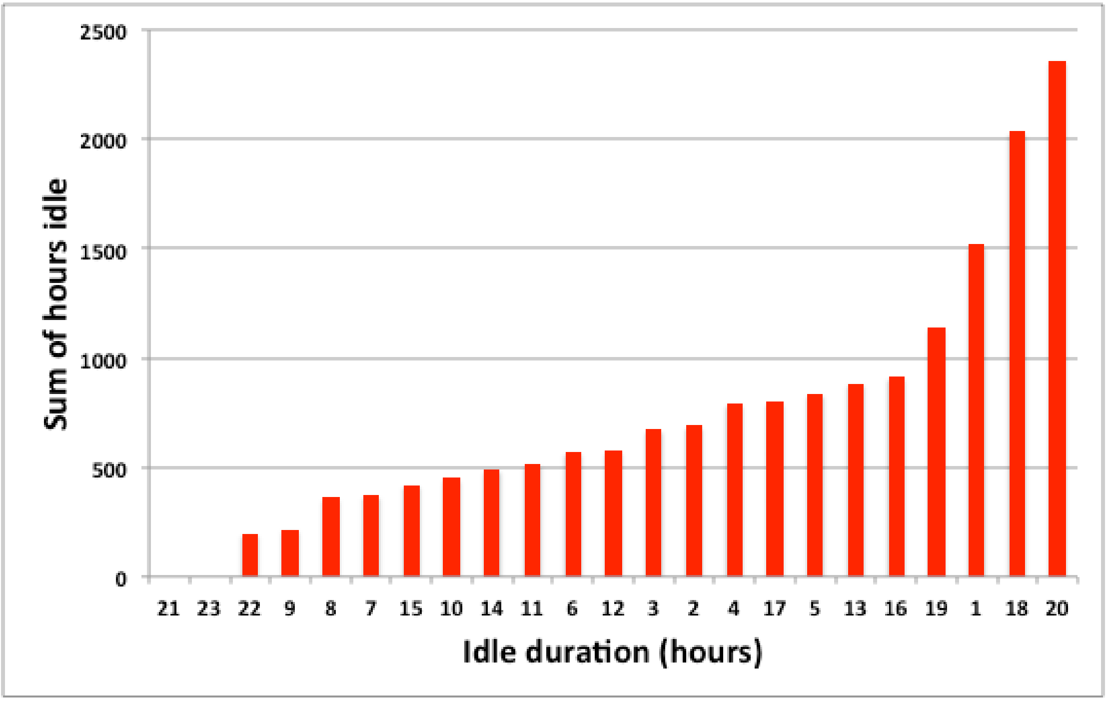
[2] If one steriliser is permanently switched off in addition to routine steriliser switch offs the maximum number of steriliser-hours available per day falls to about 58 (80-22) hours, given that the sterilisers will be off for at least 2 hours per night.

From the observed steriliser usage noted in Figures 8 to 10, calculations were made about how much difference in electricity and water use there would have been if a new policy had been introduced, of switching the steriliser off instead of idling when no loads were waiting. The break-even point occurred at less than two hours of idle time (see 7.2 Introduction).

The sterilisers were idle on 3,343 separate occasions for the total of 16,788 hours. When idle, the number of separate occasions the sterilisers were idle for two hours or less was 1,862 (56%), and greater than two hours on 1,481 (44%). If such a policy had been in place the sterilisers would have to be turned back on again within two hours on more than half the occasions. Since there were four sterilisers and there were 1,862 separate occasions of idle periods less than two hours per day for the year, *each* steriliser would have to be turned back on again just over once/day (i.e. 1,862/(365x4 =1.3)).

The sum of idle hours when the sterilisers were idle for two hours or less was 2,207 (13.1%) hours and when idle for more than two hours was 14,596 (86.9%) hours. Figure 11 indicates the sum of idle hours for each idle duration, showing that long idle periods form the majority of the total idle time.

Figure 11 Sum of hours idle for idle duration for the 4 sterilisers for one year.[1]



[1]The y-axis (sum of hours idle) is given in ascending numbers of hours. The x-axis is the idle duration (1-24 hours), NOT hour of the day. Thus, as noted on the x-axis (idle duration), the steriliser is never idle for 21 or 23 hours and is idle for 20 hours for the longest duration (i.e. the greatest sum of idle hours) over the year.

To find the difference in electricity and water use there would have been with the 'switch off' policy the sum of hours when the sterilisers were idling more than two hours was deducted. Given that the steriliser electricity and water use per idle hour was 5.3 kWh and 81 litres respectively, the savings from such an approach would be 65,662 kWh and 1,003,509 litres per year. From Chapter 6 it was known that the four sterilisers used approximately 40% of their electricity and 21% of their water whilst idle. Thus, the overall savings for four sterilisers with this switch-off policy as a percentage of total electricity use would have been approximately 65.7/255.6 MWh (26%) and 1,003/7,560 kilolitres (13%).

An alternative approach would be to switch off sterilisers during periods of low demand. From 10 a.m. onwards it was infrequent for all four sterilisers to be simultaneously active. A switch-off policy of one steriliser from 10 a.m. onwards would lead to delaying some loads until later in the day on approximately 1/10 week days and 1/1,000 weekend days, but would save 12 hours of idle steriliser electricity and water consumption per day, equating to 23,214 kWh and 354,780 litres per annum.

Another opportunity would be to switch off a second steriliser from midnight. This would have saved 1,252 idle steriliser hours per annum, or 6.6 MWh and 101 kilolitres. These combined switch-offs would thus have saved 29.9 MWh and 456 kilolitres of water. The potential saving for four sterilisers was approximately 29.9/255.6 MWh (12%) and 456/7,560 kilolitres (6%); half as much as the first switch-off strategy.

7.6 DISCUSSION

Analyses of the use of a hospital’s four sterilisers for one year identified potential savings of electricity and water. The sterilisers were idle for almost half of the total hours for the year, longer than they were active, and they were off for only 15% of the time. Steriliser idling for 12 hours or longer accounted for half of the total idle duration, and two or more sterilisers were idle for almost 70% of the total hours.

Opportunities were identified to improve the efficiency of steriliser use, suggesting two switch-off strategies which could lead to large environmental savings. The first strategy to switch off sterilisers when idle, would save 26% of total steriliser electricity use and 13% of the water. An alternative strategy is to always switch off one steriliser off from 10 a.m. and a second one off from midnight leading to electricity and water savings approximately half that of the first strategy. The average 4-person household in Melbourne, Australia has an annual usage of 6.6 MWh of electricity (158) and 220 kilolitres of water (187). The first strategy of switching off when idle is equivalent to an electricity switch off of 10 households and a water switch off of 4 households. These methods examining how hospital staff use sterilisers could be applied to all hospitals.

This observational study has limitations. Steriliser active time was overestimated since if a cycle occurred during any part of an hour it was counted as an active hour, and because all steriliser cycles were less than one hour (i.e. idle time is likely greater). No account was made for failed cycles, cleaning and validation although from hospital records and anecdotally these periods were limited. Other aspects of the switch-off policies other than electricity and water savings were not considered.

However, switching steam sterilisers on and off up to several times per day depending upon the switch-off strategy is unlikely to impede correct functioning.

Concerns are recognised regarding the timely completion of steriliser cycles caused by switch off strategies. A Bowie Dick cycle is required to be once daily for any steriliser that is active for that day(139). A Warm Up cycle is required prior to a standard 134 °C cycle whenever a steriliser is brought out of deep sleep (switched on) and when a steriliser has been idle for two or more hours. Switch-on requires an extra 15 minutes of pre-Warm Up prior to the Warm Up. Discussions with CSSD staff suggest that they already do a ‘sleeping steriliser’ pre-Warm Up while they wrap items for sterilisation, leading to minimal delays. Other possible concerns about the effects of steriliser switch-off on CSSD staff workflow are beyond the scope of this study.

This study’s specific findings may not be generalisable to all hospitals. For example, hospitals catering only to elective patients may already switch off after hours. By having access to the timing of all hospital steriliser cycles and using relatively straightforward computer software one could identify potential steriliser switch off periods. Any hospital using a similar system of quality assurance could conduct a similar analysis.

Steam will remain as the most common mode to sterilise reusable surgical equipment for the foreseeable future as it is reliably microbicidal and sporicidal, and rapid(182). Yet steam is also highly energy and water consumptive, which can be mitigated both by how a steriliser is constructed and how hospital staff use it. This study provides a method for hospital staff to analyse their steriliser activity and efficiency. Others may find simple opportunities to switch off sterilisers as occurred as a result of this study. Such scenarios do not require any financial outlays and can have considerable immediate financial and environmental returns. These methods could be applied elsewhere within hospitals (e.g. an operating room’s air conditioning and ventilation or a CT scanner). An idle steriliser is, put simply, inefficient, and a switch off could be rewarding.

7.7 CONCLUSION

This study concludes the thesis section examining ‘Reuse’. Chapter 4 asked why some surgical items (metalware) are labelled single use or reusable in the first place. Chapter 5 was a life cycle assessment comparing reusable with single use central venous catheter insertion kits, finding that steam sterilisation was the major contribution to the ‘carbon footprint’ of the reusable kit.

Chapters 6 and 7 arose out of concern that the foundations to process inputs for steam sterilisation for life cycle assessments of reusable metalware may be imprecise. Chapter 6 measured the electricity and water use of a hospital steam steriliser and identified possible productivity and efficiency improvements. This chapter complements Chapter 6 by examining how hospital staff use a group of steam sterilisers. The sterilisers were idle for more than half of the year and idle periods were often long, indicating that it would be possible to switch off at least one and sometimes two of the sterilisers. As a result of these steam steriliser studies hospital staff have rotated off one steriliser continuously, with further efficiency changes underway. Perhaps more importantly, the methods used in this study could be used in many hospitals to achieve considerable steriliser efficiency gains for minimal outlays.

CHAPTER 8: RECYCLE

A SURVEY OF ANAESTHETISTS' VIEWS OF RECYCLING

8.1 BACKGROUND

The focus of Chapters 8 and 9 moves from Reuse to Recycle. Within the operating room (OR) and intensive care unit (ICU) there are many items that one could reduce the usage of, or reuse. Chapters 3 to 7 have detailed several examples of such reducing and reusing. There are many other OR and ICU items for which Reduce and Reuse is unfeasible, at least in developed world settings. Just a few examples of non-reusable items include: (i) the plastic wrap that is used to enclose instruments to be sterilised, as the wear and tear from sterilisation leads to deterioration of such plastic, (ii) all cardboard and paper products, and (iii) used plastic intravenous fluid bags. Many non-reusable OR and ICU items could, however be recycled.

In the majority of circumstances it is environmentally beneficial to recycle, i.e. less energy and other resources are required to recycle an item rather than sourcing it from new material(25, 195). If recyclables must be transported long distances this reduces any environmental benefits. Recycling of more 'energy dense' items has greater energy (and potentially CO_2 emissions) benefits per unit mass. Thus, recycling aluminium and steel has greater environmental benefits per kg than recycling plastics and finally paper and cardboard when compared with using new items made from such materials. There may be other reasons to recycle beyond reducing the environmental footprint, such as conserving resources or imprecise feelings of 'doing good', and these factors may have greater sway on an individual's decision to recycle(97).

Prior to commencing any OR and ICU recycling programs it is integral to examine whether it is feasible to recycle, what can be recycled, and how much could be recycled. Feasibility investigates not only whether it is possible to recycle given busy OR and ICU environments, but whether staff attitudes to recycling are problematic or supportive and what staff see as opportunities and barriers to recycling. This chapter examines behavioural factors that influence the likelihood of successful recycling.

Chapter 9 examines what could be recycled in the OR and ICU, and waste audits pre- and post-recycling programs in the OR and ICU.

While an interest in the environment in their personal lives has been found to increase the likelihood that individuals would recycle at the hospital, often environmentally sustainable personal behaviours are not carried into the workplace(49, 96). Topf examined staff indifference to unsustainable hospital practices(97), suggesting that hospital environments encourage environmental ‘numbness’, and elicit a range of coping mechanisms including denial that unsustainable behaviour is occurring; overly critical thinking that may prevent change; myths that green practices and buildings are prohibitively expensive; temporal justification (i.e. staff being too busy to plan for long term goals); and the so-called ‘moral offset’ – “I’m doing enough good just being a doctor/nurse”(97).

Group coping mechanisms include diffusion of responsibility (someone else will solve the problem) and ‘groupthink’ (the illusion of unanimity due to the leader’s influence)(97). By supporting employees to make ethical decisions that align with their own values, they are more likely to take action to address these concerns(98). There has been very little research within healthcare about which of these psychological factors are the most important to address in order to encourage sustainable practices and minimal understanding of patients’ views of healthcare sustainability(97).

There is evidence from psychological studies that there may not be a strong positive correlation between those who recycle and those who also reduce and reuse(131). Recycling is a very obvious activity that is often observed by other staff members; whilst reducing or reusing may be inconspicuous (e.g. one may be unaware that a drug tray is reused after thermal disinfection rather than single use). Such differences may explain why recycling is avidly approached by groups of staff, whilst reducing and reusing is less enthusiastically welcomed(131).

This chapter examines anaesthetists’ views of OR recycling. An appreciable proportion of hospital waste stems from the OR(95). Further, anaesthetists form a considerable ‘bloc’ of OR doctors who are involved with waste generation and could have a leadership role in recycling. Whilst a survey of all hospital staff in many hospitals would be ideal, such a survey would be challenging to conduct across multiple craft groups (medical residents to consultants, nurses, theatre technicians), and consequently could have a lower response rate. A survey of intensive care unit doctors would also be useful, but was precluded by various constraints.

This chapter is based upon the article: ‘A survey of anesthesiologists’ views of operating room recycling’ by McGain F, White S, Mossenson S, Kayak E, Story D, Anaesthesia and Analgesia 2012;114(5):1049-5.

8.2 INTRODUCTION

Financial and environmental concerns are stimulating interest in hospital waste management and recycling programs(32, 66, 95, 117, 118, 120, 196). Healthcare generates enormous quantities of waste. On any given day of the year, United States hospital staff will add to landfill more than 6,000 tons of rubbish(197). Twenty to thirty percent of all hospital waste has been shown to arise from operating rooms (ORs)(95) with at least 40% of this waste shown to be potentially recyclable(32) and 25% likely to be of anaesthetic origin(119). Clinical (infectious) waste from hospital patients can vary from 0.4 kg/patient/day in Germany to 5.5 kg/patient/day in the UK and correspondingly, hospital recycling amounts are likely to vary greatly within both hospitals and nations, likely due to variable rates of packaging and reusables(96).

There are multiple published studies of operating room recycling in general, including several led by anaesthetists(129, 130, 198) Surveys of hospital staff’s attitudes to medical waste and recycling have found that an interest in recycling and recycling at home predicts a desire to recycle at work(96, 199, 200). Anecdotally, however, many anaesthetists appear to be unaware of OR recycling programs or consider them ineffective.

Anaesthetists’ attitudes to recycling are important to address future improvements in OR recycling programs given their central role within the operating service. We surveyed views of recycling held by anaesthetists in Australia, New Zealand (ANZ) and England in either regional or metropolitan and public or private practice.

8.3 RESEARCH QUESTIONS

1. Is operating room recycling standard practice in Australia, New Zealand and the United Kingdom?

2. Are anaesthetists willing to increase recycling within the operating suite?
3. In the opinion of anaesthetists what factors enable and impede the introduction of operating room recycling in an operating suite?

8.4 METHODS

Prospective approval for this survey was obtained via the Human Research Ethics Committee at Western Health, Melbourne, Australia (Low Risk Research Panel No: 2009. L11). Written informed consent was waived by the ethics committee as consent was implied if the survey was returned. The survey was piloted with ten anaesthetic staff of the Western and Austin Hospitals in Melbourne, Australia.

In this 11-question survey the attitudes of anaesthetists to operating room waste recycling was examined. The 11-questions are given at the end of Methods. A guide to survey research in anaesthesia was followed(201). Ten questions elicited closed responses, while the final question was an open one allowing free text. Of the closed questions, four related to demographics, a further three elicited a response on an agreement scale of the Likert type and two invited a 'one of' response. The Likert Scale had five points, strongly agree-agree-uncertain-disagree-strongly disagree. Anaesthetists defined their type of hospital practice: including metropolitan (large city) or regional. The anaesthetic practice was also divided into predominantly public hospital (covered by government funded universal health care often with academic affiliation) or private (fee paying patients, usually with no academic affiliation).

Respondents were asked what were the barriers to recycling in operating rooms, which included 'staff attitudes'. 'Staff' was undefined, although in a pilot study anaesthetists understood this to mean potentially all people working within the OR. Anaesthetists were asked if they themselves were willing to provide their own money and time to increase OR waste recycling. In none of the jurisdictions included in the survey was OR waste recycling mandatory.

A web survey was then developed using Survey Monkey (Portland, Oregon, USA). The survey was emailed to 500 randomly selected Fellows of the Australian and New Zealand College of Anaesthetists (ANZCA) in late 2009 via the ANZCA Trials Group. This sample size was calculated by ANZCA staff and was based on the following assumptions: the acceptable margin of error (amount of error that is inherent from random sampling or the anticipated precision of the estimate given the sample size) is +/- 5% for a proportion, ANZCA has 4,500 Fellows(202), the response rate is 60% and the response distribution (the proportion that agree: disagree) is 50:50(203).

Unlike ANZCA, the Royal College of Anaesthetists (RCoA) in England does not have an organized service that can send surveys to a sample of College Fellows. Therefore requests to complete the survey were also emailed out to administration staff at all 168 Anaesthetic Departments of English National Health Service (NHS) hospitals (but not to private hospitals) asking that the email be sent on to all consultant anaesthetists in each department (approximately 5,000 consultants)(204) to complete the web survey. Reminder emails were sent to all Fellows in Australia and New Zealand (but not England) four and ten weeks later in late 2009. Overall demographic survey data on the Fellows of ANZCA(202) and the RCoA(204) were obtained.

Data are expressed as absolute values and proportions with 95% confidence intervals for the proportions. Statistical analysis was performed with access to Vassar Stats-Website for Statistical Computation using Wilson's method to calculate the 95% confidence intervals for the proportions (Vassar College, New York, U.S.A.)(205) and two statistical source papers noted on this website.(206, 207). Data are reported as the absolute number, then percentage and 95% CI as recommended by the American College of Physicians(208).

Survey Questionnaire

Question One
I am:
1. Female, <45 years of age
2. Female, >45 years of age
3. Male, <45 years of age
4. Male, >45 years of age

Question Two
I work most often in (SELECT ONE):
1. Australia/New Zealand
2.The United Kingdom

Question Three
I work most often in a (SELECT ONE):
1. Metropolitan area.
2. Regional area.

Question Four
I work most often in a (SELECT ONE):
1. Public hospital
2. Private hospital

Question Five
I recycle at home.
Strongly disagree-disagree-uncertain-agree-strongly agree

Question Six
Anaesthesia waste is recycled in the operating rooms I usually work in
Strongly disagree-disagree-uncertain-agree-strongly agree

Question Seven
I would like to recycle anaesthesia waste.
Strongly disagree-disagree-uncertain-agree-strongly agree

Question Eight
Which ONE or MORE are barriers to recycling in operating rooms (select AS MANY as applicable):
1. Staff attitudes
2. Cost
3. Inadequate information
4. Safety
5. Time
6. Lack of space
7. Lack of recycling facilities
8. None of these (Go to Q. Ten)

Question Nine
Which ONE of the following is the greatest barrier to recycling? (select ONE only)
1. Staff attitudes
2. Cost
3. Inadequate information
4. Safety
5. Time
6. Lack of space
7. Lack of recycling facilities

Question Ten
To increase recycling in operating rooms I am willing to provide the following (select ONE or MORE):
1. Time to educate others
2. Time to educate myself
3. Funds to educate others
4. Funds to educate myself
5. None of the above

Question Eleven
Do you have any additional comments about recycling in operating rooms or this survey?

8.5 RESULTS

This survey was completed by 780 anaesthetists. Of 500 ANZCA Fellows surveyed, 210 (41%) responded. In England 570 Fellows responded from the 168 Anaesthetic Departments. The response rate in England is unclear because the survey was sent to Departmental administrators and the number of consultants who then received the survey is unknown. In the unlikely event, however, that every consultant in England received the survey the response rate would be 11%. The confidence interval (CI) was +/- 3.2%, the CI was +/- 6.6% for ANZ, and the English CI was +/- 3.8%(203). Thus, for example, if this survey was performed a very large number of times, on 95% of occasions the results for the overall group would fall within 3.2% of the results of the survey. Respondent age and gender were similar in ANZ and England (Table 14) and similar to the age and gender profiles for the two Colleges (ANZCA and RCoA). There were, however, no available data of the overall proportion of Anaesthesia consultants in England in private or regional practice.

Table 14 Demographics of Survey Respondents and Entire Workforce for Australia and New Zealand, and England.

Demographic	ANZ Respondents n = 210	ANZCA Survey(202) N = 4509	English Respondents n = 570	RCOA Survey(204) N=5044
Male, n (%)	144 (68%) 95% CI: 62 to 74%	3287 (73%)	360 (63%) 95% CI: 60 to 68%	3589 (71%)
Age >45 years, n (%)	107 (51%) 95% CI: 44 to 57%	2416 (54%)	286 (50%) 95% CI: 47 to 54%)	2715 (54%)
Regional Practice, n (%)	51 (24%) 95% CI: 19 to 30%	1,195/4,437 Respondents (27%)	295 (52%) 95% CI: 48 to 56%	Unknown
Private Practice, n (%)	93 (44%) 95% CI: 38 to 51%	679/1,519 Respondents (45%)	Survey of public practice only	Unknown

Of the 780 survey respondents, the first 10 questions (see Methods above) were each answered by at least 98% of respondents. There was a strong agreement in the responses overall and across different countries and place of practice on questions on recycling practice. For anaesthetists overall and across England, Australia and New Zealand, in regional and metropolitan areas and in both public and private hospitals: 1. more than 90% recycled at home, 2. more than 90% wished to recycle at work, but 3. only 11% agreed or strongly agreed that OR recycling of anaesthetic waste occurred (Table 15).

When asked what was the greatest barrier to recycling the overall responses in descending order were: 1. inadequate recycling facilities 381 (49%), 2. staff attitudes 133 (17%), and 3. inadequate information on how to recycle 121 (16%). These three barriers were the greatest impediments to recycling across all countries and workplaces. Time, safety, inadequate recycling space and cost were each thought by less than 5% of respondents to be the greatest barrier to recycling. The majority of anaesthetists practicing in all areas were willing to provide time to learn 571 (73%)

and time to educate others 435 (56%), (but would not contribute their own money) to increase recycling practices within operating rooms.

Table 15 Recycling at home and in the operating suite.

Question No.	Response-overall, by country, region and workplace				
	Overall N=780	**England N=570**	**ANZ N=210**	**Regional N=340**	**Private N=95**
Q. 5 "I recycle at home" Agreed or Strongly Agreed. N, (Proportion), 95% CI	**744 (95%) 94 to 97%**	541(95%) 93 to 97%	198 (94%) 90 to 97%	326 (96%) 93 to 98%	90 (95%) 88 to 98%
Q. 6 "Operating suite waste is recycled in the operating suites I work in most often" Agreed or Strongly Agreed. N, (Proportion), 95% CI	**87 (11%) 9 to 14%**	66 (12%) 9 to 15%	21 (10%) 7 to 15%	36 (11%) 8 to 14%	9 (10%) 5 to 17%
Q. 7 "I would like to recycle operating suite waste" Agreed or Strongly Agreed. N, (Proportion), 95% CI	**725 (93%) 91 to 95%**	530 (93%) 91 to 95%	193 (92%) 87 to 95%	314 (92%) 88 to 94%	88 (93%) 87 to 97%

The final question (Q. 11) was answered by 215 (28%) and was open-ended: "Do you have any additional comments regarding operating room recycling?" The most common themes to emerge from answers to the last question were:

- 47 wrote that recycling needed to be routine,
- 47 were concerned by recycling safety issues such as inappropriate disposal / mixing of items (i.e. contamination of landfill waste with infectious waste),
- 40 felt that the hospital administration was unconcerned by the non-existance of OR recycling,
- 28 considered that the environmental effects of single-use devices were more important than recycling,
- 24 noted that recycling needed to be driven by the 'top down' hospital hierarchy, and 16 wrote that waste minimization was more meaningful than recycling.

8.6 DISCUSSION

Most anaesthetists who responded to this survey consider operating room recycling to be important, regardless of country (England, or Australia and New Zealand), location (regional or metropolitan) or practice (public or private). Only one in nine respondents, however, agreed or strongly agreed that recycling occurred in their operating rooms A significant majority of anaesthetists would be prepared to commit time, to OR recycling and the education of others to do so, but few would commit their own money.

Survey respondents felt that there were three major barriers preventing OR recycling from becoming more widespread: (1) inadequate recycling facilities, (2) inadequate information on how to recycle, and (3) staff attitudes. In contrast cost, lack of time, lack of space, and safety issues were thought to be relatively insignificant barriers to recycling. In free text responses many felt that greater support for OR recycling was needed from hospital administration and that recycling should be routine, although safety and infection control issues needed to be addressed.

There are several limitations to this email survey, which had a response rate of 41% for Australia and New Zealand, but unknown for England (possibly as low as 11%). The question arises as to whether those who did not respond differ from those who did. Since the enthusiasm for waste recycling was very high (about 95%) it is possible that anaesthetists keen on recycling responded while those less enthused did not respond. Both the ANZ and English samples have similar age and gender profile to their respective Colleges(202, 204). There are no data for the proportion of the total English workforce employed in private or regional practice, but for ANZ such proportions for the entire workforce were similar to those for the respondents to our surveys(201). Despite the response rates and possible non-response bias, because 780 anaesthetists responded the 95% confidence intervals for the proportions are narrow: +/- 3.2%. The overall number of respondents gives fairly precise proportions(203).

Previous studies have examined hospital staff's attitudes to waste management and recycling(199, 200). Tudor et al used the theory of planned behaviour(209) to link intended behaviour and actions of staff in healthcare waste management in the Cornwall National Health Service (NHS), United Kingdom (UK)(96). The more staff believed waste to be a major work issue and were encouraged to conserve materials the greater the potential for them to perform sustainable waste management actions(200). Tudor et al also found, however, that the actual waste management actions of employees in healthcare often bears little resemblance to their stated intentions due to perceived attitudes and the behaviour of others (particularly their superiors) and lack of behavioural control(200). Staff need to understand the relevant environmental and financial benefits from waste recycling if they are to engage in the process.

While many anaesthetists may have the intent to recycle, and despite the work of groups to improve recycling rates such as the UK National Health Service Sustainable Development Unit (SDU) and the U.S. based Healthcare Without Harm, the volume of healthcare waste, including operating room waste, continues to rise unabated. We highlight the view held by some anaesthetists in the free text (Q.11) of our survey that while recycling is important the more important point is minimizing the amount of waste produced through actions such as reducing packaging and single use devices. The UK’s SDU has found large opportunities to improve the financial and environmental sustainability of healthcare by reducing packaging(16).

Few anaesthetists would commit their own money to OR recycling, probably because they would never get such money back. It is possible that if recycling led to financial savings, such savings could be shared amongst those who committed. Normalisation of financial commitment to sustainability activities within healthcare such as recycling, could lead to collective behaviour change.

This is a focused and therefore limited survey of OR waste recycling only. OR recycling can often save rather than cost money and can significantly reduce the environmental effects of waste(197). Future surveys of operating room recycling could include the types of recycling available (electronics and metals, different plastics), clarifying why some staff are resistant to recycling, identifying which staff would be most influential in improving recycling rates, and examining the effects of improving recycling facilities and staff education. Examples of further surveys of the umbrella topic of operating room sustainability include: 1. what and why certain items are single use versus reusable (laryngoscopes, laryngeal masks, anaesthetic circuits), 2. exploring why there is such variation by different medical craft groups in the use single use or reusable equipment such as gowns and drapes, and 3. an understanding of the environmental effects of anaesthetic agents, and indeed all drugs and devices used by anaesthetists.

These findings suggest that anaesthetists' views may not be a barrier and efforts to improve operating room recycling should be aimed elsewhere, for example at improved recycling facilities. Importantly, providing evidence that increasing recycling facilities in operating rooms can be financially and environmentally successful (before-after audits) will be integral to ongoing recycling. Excellent examples and case studies of operating rooms that are transitioning to improved sustainability are available at such websites as 'Greening the OR'(32). A combination of education, encouragement and leadership from senior anaesthetists and hospital staff could lead to significant operating room recycling becoming the norm.

8.7 CONCLUSION

This chapter has surveyed anaesthetists' views of recycling in order to explore whether it was feasible to recycle within the OR. That is, would the majority of a significant group of OR doctors consider that OR recycling was useful and pragmatic, and would they assist in recycling? Recycling was occurring in few ORs, but a significant majority of anaesthetists would be prepared to recycle. The major barriers to recycling were felt to be inadequate recycling facilities and information on how to recycle, and resistant staff attitudes. Interestingly cost, time, space and safety were thought to be relatively insignificant barriers to recycling. Such information proved useful in the next phase of this PhD – introducing recycling programs to the OR and ICU and subsequently auditing such programs, detailed in Chapter 9. A focus was placed upon staff education on how to recycle, overcoming negative staff attitudes to recycling and providing adequate recycling facilities.

CHAPTER 9: RECYCLE
AUDITING OR AND ICU RECYCLING PROGRAMS

9.1 BACKGROUND

Chapters 8 and 9 explore recycling within the operating room (OR) and intensive care unit (ICU). Chapter 8 appraised the feasibility of recycling, i.e. whether hospital staff attitudes to recycling are problematic or supportive and what staff see as opportunities and barriers to recycling. Anaesthetists are an important cohort of doctors based in the operating room. A survey was performed of anaesthetists based in Australia, New Zealand and England, finding that: (i) recycling was occurring in few ORs, (ii) more than 90% of anaesthetists were prepared to recycle, and (iii) the major barriers were thought to be inadequate recycling facilities, information on how to recycle, and resistant staff attitudes.

After discussions with other staff about OR and ICU recycling that were predominantly supportive, recycling programs were begun in the OR and ICU. As a result of the survey in Chapter 8 a focus was placed upon staff education on how to recycle, overcoming negative staff attitudes to recycling, and providing adequate recycling facilities.

Chapter 9 examines what can be recycled, and how much could be recycled within the OR and ICU. The focus of this chapter is upon waste audits post-recycling programs in the OR and ICU. Prior to enrolment in this PhD the candidate undertook and published several audits of OR and ICU waste pre-recycling and clarified the composition of medical items that could potentially be recycled. These studies are summarised in the following paragraphs as they provide a useful background to the final post-recycling audits and the successes/failures of OR and ICU recycling:

1. McGain F, Clark M, Williams T, Wardlaw T. Recycling plastics from the operating suite. Anaesthesia and Intensive Care. 2008;36(6):913-4.
2. McGain F, Story D, Hendel SA. An audit of Intensive Care Unit recyclable waste. Anaesthesia 2009; 64 (12): 1299-1302.

3. McGain F, Hendel SA, Story D. An audit of potentially recyclable waste from anaesthetic practice. Anaesthesia and Intensive Care 2009; 37(5):820-823.

Prior to starting recycling within the OR and ICU there were several other concerns to address. Hospital infection control staff were involved from the beginning of the recycling programs. Only non-infectious items would be recycled, i.e. there would be diversion of non-infectious hospital waste to recycling. Clarification of the composition of medical items was achieved early with an associated pilot recycling program(130). Recycling of aluminium, steel, paper and cardboard was straightforward as these were readily identified as such by hospital staff. Unlike household plastics however, many medical plastic products are not identified with the international plastics coding classification number and triangle(210). Further, the national Australian advisory body on plastics, the Plastic and Chemical Industry Association, did not hold an inventory of medical plastics.

Anecdotally in Australia, general awareness of kerbside council recycling was thought to be poor. Perhaps potentially low rates of correct recycling could be due to the large number of different types of recyclables. Most recyclable items from the OR and ICU, however, were cardboard and paper, or varieties of plastics, potentially improving the likelihood of successful recycling.

Clarification of the different plastics used in common medical items was achieved by contacting the manufacturers and suppliers. Polypropylene, polyethylene and polyvinyl chloride (PVC) comprised the majority of the plastic types of items used(130). Knowledge of different plastic types is important for recyclers, particularly PVC, as this cannot be recycled with other plastics due to its markedly different melting temperature and physical characteristics (approximately 50% chlorine by mass)(211). As a result of this plastic identification a pilot recycling program was commenced in the OR(130), including novel recycling of medical PVC thereafter(212).

Waste audits were performed prior to recycling within the OR and ICU in 2008. The methods employed in both waste audits were identical to the post-recycling audits and are detailed under Methods (Section 9.4). The initial OR waste audit was focussed upon anaesthesia waste (defined as waste emanating from the anaesthetist’s trolley or the anaesthetic bay). For five days in the six-theatre hospital all OR waste was weighed and all anaesthesia waste was examined and categorised. Total OR waste was 357 kg (48% infectious waste and 52% general waste). Anaesthesia waste was 90 of the 357 kg of total OR waste with plastics forming almost half of the total mass. Of the 90 kg, 66kg was general waste of which 38 kg (60%) was recyclable. There was minimal contamination of general waste with infectious waste. Recycling of a significant proportion of anaesthesia waste was thus possible.

The 10-bedded ICU pre-recycling waste audit occurred over seven consecutive days(120). The total ICU waste for the week was 540 kg, representing 5% of total hospital waste. Of the 401 kg of ICU general waste, recyclables were 230 kg, being mainly plastics, cardboard and paper. Almost 60% of ICU general waste could be recycled with appropriate safeguards, education and training. There was minimal infectious waste cross-contamination. Unlike the OR waste audit where infectious waste formed almost half of all waste, only 25% of total ICU waste was infectious, indicating differences in waste makeup, inadequate waste separation by OR staff, or both(120).

Recycling programs were then embarked upon with subsequent auditing of the OR and ICU recycling. The audit of OR recycling examined all OR waste in detail rather than the more limited detailed audit of anaesthesia waste pre-recycling(119).

The remainder of this chapter is an expansion of the following publications:

1. Part A. OR waste post-recycling(213).

   McGain F, Jarosz KM, Nguyen M, Bates S, O’Shea K. Auditing Operating Room recycling: a management case report. Anesthesia and Analgesia Case Reports 2015 Aug 1;5(3):47-50.

2. Part B. ICU waste post-recycling(214).

   Kubicki M, McGain F, O’Shea K, Bates S. Auditing an ICU recycling program. Critical Care and Resuscitation. 2015 Jun;17(2):135-40.

Since the methods used are very similar in both studies these are truncated in Part B. Discussion of differences in the Results between the OR and ICU waste recycling programs occurs in the Conclusion.

PART A. OR WASTE POST-RECYCLING

9.2 INTRODUCTION

There is growing awareness of the effects of unsustainable practices within healthcare, including anaesthesia(32, 105, 117). Healthcare consumes large amounts of resources such as oil based products, energy and water and has a ‘carbon footprint’ (i.e. CO_2 emissions); e.g. the English National Health Service (NHS) is responsible for over 3% of England’s total CO_2 emissions(8). Hospital procurement is the purchase of all goods entering and exiting hospitals. Hospital procurement and waste disposal contributes more to CO_2 emissions than direct hospital energy consumption and transport to and from hospitals combined(8). ‘Waste’ forms a subset of procurement and represents 3% of the U.K.’s total CO_2 healthcare footprint – similar to food and catering(8).

Approximately 20% of hospital waste stems from the OR(95, 117, 215). Up to a quarter of this waste is generated primarily by anaesthestist.(119). Recycling of metals, plastics and paper and cardboard usually requires less energy than manufacturing new product(25), although this varies with location. Disposal of infectious waste is more expensive (and energy consuming) than general waste as infectious waste requires closer monitoring/regulation, often more distant transport, incineration and/or chemical treatment, and placement into prescribed, special landfill(95, 96). Correct infectious and other waste segregation by hospital staff is cost effective(215). Several studies have examined the recycling potential of hospital waste both generally(95, 96), and in operating rooms specifically(103, 117-119). Further, novel approaches to OR recycling have been reported(130, 216). There is strong support for OR recycling amongst anaesthestists in several countries surveyed to date(217). There is, however, a paucity of data regarding the effectiveness and financial feasibility of OR recycling programs.

In 2008, waste audits were performed in the OR and ICU at our hospital when no recycling was occurring. Recycling of plastics and cardboard/paper commenced thereafter. This study is a follow-up audit of OR and Day Procedure waste post-recycling which occurred over one continuous week.

9.3 RESEARCH QUESTIONS

1. What are the weights of OR general waste, infectious waste and recyclables and how does this compare with total hospital waste?

2. What is the weight of truly infectious OR waste within all waste and recycling streams?

3. What is the weight of OR recyclables remaining within the general and infectious waste?

4. What is the ratio of achieved OR recycling to the potential for further recycling?

5. What is the financial cost in Australian dollars of OR waste disposal and how does this compare to the pre-recycling audit(119)?

9.4 METHODS

A prospective audit was undertaken of all waste and recycling streams of the 6-theatre OR and Day Procedures Unit (DPU) at the 300-bed Footscray Hospital, a university-associated hospital in Melbourne, Australia. Approval for this study was obtained from the Western Health Low Risk Ethics Committee (HREC/11/WH/109, 13/12/2011). The audit methodology was based upon our previous audits(119, 120). Without notifying staff, the audit was performed for the second week of December 2012, a standard operating week. Only waste and recyclables within the OR and DPU area were examined. Total hospital waste data, the total number of operations and procedures in the week of the audit as well as the calendar years 2009 (pre-recycling) and 2012 were obtained. The number of patients having operations/procedures with infections requiring contact precautions was also noted, as treating such patients requires disposable gowns and gloves. Infectious waste bags from patients with infections requiring contact precautions were identified by the particular type of disposable gowns present in the bags.

Recycling was defined beforehand as: ‘total’, ‘potential’ and ‘achieved’ (actual). Total recycling consisted of all recyclables that were not considered infectious waste. ‘Potential recycling’ was defined as that which was acceptable to hospital staff and the recycling companies and excluded very small plastic pieces and items that recyclers were unable to take – those composed of multiple plastic types (e.g.

intravenous fluid giving sets) or deemed inappropriate (e.g. dirty suction catheters). The achieved recycling was that measured in the various recycling streams. The achieved to potential recycling was thought to be the ratio most indicative of the OR recycling program's progress.

In this follow up audit we examined both OR and DPU waste and recycling streams as we wished to examine the results of commencing recycling in two related areas that share the same waste and recycling disposal section of the hospital. Since the OR and DPU waste was processed in one hospital area it was impractical to separate the two sources (OR or DPU). All waste was measured for at least 5 hours each day for seven continuous days, but did not determine the waste from each individual procedure as this was not feasible. In 2009, there was no OR recycling and we audited only anaesthesia OR waste in detail(119). In 2010, a pilot OR recycling program commenced and evolved gradually to involve the DPU and other hospital areas over the years 2010-2011. Meetings and education sessions were held with the recyclers and hospital staff. Pilot 'OR plastic runs' were sent to the recyclers for confirmation of appropriateness and adherence to an older guideline(130).

Routine practice, after initiating the recycling program was to place general waste into green waste bags and infectious (clinical) waste into yellow waste bags. Recycling occurred in the following separated streams: 1. paper and cardboard (boxes, paper towels), 2. polypropylene (sterile surgical, 'blue' or 'green' wrap), 3. mixed plastics (plastic bottles and ampoules, clear wraps), 4. polyvinylchloride – PVC (intravenous fluid bags, oxygen masks and tubing) and 5. commingled items (i.e. unsorted tins, cans, plastic bottles). There was thus some overlap between commingled and mixed plastic recycling.

Recycling of cardboard and paper and surgical wrap was simple as these products were easily identifiable and limited in variability. Recycling of mixed plastics and PVC required greater education and preparation. Some plastics were deemed by the affiliated recycling companies and hospital staff to be non-recyclable: i.e. inappropriate appearance (urine), problematic 'syringes' (despite being needleless) or PVC suction tubing ('sputum'), or too difficult to recycle since they were not the desired plastic (e.g. polystyrene, polyurethane). Nursing staff have been integral to the recycling program since its inception and coordinated new staff's involvement, remaining vigilant to recycling contamination.

For the recycling of mixed plastics and surgical (blue or green) wrap, in each of the ORs and the DPU, brackets were installed onto which plastic liners (bags) were placed to accommodate different recycling streams. Bins for holding paper and cardboard were also installed. At the completion of each operation the bags containing general and infectious waste, and the plastics and paper and cardboard recycling streams, were emptied into larger bins at the periphery of the operating suite. PVC plastic was removed at the end of each operation with the patient and taken to Recovery, otherwise known as the post anaesthesia care unit (PACU), where it was placed into a large PVC bin. Hospital environmental services staff took the recyclables thereafter to a central region where the recyclables were kept prior to removal by recycling companies.

All plastics were weighed, with identification of all plastics and potential recyclable plastics. Paper (including paper towels) was weighed as it was found, i.e. with varying moisture content. Glass drug ampoules have rubber and aluminum stoppers, which preclude them from currently being recycled. The majority of the cardboard (large boxes) was separated at the OR and DPU front door, was subsequently compacted, and excluded from this study. Since we commenced hospital cardboard recycling after our first OR waste audit and we were interested in the volumes of cardboard recycling, we examined just one day of this cardboard ‘waste’ to give an indication of the extra cardboard that was not entering the OR and DPU area, but which ultimately stemmed from the OR and DPU. Small cardboard boxes and paper that enters the OR and DPU area are recycled together at our hospital. This cardboard and paper is placed into OR and DPU paper and cardboard recycling bins (not compacted, i.e. more expensive to process) and was audited.

Direct and indirect financial costs for disposal of waste/recycling streams were obtained. Neither labour costs nor the purchase costs of bins were measured. Hospital data were examined for the average number of operations and procedures per day and the average operation and procedure time. The financial costs for waste and recycling included, as applicable, disposal cost/kg, the price of bags, compactor costs, collection and transport fees, and bin hire (i.e. bins not owned by the hospital). Only general waste and cardboard were compacted. Paper and cardboard was recycled in reusable bins and PVC recycling was not bagged (i.e. no purchasing of bags was required for these recycling streams). All reusable bin weights were subtracted from the reported weights.

The bag cost/kg waste was calculated as the cost per bag divided by the average amount (in kg) found in the bags of an average of 20 bags for each waste stream. Recycling costs differed markedly according to the contracted recycler. Polypropylene, mixed plastics and PVC were collected without charge, the only costs being bags for polypropylene and mixed plastics. Recycling bins for these streams had been purchased or awarded from a previous grant. Paper and cardboard and commingled bin disposal costs included collection and transport fees and bin hire.

Infectious waste included materials contaminated with blood and other infectious body fluids(218). Researchers wore protective gloves, glasses and scrubs. Researchers sorted materials from each respective bin and bag into infectious, general and recyclable waste to assess the compliance of the recycling program. Non-recyclable waste and recyclables were subsequently classified and weighed. A conservative approach was taken to the potential for recycling, rejecting all items that contained body fluids. Any infectious fluids (such as blood products) were not weighed separately, but included as infectious waste. Non-infectious fluids found in the waste (e.g. crystalloids) were poured into buckets and weighed, forming a subcategory of general waste. Plastic bags that contained non-infectious fluids were considered to be ‘potential recycling’ (not achieved).

Waste was weighed on digital scales, correct to the nearest 10 grams and rounded to the nearest kilogram at the end of the week. Sharps bins were not examined. In our hospital most operations and procedures were performed with staff wearing sterile, reusable surgical gowns and drapes. Select operations (particularly orthopaedic) were performed entirely with single use surgical gowns and drapes. Approximating the proportion of total waste due to these single use gowns and drapes was thought useful. These single use items were thus weighed for one weekday only as an approximate proportion of total waste. This study presents purely descriptive data (weights and ratios of waste to recyclables) with no inferential statistical analyses.

A currency converter (152) on the 17/6/2015 was used to convert AUD$1 to USD$0.77.

9.5 RESULTS

For the one-week audit, the total mass of the six-theatre OR and DPU waste was 1,265 kg from 237 procedures. General waste was 570 kg (45%), infectious waste was 410 kg (32%) and 285 kg (23%) were recyclables (Table 16). Financial costs for the different waste streams are given in Table 17. The proportion of total hospital general and infectious waste arising from the OR and DPU was 10% (1,265 of 12,415 kg). Of the 285 kg of achieved recycling, there was less than 1kg of contamination with general waste and no infectious waste contamination.

Table 16 Waste and recycling stream masses for the one-week audit.

Waste type	Mass (kg) (total = 1,265)	**(% total)** (% each stream)
General	**570 kg**	**(45% total)**
General	321	(56%)
Infectious	6	(1%)
Recyclable	243	(43%)
Infectious	**410 kg**	**(32% total)**
General	76	(19%)
Infectious	283	(69%)
Recyclable	51	(12%)
Recyclables	**285 kg**	**(23% total)**
Paper and cardboard	66	(23%)
Plastic-polypropylene	146	(51%)
Plastic-mixed	43	(15%)
Plastic-PVC	23	(8%)
Commingled	7	(2%)

Table 17 Costs of waste and recycling disposal in AUD$.

Type of waste or recycling	Disposal charge per kg	Bag cost per kg	Compaction, collection, and transport	Bin hire	Total cost per kg AUD$
General waste	$0.14	$0.03	$0.06	$0.01	**$0.24**
Infectious waste	$0.90	$0.08	Nil	Nil	**$0.98**
Paper and cardboard	Nil	Nil	$0.53	$0.04	**$0.57**
Plastic-polypropylene	Nil	$0.10	Nil	Nil	**$0.10**
Plastic-mixed	Nil	$0.22	Nil	Nil	**$0.22**
Plastic-PVC	Nil	Nil	Nil	Nil	**$0.00**
Commingled (plastic, tins)	Nil	Nil	$0.71	$0.05	**$0.76**

In the general waste stream, the 243 kg of recyclables consisted of: 97 kg paper and cardboard, 141 kg plastics, 2 kg aluminium and 3 kg glass. The 141 kg plastics were: 55 kg polyethylene, 30 kg polypropylene, 14 kg polypropylene and polyethylene copolymers, 32 kg PVC and 10 kg other (non-recyclable) plastics. Plastics that were inappropriate or too difficult to recycle were then excluded from further analyses, including conservatively half of the PVC, leaving 101 kg of possibly recyclable plastics. On one weekday only the weight of single use surgical gowns and drapes was 4 kg in the general waste stream.

In the infectious waste bags, 31% was not infectious (Table 17), indicating that truly infectious waste was approximately 23% of all waste. Recyclables found in the infectious waste stream were 16 kg paper and cardboard, 34 kg of plastics and 1 kg aluminium and glass. The plastics included 10 kg polyethylene, 5 kg polypropylene, 2 kg polypropylene and polyethylene copolymers, 8 kg PVC and 9 kg of other plastics. Potentially recyclable plastics (conservatively half of the PVC) thus totalled 19 kg. On one weekday only, the weight of single use infectious surgical gowns and drapes was 10 kg.

The potential plastic recycling amount was thus the sum of the 212 kg achieved in the recycling stream, 101 kg in the general waste and 19 kg in the infectious waste (total of 332 kg), indicating a plastic recycling rate of 212 kg achieved of 332 kg potential (64%). The paper and cardboard recycling rate was 66 kg achieved of 178 kg potential (37%), and there was 7 kg of commingled recycling. The overall achieved to potential recycling rate was: 285/ (332+178+7) = 285/517 kg (55%).

For the week of the audit, 237 procedures were performed (167 in the OR and 70 in the DPU). In 2012, there were 9,868 procedures performed – 6,735 in the OR and 3,133 in the DPU, i.e. 189 per week. The average number of operations and procedures respectively per day were: 27.2 and 12.1 in 2009, and 27.1 and 12.7 in 2012. The average duration per operation and procedure was respectively 89 and 32 minutes in 2009, and 79 and 34 minutes in 2012 (with similar durations for 2010 and 2011).

In the audit week, 10 patients had procedures requiring contact precautions, while 371 patients had procedures requiring contact precautions in 2012 (approximately 7 per week). For one day the weight of cardboard separated at the front of the OR and DPU (not included in this audit) was 49kg. Three sharps needles were found, all located in the infectious waste stream (rather than within the sharps bins). There were 13.1 kg of non-infectious fluids (predominately crystalloids) found in the general (10.7 kg) and infectious (2.4 kg) waste streams, with minimal fluids in the recycling streams.

The overall financial costs per kg of different waste streams are detailed in Table 17. For general and infectious waste the majority of the costs were the fees charged per kg of waste. For recyclables the majority of the costs were for fixed fees such as collection and transport, although for polypropylene, mixed plastics and PVC the recyclers did not charge.

9.6 DISCUSSION

This study was an audit of a hospital’s six-theatre OR and Day Procedure Unit waste for one continuous week in the setting of routine recycling. Of the approximately 1.3 tonnes of waste per week (representing 8% of all hospital waste), almost a quarter was being recycled. Infectious waste was 410 kg (32%) of all waste, although only 283 kg was truly infectious. The achieved recycling had no infectious contamination and less than 1% contamination with general waste. The achieved recycling represented more than half (55%) of what was potential (realistic). Overall, recycling was financially cost neutral compared with no recycling.

Factors which have increased the amount of waste examined in this current study compared with the prior study(119) of OR waste alone are the inclusion of day procedure waste (one third of the total number), 5% more procedures, and a greater use of single use drapes and gowns (60 kg of waste per week). The proportion of all OR waste that was infectious in the pre-recycling OR audit was 48%, suggesting that more than 50% of ‘infectious’ waste was not truly infectious. While the above factors make direct comparisons uncertain, it appears that the proportion of non-infectious waste entering the infectious waste stream has reduced by at least 10%.

Through education programs reductions of infectious waste by 75% can occur(103). In our hospital no such directed education occurred aimed specifically at reducing the infectious waste volumes, but there were informal educational activities to encourage safe OR and DPU recycling (e.g. “If in doubt, chuck it out”). Pre-recycling however, staff anecdotally indicated that they were less concerned whether recyclables entered the infectious or general waste streams as such ‘waste’ could not be recycled anyway. The introduction of OR recycling may be an indirect method to reduce non-infectious waste entering the infectious waste stream through education and/or shift in attitudes. Given that disposal of infectious waste is at least 4 times the cost of general waste, a conservative 10% (100 kg) reduction in infectious waste per week in our hospital’s ORs will lead to savings approaching AUD$4,000 (USD$3,080) per annum.

Beyond the reduction in infectious waste the financial benefits of OR recycling were minimal given that hospital general waste costs only AUD$0.24 per kg. Apart from labour, we included all costs for waste disposal and found large variation in costs per kg for recyclables. Our hospital has contracts with smaller recyclers that do not charge for collection and transport. Paper and cardboard as well as commingled bins are expensive to collect and transport, but bin hire costs for all waste streams are not a major contributor. If greater recycling were achieved of paper and cardboard by 100 kg/week the recycling program would become a cost burden of AUD$2,000 (USD$1,540) per annum, unless compacting or an altered fee structure was arranged or an alternative vendor hired.

This audit did not formally examine the extra time taken to separate recyclables into different streams. Between 2009 and 2012 there was neither a significant change in the number of operations per day, nor the average duration per operation or procedure. Hospital staff also anecdotally noted there were no delays in operating times caused by recycling. Since the recyclables were sorted by OR staff one would not expect that waste disposal staff (beyond the OR) would require greater time to process the recyclables.

This study has limitations. One week may be an inadequate sample of OR and DPU waste, although the number of procedures for the week and the number of patients requiring contact precautions was broadly similar to the average per week for the year 2012. The researchers were conservative in their assessment of the recycling potential for waste – discarding items that were contaminated with body fluids and those which were potentially troublesome to recyclers (including suction tubing and needleless syringes). Small amounts of aluminium are recycled from suture sets, but not complex single use metal and plastic devices. This study of OR and DPU waste was more extensive compared with the prior study of OR waste alone, which focussed upon anaesthesia waste(119), so they are not truly pre- and post- intervention studies.

Reprocessing is a term used for making single use devices (e.g. laparoscopy ports) patient ready again, by repairing and refashioning(132). Reprocessing is a multi-billion dollar industry in the USA and elsewhere(132), but is currently non-existent in Australia and rare in the UK. Reprocessing can reduce OR waste significantly, but it is unclear (and probably unlikely) if waste reduction from reprocessing would be as significant as commencing a recycling program or reverting back to reusable gowns and drapes from disposables. In our hospital there are few reusable, double steel surgical tray sets that would reduce the requirement for expensive surgical ('blue' or 'green') polypropylene wrap.

As a proportion of all hospital waste, OR waste in this study was less than half of that reported in the USA(215), which may be due to the lower total amounts of single use waste per procedure in Australia or reflect a more mixed medical and surgical throughput in our hospital. There is wide variation in the amount of waste generated per patient per day, even in neighbouring countries (e.g. UK waste is 5.5 kg per patient per day compared with France, at 1.9 kg per patient per day)(96).

For one day only, the weight of single use surgical gowns and drapes was 10kg, indicative of 60 kg per week or 60kg of 410kg (15%) of all OR and DPU infectious waste. In our hospital, only orthopaedic surgeons routinely wear single use sterile gowns, which are a combination of polypropylene and cotton and cannot be recycled. Further, ‘surgical packs’ (where single use gowns, drapes, cotton etc. are bundled in together) are routinely used only in orthopaedic and some urological procedures. There are few recyclable components to these ‘packs’. Hospitals that have a large orthopaedic surgical presence or entirely use single use theatre packs (e.g. in the USA) will produce considerably more waste/procedure than that found in our study.

Most reusable surgical instruments were sterilised together in large OR trays and wrapped in single use polypropylene covering. Undoubtedly there was redundancy in such an approach, i.e. not all of these instruments were used for all operations, so wastage of plastic wrap occurred to cover these large trays. A potential solution to reduce plastic wrapping would be to wrap more reusable surgical equipment as single items. Wrapping of single items, however, uses more plastic per item, and there could be a resultant increase in required plastic wrap despite the use of fewer instruments.

Almost two thirds of paper and cardboard was not being recycled, the majority by weight comprised of paper hand towels. The high financial cost of paper and cardboard recycling versus general waste indicates that reducing the quantity of paper towel waste is preferable to increasing the recycling rate. Paper towel waste could be reduced by using environmentally friendly hand drying systems (achieving more than 50% reduction in carbon emissions compared to disposable paper towels)(219).

Hospital plastic recycling with local recycling contractors was cost beneficial. There are, however, barriers to recycling including; financial costs for hospitals with different recycling contractors, geographical distance from recyclers, contamination with infectious and general waste, difficulties identifying, separating and segregating waste, adequate space for appropriate recycling bins, and staff knowledge and motivation(217). Resistance to change is a well-documented challenge to hospital waste recycling(96, 97). Local plastic recyclers were recruited who convert the polypropylene, mixed plastics and PVC into furniture and agricultural pipe, revealing to staff the ‘fruits of their labours’.

Recycling is usually less energy intensive than producing new product, particularly for metals and most plastics, but not always for paper products. Our 11 tonnes/annum of OR polypropylene, mixed plastics and PVC recycling produces 15 tons less CO_2/annum than manufacture of new plastics(25), equivalent to approximately 7,000 litres of petrol(114). Given that burning 1 litre of petrol emits 2.28 kg CO_2, the average fuel efficiency of Australian cars is 10 km per L (24 miles to the gallon), and the average distance travelled/car/annum is 14,000km(220) our OR recycling is equivalent to taking 5 cars off the road. Concerns such as peak oil (and therefore more expensive plastics) improve the incentives for plastic recycling.

In Australia and many other countries, the majority of new paper manufacturers use wood pulp biomass from newly felled trees as part of the energy feedstock for paper production. The recycled component of paper cannot make use of this energy source as trees are not being felled. Thus, any CO_2 emission reductions from Victorian paper recycling are attenuated by less wood pulp biomass and the reliance upon CO_2 emissions-intensive coal-based electricity(114). There are, however, other benefits from recycling paper, such as less water use and fewer chemical pollutants(25).

Both the financial and environmental savings from recycling 11 tonnes of OR plastics per annum may be relatively small. Such considerations however, will become increasingly important as oil and thus plastics become more expensive and steps are made to reduce the considerable carbon emissions stemming from healthcare activity(3). Procurement is the primary contributor to healthcare’s CO_2 emissions(8). Increasing hospital waste recycling, together with increasing reprocessing, reusing and reducing packaging could significantly reduce CO_2 emissions.

This waste audit has shown that it is feasible to recycle more than half of potentially recyclable OR and DPU waste, this representing almost one quarter of all waste. At our hospital’s OR and DPU more than 13 tonnes of recycling now occurs per annum, 75% of this being plastics. There has been no infectious contamination of recyclables and no cost burden to the hospital. There appears to have been at least a 10% reduction in the amount of waste entering the infectious waste stream as staff have become more engaged in waste management. OR recycling can improve resource use and be both financially and environmentally sustainable and beneficial.

PART B. ICU WASTE POST-RECYCLING

9.7 INTRODUCTION

In the US over 7000 tonnes of healthcare waste is produced per day(103). Recycling of waste is one strategy to conserve natural resources, reduce landfill and the carbon footprint(103, 221). In our pre-recycling audit of ICU waste it was found that approximately 40% of the waste could potentially be recyclable(120). There is, however a paucity of data regarding the effectiveness of recycling within the ICU.

In our hospital it was shown that a recycling program implemented in the OR was efficacious, with approximately 55% of potentially recyclable waste (almost 25% of all waste) being recycled, without incurring additional cost(213). It was unclear, however, that these findings would also apply to recycling within the ICU, particularly given that there were different ratios of waste in the ICU compared with the OR (less polypropylene sterile wrap) and better ICU compliance with infectious waste containing only infectious waste(120). A follow up audit of ICU waste was thus undertaken.

9.8 RESEARCH QUESTIONS

1. What are the amounts of potentially recyclable materials within the ICU that are actually recycled?
2. What are the amounts of ICU waste incorrectly disposed of, including infectious waste?
3. What are the non-labour financial costs of the ICU recycling program?

9.9 METHODS

A recycling program was commenced in April 2013 at the 11-bed ICU at the Footscray Hospital. The ICU recycling program was based on a program recently implemented in the hospital’s operating suite and was divided into five streams: paper and cardboard, three plastics types (mixed polyethylene/polypropylene, polyvinyl chloride (PVC), and polypropylene surgical wrap), and commingled (a mixture of paper, aluminium, steel, glass and plastics). The remainder of the ICU waste was disposed of into general waste bins or infectious bins. Infectious waste was defined as any waste containing human tissue and/or blood(222).

Mixed plastics included a variety of different plastics used within the ICU, e.g. plastic wraps, bottles and ampoules, but some items were deemed unsuitable by the recycler, e.g. polyurethane (not valued), and plastic syringes (concern about infection transmission). Common examples of plastics have been defined previously (Methods 9.4). In commingled recycling all materials (e.g. tins, plastic bottles) are collected together to be sorted later by the recycler. There was thus some overlap between plastic within commingled materials and the mixed plastic stream. Glass drug ampoules and single use metal instruments (scissors etc.) were not routinely recycled.

Pre-recycling, each ICU patient bed area had one each of a general waste and an infectious waste bin, with half this ratio for high dependency unit (HDU) beds. Post-ICU recycling, one additional bin for paper and cardboard, and another for mixed plastics were provided at each bed area, again with half this ratio for HDU beds. Further paper and plastic bins were distributed around the ICU. PVC, polypropylene and commingled items were a minority of the recyclables, and thus only central bins were provided.

Within the ICU staff tea room three recycling bins were provided: paper, plastic and commingled. The recycling program did not extend to other non-clinical areas, such as administration. Staff were encouraged to dispose of paper and plastic in bins specific to one type of recyclable, but it was also appropriate for paper and mixed plastic recyclables to be placed into the commingled bin.

The recycling program was commenced in April 2013 with education provided to clinical and environmental services staff about correct recycling, bin placement and disposal. After allowing for three months for adjustment to the new program we performed an audit of the waste generated in the ICU over a seven-day period from August-October 2013. Due to clinical work responsibilities the seven days were not consecutive, although each day of the week was audited.

All ICU waste generated over the seven day period was removed and audited in a separate non-clinical area. Sharps bins were not examined. Waste from each stream was sorted into general waste, infectious, paper and cardboard, mixed plastic, PVC, polypropylene, commingled, syringes, and sharps. Products which were made of recyclable materials, but which recyclers deemed unsuitable (most often since the products were composed of multiple plastics), were classed as general waste (or infectious if contaminated). For example, renal replacement fluid bags were composed primarily of PVC, but also contained other plastics and were thus deemed unsuitable, i.e. general waste. Noticeable (greater than 10ml) non-infectious fluid was emptied into a separate container and weighed. Infectious fluid was not separated from the infectious waste or, if found in non-infectious waste, removed as bagged into the infectious waste. After sorting, waste was weighed (to +/-10 grams). Investigators wore protective gowns, gloves and eyewear whilst sorting the waste. Cardboard boxes delivered to the ICU were collected and weighed.

Aluminium cans and steel tins formed the majority of the commingled material, although some plastics were also present in the commingled bins. For the purpose of the audit, waste designated as commingled not originating from the commingled recycling bin was defined as aluminium and tin cans (other potentially recyclable waste was sorted into the paper, mixed plastic and PVC categories).

Although plastic syringes are not presently accepted for recycling by our recyclers, all non-infectious syringes were weighed separately to determine their contribution to waste.

During the study period, several patients required staff to observe contact precautions when caring for them, e.g. colonisation with vancomycin resistant enterococci (VRE). As per our institution’s policy, contact precautions required staff to wear non-sterile gloves and gowns when interacting with the patient. All waste associated with patients requiring contact precautions was disposed of into the infectious waste.

No inferential statistical analyses of the data were performed. One week’s analysis was chosen as this was feasible and was likely to be more indicative of the average for an entire year than sorting waste for just one day.

9.10 RESULTS

For the seven day period the total ICU waste as found was 502 kg; general waste 268 kg (53%), infectious waste 161 kg (32%), and recyclables 73 kg (15%) (Table 18). Of the 73kg found in the recycling streams, there was 70 kg of correct recycling, i.e. 2.4 kg contamination; 1.9 kg with other recyclables, 0.5 kg with general waste and no infectious contamination. The ratio of the correct actual recycling to potential recycling was 70 kg out of 145 kg (47%).

Of the 88 kg of contamination of the general waste, 81.5 kg was all recyclables (including 28 kg of paper & cardboard and 35 kg of plastics), 1.5 kg was infectious waste and 5 kg was glass bottles. Within the infectious bins, the majority of the contamination was general waste (17 kg, 11% of the total infectious bin waste). The 5kg within the PVC stream had 2kg of contaminants, including 1.3kg of mixed plastics on one of the seven days. It is likely that a bedside mixed plastics bin was inadvertently emptied into the PVC bin on that day. There was minimal contamination of the other recycling streams (Table 18).

After sorting through all bins, the amounts and proportions of waste were: 221 kg (44%) of general waste, 137 kg (27%) of infectious waste and 144 kg (29%) of potentially recyclable waste (Table 19). The 221 kg of general waste included 5 kg of glass, 5 kg of syringes (non-infectious) and 14 kg of non-infectious fluid. Of the potentially recyclable waste, 68 kg was paper and cardboard, 51 kg was mixed plastic, 14 kg was PVC, 5 kg was commingled and 6 kg was polypropylene.

In the week audited there was an average of 10 (range 9 – 11) patients in the unit each day with a mean of 5 (range 3 – 8) patients requiring mechanical ventilation and a mean of 1 (range 0 – 2) patient per day requiring haemofiltration. For the year 1/7/2012 to 30/6/2013 there was an average of 9 ICU patients per day and 4.5 patients requiring mechanical ventilation, with an average of 2.5 patients requiring haemofiltration per week. In the audited week there was a total of 15 bed days occupied by patients requiring contact precautions due to VRE, compared to an average of 10 bed days per week for 2012/13.

Table 18 Waste as found in each bin type for the seven days, and contamination (i.e. incorrect waste found in the bins). Masses of recyclables add to 73kg.

Waste stream	Mass[1] (Kg)	Contamination with other waste: kg	(%)
Total	**502**	**114**	**(23%)**[2]
General waste	**268**	**88**	**(33%)**
Infectious	**161**	**24**	**(15%)**
Recyclables[3, 4]	**73**	**2.4**	**(3%)**
Paper (bin)	19	0.1	(0.4%)
Cardboard[5]	20	0	(0%)
Mixed plastic	22	0.3	(1%)
PVC	5	2	(37%)
Commingled	3	0	(0%)
Polypropylene	4	0	(0%)

[1] Masses rounded to the nearest kilogram.
[2] Total amount of waste incorrectly disposed of.
[2] None of the recycling streams was contaminated with any infectious waste.
[3] 0.5kg of the recycling contamination was landfill, the remainder was recyclable waste incorrectly disposed of.
[4] Cardboard boxes containing consumables.

Table 19 Total mass of waste within each waste stream (post sorting), and the amount of each disposed of appropriately (i.e. into the correct bin).

Waste stream	Total mass[1] kg	(% total)[2]	Appropriate kg	(% appropriate)[3]
Total	**502**	**(100)**	**386**	**(76)[4]**
General (Landfill)	**221**	**(44)**	**179**	**(81)**
Infectious	**137**	**(27)**	**137**	**(99)**
All recyclables	**144**	**(29)**	**70**	**(48)**
Mixed plastic	51	(10)	22	(43)
Paper, cardboard	68	(14)	39	(57)
PVC	14	(3)	3	(21)
Commingled	5	(1)	2	(40)
Polypropylene wrap	6	(1)	4	(67)

[1] Masses rounded to the nearest kilogram.
[2] Total mass of waste stream as a percentage of total ICU waste.
[3] Mass of waste disposed of correctly as a percentage of the total weight of that waste stream.
[4] Total amount of waste disposed of correctly.

The financial cost of disposal of waste and recyclables from each of the streams is shown in Table 17 (see above in Part A, Results 9.5). Such costs included bin purchasing, collection and transport of the waste, but not labour. There was considerable variation in the costs of different waste and recycling streams due to different contractual arrangements, and carting and bin hire fees. Recycling of paper and cardboard and commingled waste is more expensive than disposal of landfill, but the recycling of plastics is less expensive as the local plastic recyclers provide free pick up and cartage. Based on the weights of recyclables in our audit, the cost of recycling per annum in our ICU is approximately AUD$1,000 (USD$770).

9.11 DISCUSSION

An audit was performed of waste disposal in our 11-bed ICU for seven non-consecutive days in the setting of an established recycling program. Half a tonne of ICU waste was generated with approximate proportions being general waste 50%, infectious waste 33% and 14% recyclables. Almost half (70kg /145kg) of material suitable for recycling was actually recycled. There was minor (2.4%) contamination of the recycling streams, with no infectious contamination.

The estimated financial cost of recycling in our ICU was approximately AUD$20/week or AUD$1000 per annum. This cost was due to the expense of several recycling streams. In particular, paper and cardboard formed half of the actual recycling and was more than twice as expensive as general waste to dispose of. Only 1% of infectious waste was found outside of the infectious bins, but 18% of the waste found in the infectious waste bins was not infectious (compared to 13% in the previous audit). As shown in Table 17 (Part A, Results 9.5), infectious waste disposal was four times the cost of general waste disposal and improving compliance would be financially advantageous. For example, based on the results of this audit, if the amount of contamination of the infectious bins could be halved, this would lead to a saving of nearly $500 per year.

The proportion of potentially recyclable waste that was recycled was less than in the hospital audit of operating room (OR) recycling(213). The OR is a much greater source of sterile instrument wrap (polypropylene) than the ICU. Such polypropylene is readily recycled and is financially attractive to recyclers. In our prior ICU study(120), the total amount of potentially recyclable waste was greater (240kg vs 145kg), there was more paper and cardboard (114kg vs 69kg) and more PVC (47kg vs 14kg). In our prior study syringes were considered potentially recyclable; however the 5kg of syringes found in this study were considered unsuitable. Further, renal replacement fluid bags were thought to be potentially recyclable; however because they were deemed difficult to recycle, they were general waste in this study.

The difference in the amount of recycling between the two audits (OR and ICU waste post-recycling) is predominantly explained by the differing amounts of paper and cardboard and PVC, but the reasons for this difference are not entirely apparent. The volume of cardboard boxes may fluctuate due to variability in the delivery of consumables to the unit, although this does not fluctuate more than 50% from week to week (personal communication, Angela Rees, Western Health ICU Equipment Nurse).

This study did not consider the different clinical and non-clinical (e.g. tea room) areas within the ICU separately and did not measure waste from administrative areas. The additional time and labour required for recycling was not measured. Although not directly comparable, it has been previously shown that identifying out of date stock within the operating suite to send to less developed nations (waste sorting similar to single-stream recycling) did not significantly delay operating room turnaround times(223). Such practises raise the question whether expired stock are less effective, although it is likely that use-by dates are conservative.

The impact of this program on the operation of the ICU is unknown. It was not feasible to audit the seven days continuously, but instead each day of the week was audited non-consecutively. All recycling bins were within five metres of each bed area. Sharps bins were not examined, though it was possible that some potentially recyclable waste was disposed of via sharps bins.

All statistics used were descriptive; we did not perform inferential analyses as it is uncertain if a one week audit indicates routine waste and recycling for all weeks. Nevertheless, this audit is likely to give a reasonable indication of management of waste and recycling within our ICU. Finally, although attempts have been made to quantify the volume of recycling achieved, and the financial cost to our institution, no measurement was made of other more intangible benefits such as the financial and environmental benefits of resource recovery of plastics etc., reduction in CO_2 emissions related to recycling, and effects upon staff morale (if any). Thus, the overall benefit to society of an ICU recycling program remains unmeasured.

Based on the results of this audit, it is feasible to recycle up to four tonnes from the ICU per year. With a recycling program already established in the hospital’s operating suite(213), setting up a recycling program within the ICU was not difficult. Given that the ICU only contributes approximately 5% of total hospital waste(120) expanding the recycling program to the rest of the hospital could achieve considerable recycling and is progressively under way. The benefit of this recycling is difficult to quantify. Recycling leads to a reduction in CO_2 emissions as less energy is expended in the manufacturing of products from recycled materials(25, 195). Recycling also reduces landfill and conserves natural resources(103). Further, exposing staff to recycling may lead to better compliance with recycling outside of work(224), and anecdotally, the majority of our staff were supportive of ICU recycling.

There is scope for improvement of ICU recycling, given that only 50% of potentially recyclable waste was disposed of in recycling bins. There are, however, potential barriers to recycling, including bin space, education, motivation, and financial costs. There is limited ICU space and there are now four different bins in each ICU bed area (landfill, infectious, paper and cardboard and mixed plastic). This adds complexity to waste disposal with a greater likelihood of incorrect disposal, although this appeared rare in our audit. There is only one PVC bin within the ICU (given limited ICU space and the low PVC volume) and staff must leave their bed areas to access it. In an emergency setting it would be difficult to expect staff to separate rubbish into individual components and dispose of them in the correct bins. Some staff suggested leaving all rubbish in a separate pile and sorting it later, although this practice is unlikely to be widely adopted. Anecdotally, ICU tea room recycling could be improved, although the presence of foodstuffs hampers correct waste separation.

Paper and cardboard recycling is more expensive than disposal of landfill, so increasing recycling of paper and cardboard will increase the cost to the hospital. Paper towel is a major component of the paper and cardboard waste stream, so alternatives for hand drying could be considered (hand driers and hand sanitiser rubs)(120). The cost of recycling will vary according to individual hospital contracts and the recycler’s location.

Importantly, the results of this ICU audit differ from the earlier OR waste audit, which showed that it was financially advantageous to recycle in the OR(213). The OR audit showed a higher proportion of recycling (23% total OR waste), greater polypropylene recycling (50% of all OR recycling), and a much higher baseline of infectious waste which was reduced after recycling commenced (48% reduced to 32%). The OR waste had much more polypropylene plastic which is easy to recycle due to its self-evident composition (‘surgical wrap’). Polypropylene is considered valuable to recyclers and is correspondingly less expensive than general waste for the hospital to dispose of. Significant financial savings were achieved in the OR post-recycling by reducing the proportion of infectious waste to similar levels found in this ICU audit. Such financial savings were not possible in the ICU as the level of infectious waste contamination with non-infectious waste was already much lower than in the OR and did not improve with the advent of recycling.

Sustainability within the healthcare sector involves a multi-faceted approach, of which recycling is only one component. Recycling is unlikely to save hospitals large financial amounts, whilst reducing and reusing where clinically possible, can have significant environmental and financial effects particularly if studied comprehensively, which includes the use of life cycle assessment if necessary(10). Other avenues that could be considered to improve ICU sustainability would include examining water (e.g. for linen), electricity (e.g. reducing non-essential use at night, switching off vacant isolation rooms) and procurement (e.g. excess packaging). Even more broadly would be a consideration of the unsustainability of ineffective therapies which do not improve patient care within the ICU.

This audit has shown that ICU waste can be safely and effectively recycled. There was minimal contamination of the recycling streams, although actual recycling was only half of the potential. Contrary to the audit of OR waste which could be saving the hospital greater than AUD$5,000 (USD$3,850) per year, our ICU recycling program is costing the hospital approximately AUD$1,000 (USD$770) per year. Reasons for this cost discrepancy include a different composition of recyclables in the ICU versus OR, and less opportunity to reduce the already relatively well sorted expensive infectious waste in the ICU versus the OR prior to commencing recycling. Detailed audits of area specific hospital recycling programs reveal different outcomes. Investigation of why it often remains more financially expensive for hospitals to recycle than to discard such resources as garbage would be welcomed.

9.12 CONCLUSION

These audits of recycling waste conclude the thesis section Recycle. Chapter 8 surveyed anaesthetists’ views of recycling in order to discover if a prominent group of OR doctors supported recycling and thought it to be feasible. The overwhelming majority of anaesthetists indicated that OR recycling was not occurring in their theatres, but supported recycling and indicated that the major barriers to recycling were education to commence recycling, inadequate recycling facilities, and resistant staff attitudes. With these factors in mind recycling programs were undertaken in the OR and ICU.

Chapter 9 has explored such recycling programs through detailed audits of OR and ICU waste. Recycling was found to be feasible, with minimal contamination of recycling streams with infectious waste. Recycling reduces the total environmental life cycle cost of most items, and since these studies showed feasible recycling the environmental effects of everyday activities in the OR and ICU have been reduced. Recycling does not greatly reduce the financial burden of hospital waste processing since waste disposal is relatively inexpensive per kilogram. The OR recycling program showed financial cost savings for the hospital as there was a concomitant reduction in infectious waste with the introduction of recycling. On the contrary, since adherence to correct infectious waste disposal was more rigorously adhered to within the ICU, reductions in infectious waste did not eventuate with an ICU recycling program, which thus actually increased the cost of waste disposal due to some expensive recycling streams.

Chapter 10 is a summary of the thesis and a discussion of what lies ahead for research within the domain of hospital environmental sustainability.

CHAPTER 10: DISCUSSION

This thesis has explored environmental sustainability within the operating room (OR) and intensive care unit (ICU). Environmental sustainability has been partitioned into the themes of reducing, reusing and recycling, with thesis research questions following each theme. This chapter revisits the questions posed and results obtained during the thesis. Thereafter, discussion moves to: (i) the methods used in the thesis and their wider applicability, (ii) the generalisability of the results, (iii) practical outcomes that have changed hospital purchasing, reusing and recycling, and (iv) the future research agenda for hospital sustainability.

10.1 REDUCE

Chapter 3 considered where possibilities exist for reducing the amount of equipment used per patient within the OR and ICU, of which there are many examples. A detailed study was subsequently performed of the reduction in use of one common item: anaesthesia circuits.

10.1.1 The frequency of washing anaesthetic breathing circuits.

Anaesthetic breathing circuits were chosen and their use analysed in such a manner as to not compromise patient care.

1. Was it possible to extend the use of reusable breathing circuits from the standard 24-hour interval between decontamination at our hospital to 7 days without a resultant significant deterioration in the hygienic quality of breathing circuits?
2. What were the equipment, electricity and water cost savings resulting from extended circuit use?

A before-after study of anaesthetic circuits, whereby the duration between decontamination was progressively extended, was chosen so as to not impede patient care or OR workflow patterns. Extending the interval between anaesthetic circuit decontaminations from daily to weekly was associated neither with an increased absolute number of bacterial colonies, nor with an increase in the proportion of positive microbiological results. Due to the unchanged bacterial load it was feasible to reduce the frequency of breathing circuit changes, whilst complying with Australian professional standards(142), provided daily emptying of circuit condensate was undertaken. These study findings are generalizable; small financial and environmental savings from reduced anaesthetic circuit changes at one hospital could become larger savings for an entire healthcare system and are relevant to many hospitals, particularly in developed nations.

Two prior studies of increasing the interval between decontaminations of anaesthetic breathing circuits were smaller and did not include statistical analyses(140, 141). These studies were performed in Germany and led to guideline changes in Germany, where it is now accepted practice to change circuits weekly(137). On the contrary, current guidelines require anaesthesia circuit changes for every patient in many countries including the USA(159).

Several questions arise: What cultural and institutional factors may impede improvements in sustainable anaesthesia practice? What is required to change practice? Does the place and country of research influence the likelihood that the research will be adopted? Why is there such a discrepancy between (and perhaps within) different countries’ treatment of anaesthetic breathing circuits and is this indicative of differences in the resource utilisation of many hospital devices? Future research could concentrate on these questions, including using qualitative methods (interviews and focus group discussions) and perhaps include psychologists and anthropologists.

A potential criticism of the study of anaesthetic breathing circuits is its before-after design, i.e. that it was not a randomised controlled trial. Another concern is that the study did not include searching for viruses. Studies of the anaesthetic circuit load of viruses or more fastidious bacteria would be difficult, expensive and unlikely to be pragmatic due to the required study recruitment size and duration needed to show a treatment effect. A randomised, controlled and perhaps blinded trial of prolonging circuit changes was contemplated at our hospital and considered to be impractical by staff. Randomising circuit changes to different durations in separate operating rooms, and changing this duration randomly for each subsequent circuit change, though not impossible, could potentially have impeded workflow patterns and would likely have had poor compliance.

Rates of ventilator associated pneumonia (VAP) are very low after routine anaesthesia. A large, prospective, randomised, controlled trial examining the effects of reducing the frequency of anaesthetic circuit decontamination on VAP could definitively answer whether less frequent decontamination is detrimental to patients. Such a study would be unlikely to ever be performed due to the infrequent occurrence of VAP and thus the very large trial recruitment size, cost and duration.

In summary, the Chapter 3 study of anaesthetic circuits is the most robust evidence to date to indicate what a safe duration between anaesthetic circuit decontaminations is. The study methods and data are robust enough to change hospital practice, although a conservative approach to change would be to intermittently monitor bacterial contamination counts of anaesthetic breathing circuits as part of quality assurance. Research exploring why there is such variability in the uptake of research findings of hospital environmental sustainability both within and between different countries could be rewarding both financially and environmentally. Limited implementation of evidence is a problem across many aspects of health care, described by the Australian National Health and Medical Research Council (NHMRC) as a ‘valley of death’(225).

Chapter 3 also explores the dilemma originally raised by Daschner et al of ‘protecting the patient’ or ‘protecting the environment’ (66). This dilemma can be false, i.e. with regards to the frequency of washing breathing circuits, the patient remains protected and the environment has benefitted.

10.2 REUSE

Chapters 4 to 7 examined several facets of reusing. Chapter 4 queried what makes something single use in the first place, taking metalware as an example. Chapter 5 introduced the method of life cycle assessment (LCA), examining a common item used in the OR and ICU, the central venous catheter (CVC) insertion kit. Steam sterilisation was found to be a large contributor to the environmental footprint of the CVC insertion kit. Chapters 6 and 7 thus investigated both the electricity and water use of steam sterilisers and how hospital staff use such sterilisers, identifying potential areas to improve environmental efficiencies.

10.2.1 What makes surgical metal ware single use?

Prior to comparing common reusable and single use medical equipment this thesis questioned the foundation of what makes an item single use. Within hospitals, there is a strong trend towards increase in the replacement of reusable devices with single use variants. Simple, common metalware was chosen as steel items were seen as easily recognisable and robust, and steelmaking is well understood to be energy intensive.

Chapter 4 examined:

1. Why some simple surgical metal devices were labelled as single use and how is their composition different from traditional reusable metalware?
2. What were the broader ecological and social issues that might influence a decision to purchase single use surgical metalware?

Within the past decade there was a 10-fold increase of single use stainless steel surgical metalware in our hospitals driven by losses of the alternative expensive reusable metalware, occurring primarily where instruments were not ‘double counted’ such as in the ICU and emergency department (i.e. outside of the OR).

In Chapter 4 single use metalware was found to have the same chemical composition as reusable metalware, i.e. both were stainless steel. Physically, the single use metalware had a rougher surface leading to rusting when steam sterilised. When this single use metalware underwent simple reprocessing it became physically and visually indistinguishable from reusable metalware despite multiple washings and sterilisations. To reprocess such single use metalware to become reusable is made challenging by Australian regulations and currently would be financially unviable.

National bodies regulating medical devices could contribute to the transition towards improved healthcare sustainability and ask of manufacturers why any stainless steel items are ‘single use’. There are broader ecological and social issues that might influence a decision to purchase single use surgical metalware such as the ‘fair trade for surgical instruments’(176), but these also appear to be subsumed by the financial advantages of using single use metalware.

Chapter 4 explored what makes common surgical metalware single use. Similar investigations could occur for multiple other metal, plastic and even linen items used in the OR, ICU and beyond. Investigation of plastic and linen devices in particular would have to include analyses of how significantly deterioration occurred with successive decontaminations and sterilisations. Linen is very energy and water intensive to make(65), but since it is inexpensive and unlikely to be replaced with a reusable variant such research could be ineffective at instituting change. On the other hand, investigation could pragmatically target more financially expensive devices such as single use stapling guns in the OR. If there is found to be minimal difference between reusable and single use devices one could question the validity of such labelling. Perhaps the existence of the reprocessing industry, which makes single use devices patient ready again, indicates that such devices are not single use. In many countries reprocessing of single use devices is well under way, including a multi-billion dollar industry in the USA(132), yet in Australia it is non-existent due to a small market size and regulatory barriers(10). Further life cycle assessments could clarify if there are environmental benefits to reprocessing in lieu of simply using another single use device(10).

10.2.2 The life cycle of reusable and single use CVC insertion kits

The method of life cycle assessment was introduced in Chapter 5. LCA is a ‘cradle-to-grave’ approach for determining the financial and environmental costs of a product over its entire life(9, 21). A process based life cycle comparison was made of the environmental effects of single-use and reusable versions of a device commonly used in the OR and ICU. The chosen item was a central venous catheter (CVC) insertion kit; containing simple surgical metalware, plastic gallipots, and enclosed in plastic wrap. We asked:

1. What were the complete financial and environmental (CO_2 emissions, water use, metal use, toxicity) costs of the reusable and single use CVC insertion kits?
2. What effect did the source of electricity have upon CO_2 emissions?

The reusable kit was less financially expensive. The reusable kit had greater CO_2 emissions and water use, but lower solid waste and mineral use, whilst other environmental effects were similar(189). The CO_2 emissions and water use of the reusable CVC insertion kits were respectively three and ten times that of the single use CVC insertion kit. Steam sterilisation contributed the majority of the CO_2 emissions for the reusable kit, whilst decontamination (washing) was also important, though less so. A reusable CVC insertion kit made patient ready in a hospital with gas co-generation instead of electricity sourced from brown coal would produce similar CO_2 emissions compared with a single use kit.

This LCA was useful for three main reasons: (i) if the electricity source for steam sterilisation and decontamination were brown coal, the CO_2 emissions could be much greater for reusable than single use items, (ii) due to steam sterilisation's unexpectedly large energy and water use, studies were commenced examining the hospital sterilisers in greater detail (thesis chapters 5 and 6) to clarify if the study's findings were realistic, (iii) the study indicated just how incomplete our knowledge of the environmental effects of even simple hospital devices was and redirected the thesis away from further LCAs and towards greater investigation of a common reusable device input: steam sterilisation.

LCAs could be performed for similar surgical devices with increasing ease and accuracy as the details of the environmental effects of processes such as sterilisation and decontamination are investigated. Such investigations could provide useful data for the life cycles of entire operations (and the treatment of ICU patients) which to date have relied upon manufacturers' specifications(35) or have not included the effects of such processes as steam sterilisation(188).

In LCA it is particularly important when comparisons are made between different processes (e.g. reusable or single use approaches) to examine carefully the inputs that are different. If inputs are common to both approaches (e.g. a plastic wrap of the final product) generally it is not vital to have the most precise data of such inputs. For example, knowledge of the environmental effects of the plastic wrap coating a sterilised single use device is of lesser use compared with details of steam sterilisation, as reusable devices are comparably wrapped in plastic coating of similar weight and type, but single use devices are not repeatedly steam sterilised.

10.2.3 Steam sterilisation's energy and water footprint

In Chapter 5 steam sterilisation was found to contribute considerably to the environmental footprint of reusable surgical equipment(189). It was postulated though that the assumptions used for the steam steriliser's energy and water use in the LCA were inaccurate. The study in Chapter 6 clarified whether the energy and water data used for steam sterilisation for the life cycle assessment detailed in Chapter 5 were realistic. It was unclear what the patterns of electricity and water consumption of a standard hospital steriliser were over a prolonged period, including the consumption when the steriliser was idle, so we asked:

1. What was the total electricity and water consumption of the steriliser, and the amounts of steriliser electricity and water use for standard 134 °C cycles, accessory cycles and idling?
2. What were the averages of electricity and water consumption per kilogram of equipment for: (i) standard 134 °C cycles, and (ii) total steriliser use?
3. What were the relationships between the total mass of equipment in mixed and single-type only steriliser cycles and electricity and water consumption?
4. What were the marginal costs (i.e. cost per unit in kWh/kg and litres/kg) of electricity and water per mass of items per steriliser run?

The electricity and water use of a hospital steam steriliser was measured over more than 300 days. A large proportion of electricity (40%) and water (20%) use occurred during idle times; heavier loads were more efficient, almost one in three steriliser loads were light and thus inefficient, and the load type (e.g. linen) was of little importance. Linear regression analyses provided only moderately predictive equations of electricity use/mass, but not water use. One steriliser's daily electricity and water use was equivalent to 10 households, whilst one standard 134 °C cycle used approximately one day's worth of household electricity and water.

This study was important for four reasons: (i) generalisability: the methods used to calculate steam steriliser electricity and water use could be emulated in many countries elsewhere for modest capital investment (approximately AUD$5,000 inclusive of software), (ii) steam sterilisation can contribute appreciably to the total CO_2 emissions and water use of making a reusable surgical item patient ready again, (iii) the steriliser load type (e.g. linen) is of minimal importance and could be ignored when calculating the energy and water use of a reusable item, i.e. only load mass is important, and (iv) steam sterilisation's environmental effects could be mitigated by the manner in which the steriliser is used (idle duration, steriliser stacking and source of electricity).

It is uncertain how important the volume of space occupied by a device in a steam steriliser is and whether it could limit the load mass considerably (e.g. for less dense plastic bowls). Research examining the minimum steriliser load mass according to different steriliser stacking regimens could be insightful.

The results of this study should inform future life cycle assessments of operating room and ICU items and procedures. For example, the Chapter 5 study of CVC insertion kits(189) indicated that the reusable insertion kit had thrice the CO_2 emissions of the single use kit. The primary reason for the high CO_2 emissions of the reusable kit was steam sterilisation's electricity use of 3.6 kWh per kg items sterilised. The Chapter 5 study of steam sterilisers, however found that the electricity use was 1.9 kWh per kg items sterilised including idle periods and half that again if only including standard steriliser loads.

If the LCA of CVC insertion kits(189) had used the most recent data (1.9 kWh per kg sterilised versus 3.6 kWh per kg) for steam sterilisers, the CO_2 emissions for the reusable kits would have been at least one third lower. The CO_2 emissions for the reusable kits could be another one third lower again depending upon how efficiently hospital steam sterilisers are used. Thus, the differences found in our original study of CVC insertion kits between the CO_2 emissions from the reusable versus single use CVC insertion kits could be markedly reduced depending upon how steam sterilisers were used. Such differences in the inputs to life cycle assessments can thus have profound effects on whether a reusable item has greater environmental effects than single use variants. Future LCAs of reusable surgical items could use Chapter 6's study calculations of electricity and water use/kg load sterilised, whilst load type could be excluded. Further, considerable efficiency gains in steriliser use are possible through reducing idle periods as well as increasing steriliser load masses.

10.2.4 Hospital Steam Steriliser Usage: Could we switch off to save electricity and water?

Chapter 6 found that steam sterilisers used a considerable amount of electricity and water when idle. Further investigation of how hospital staff used a bank of such steam sterilisers was undertaken in Chapter 7.

1. How were the four hospital sterilisers used during one full year, including details of periods spent in active use, idle or switched off?
2. Based upon data from Chapter 6, how much electricity and water were used by the sterilisers during these different periods (i.e. active, idle or off)?

3. What would have been the consequences for electricity and water use of two alternative usage policies based upon switching sterilisers off when not needed?

The sterilisers were idle for almost half of the total hours for the year, longer than they were active, and they were off for only 15% of the time. Steriliser idling for 12 hours or longer accounted for half of the total idle duration, and two or more sterilisers were idle for almost 70% of the total hours. Opportunities were identified to improve the efficiency of steriliser use. The first strategy to switch off sterilisers when idle would have saved 26% of total steriliser electricity use and 13% of the water. An alternative strategy to always switch off one steriliser off from 10 a.m. and a second one off from midnight would have led to electricity and water savings approximately half that of the first strategy.

As a result of discussions about these steam steriliser studies hospital staff have rotated off one steriliser continuously, saving approximately AUD$10,000, with further efficiency changes underway. More importantly, the methods used in this study are generalisable. By having access to the timing of all hospital steriliser cycles and using relatively straightforward computer software one could identify potential steriliser switch off periods. Any hospital using a similar system of quality assurance could conduct a similar analysis to potentially achieve considerable steriliser efficiency gains for minimal financial outlays. The methods used in Chapters 5 and 6 to identify steam steriliser energy and water use and how sterilisers were used could be applied elsewhere within hospitals, (e.g. an operating room’s air conditioning and ventilation or a CT and MRI scanner).

It is possible to replace steam sterilisation with other rapid sterilisation methods such as hydrogen peroxide or ethylene oxide, although generally such other methods are more financially expensive and from a microbiological viewpoint steam remains the gold standard(182). Chapter 7 identified how staff use a bank of sterilisers, including the duration and timing of idle periods. Similarly useful research could examine steriliser load optimisation – i.e. how to stack a steriliser. Simple queries could be asked such as “How often are all racks used?” “Could another rack be added without compromising sterilisation?” and “How is equipment stacked?”

Collaborative research between hospital staff and engineers to improve steam steriliser energy and water use at the outset of manufacture is another stream of enquiry that could have appreciable effects, but would require greater financial investment than in-situ studies of how hospitals use exisiting steam sterilisers.

10.3 RECYCLE

Chapters 8 and 9 examined OR and ICU recycling. For many items within the OR and ICU one cannot reduce their use indefinitely, nor can they feasibly be reused, yet they could be recycled. Prior to commencing any recycling programs it would be useful to examine the feasibility of recycling as well as what could be recycled, and how much could be recycled. Feasibility includes whether it is possible to recycle in the OR and ICU environments, staff attitudes to recycling, and what staff see as opportunities and barriers to recycling. Prior studies at our hospital indicated that approximately one third of all waste in the OR and ICU could be recycled(119, 120). As a result of the survey in Chapter 8 indicating strong support for recycling, programs were begun in the OR and ICU to commence recycling. Audits were undertaken of such recycling programs.

10.3.1 A survey of anaesthetists' views of recycling

Chapter 8 examined behavioural factors that could influence the likelihood of successful recycling, focussed upon the views of anaesthetists, a large group of OR staff.

1. Is operating room recycling standard practice in Australia, New Zealand and the United Kingdom?
2. Are anaesthetists willing to increase recycling within the operating suite?
3. In the opinion of anaesthetists what factors enable and impede the introduction of operating room recycling in an operating suite?

Most (more than 90%) anaesthetists who responded to this survey consider operating room recycling to be important, regardless of country, location (regional or metropolitan) or practice (public or private). Of the respondents, less than 10% however agreed that recycling occurred in their operating theatres. A significant majority of anaesthetists would be prepared to commit time to OR recycling and the education of others to do so, but few would commit their own money. The three major barriers respondents believed were preventing OR recycling from becoming more widespread were: (1) inadequate recycling facilities, (2) inadequate information on how to recycle, and (3) staff attitudes. In contrast, cost, lack of time, lack of space and safety issues were thought to be relatively insignificant barriers to recycling.

This survey indicated that anaesthetists were strongly supportive of OR recycling and that effort to commence such recycling should be focussed not upon convincing them to do so, but in aiding them to achieve successful recycling programs. It is unknown if other medical craft groups such as surgeons and intensive care physicians also are supportive of OR and ICU recycling. There is some evidence that nurses are supportive(49), but this may not apply to the OR and ICU. Nurses appear to undertake the majority of hospital recycling, for they clean up after procedures and operations and are thus the primary hospital staff required for recycling to be successful. Nevertheless, leadership in recycling programs from anaesthetists, surgeons and intensive care physicians could be vital and requires further investigation. It is also unclear whether a culture of OR and ICU recycling leads to other more sustainable behaviours such as reducing and reusing the use of hospital equipment. There is some non-healthcare related evidence that a predisposition to recycle may bear little relationship with a desire to reuse or reduce(131), indicating a role for future qualitative research focussed upon hospital staff.

10.3.2 OR and ICU recycling programs

Studies of recycling programs focussed upon staff education on how to recycle, overcoming negative staff attitudes to recycling, and providing adequate recycling facilities. Chapter 9 detailed post-recycling program audits of what and how much could be recycled.

1. What were the masses of OR and ICU general waste, infectious waste and recyclables over seven days?
2. What were the masses of actual and potential OR and ICU recyclables remaining within the general and infectious waste?
3. What was the financial cost of OR waste disposal and how does this compare to the pre-recycling audits?

For the audit of the six-theatre OR and Day Procedure Unit waste, of the 1.3 tonnes of waste almost a quarter was being recycled. Infectious waste bins contained one third of all waste, although truly infectious waste was one quarter of all waste. The proportion of non-infectious waste entering the infectious waste stream appeared to fall by at least 10% compared to pre-recycling audits. The achieved recycling had no infectious contamination and minimal contamination with general waste. The achieved recycling represented more than half of what was potential (realistic). Overall, recycling was financially cost neutral compared with no recycling, although if the apparent reduction of infectious waste was included savings approached AUD$10,000 (USD$7,700)(152) per annum.

For the audit of waste disposal in the 11-bed ICU, half a tonne of waste was generated with: general waste 53%, infectious waste 32% and 15% recyclables. Infectious waste bins contained 32% of all waste, with truly infectious waste 27% of all waste. Almost half of the material suitable for recycling was actually recycled. There was minor (2.4%) contamination of the recycling streams, with no infectious contamination. The estimated financial cost of recycling for one week in the ICU was approximately AUD$20 per week or AUD$1000 per annum. This cost was due to the expense of several recycling streams. In particular, paper and cardboard formed half of the actual recycling and was more than twice as expensive as general waste to dispose of.

Infectious waste disposal was four times the cost of general waste disposal and improving compliance would be financially advantageous. The OR recycling program showed financial cost savings for the hospital as there was a concomitant reduction in infectious waste with the introduction of recycling. Adherence, however, to correct infectious waste disposal was more rigorously adhered to within the ICU. Thus, reductions in ICU infectious waste did not eventuate with a recycling program, increasing the cost of waste disposal due to some expensive recycling streams.

The recycling audits indicated that: (i) if education and facilities are provided recycling is feasible and relatively straightforward to perform and infectious waste contamination is rare, (ii) recycling can at least be financially cost neutral, or at worst have a minor cost impost, (iii) it is unclear why the financial costs for different recycling streams vary considerably.

There are limits to how much recycling can be performed. Efforts to increase the achieved recycling as a proportion of the potential recycling should perhaps rather be directed to reducing and reusing equipment. Reducing the use of paper products such as hand towels with hand gels and air dryers, and plastic sterile wraps with reusable stainless steel cases, could be both financially and environmentally rewarding, although deserving of further study(213). Further, recycling does not save large amounts of money unless there is a reduction in the infectious waste amounts as the costs for recycling many items is similar to the cost for general waste disposal.

The reduction in CO_2 emissions from recycling plastics from the OR was 15 tonnes for one year. As Chapter 3 has shown, reducing the use of anaesthetic circuits via less frequent decontaminations saved approximately AUD$10,000 per annum and 3.6 tonnes of CO_2 emissions. Circuits are but one example of many items whose use could potentially be reduced and there are likewise many items that could be reused. Similarly, studies of the electricity and water use of hospital steam sterilisers (Chapters 7 and 8) ended with savings of more than AUD$10,000 and 85 tonnes of CO_2 emissions per annum via reductions in steriliser idle periods. This thesis has shown that exploring recycling for all items used in the OR and ICU has appreciable environmental effects, but these are likely to be less than the environmental benefits of feasibly reducing and reusing all OR and ICU items and procedures. Nevertheless, such statements are anecdotal as such research examining and contrasting reducing, reusing and recycling is in its infancy.

FUTURE SUSTAINABILITY RESEARCH

This thesis has highlighted that many aspects of our understanding of hospital sustainability are immature and that there are large research opportunities in the field. This chapter ends by discussing the wider applicability of the methods and results of the thesis and the future research agenda for hospital sustainability.

The methods used in this thesis were straightforward and could be generalised to many other hospital devices and procedures. The study in Chapter 3 of the microbiological loads of anaesthetic circuits could be applied to other hospital equipment such as breathing circuits used in respiratory and sleep medicine and in the ICU. Chapter 4's study of metal ware required the use of a mass spectrometer and surface roughness meter, though these were relatively inexpensive, and studies of plastics for example could be performed similarly.

Process based life cycle assessment was used in Chapter 5 to measure the environmental effects of central venous catheter insertion kits. Financial costs may prohibit the rapid uptake of healthcare LCAs due to labour costs, although these are likely to fall as more medical items and procedures are examined. As the financial and environmental costs of healthcare rise LCA will increase in relevance. Comparisons between input-output LCAs and the more expensive process based LCAs could clarify whether input-output LCAs could suffice for large numbers of devices and procedures. LCAs of medications will also come to the fore.

Chapters 6 and 7 examined the electricity and water consumption and in-situ hospital use of steam sterilisers. Electrical current and water flow meters could be applied to other hospital equipment. Examining the timing of steriliser loads with the aid of software and basic computer programming could be adapted for other hospital devices. Chapters 8 and 9 involved a survey of anaesthetists' views of OR recycling and audits of waste, both of which are readily achievable. Surveys of various hospital staff groups' views of recycling could be instructive and guide not just recycling programs, but also efforts to improve procurement, reducing and reusing. All studies completed in this thesis have applicability beyond just a single hospital. The methods used are generalisable to many hospitals in developed and developing nations since methods of decontamination, sterilisation, procurement and waste disposal follow national healthcare standards which are reflected by international standards.

Not all of the studies contained within this thesis have led to financial or environmental savings for hospitals. The studies of why some metal ware is classed as single use, the LCA of CVC insertion kits and recycling ICU waste did not yield any environmental savings. Nevertheless, there was a decision by staff to adopt the findings of several hospital projects that did record financial and environmental improvements. Research examining why the results of this thesis have or have not been adopted by other hospitals is likely to be revealing. Just why some hospital staff behave in environmentally responsive manner and others do not needs further clarification.

Research studies in this thesis that led to financial savings of more than $AUD30,000 (USD$23,000) per annum were: reducing the frequency of anaesthetic circuit decontamination, reducing the steam steriliser idle periods, and recycling OR waste. Although the financial (and perhaps environmental) savings resultant from this thesis may seem insignificant, there are at least three reasons to counter such a view; 1. the methods used herein (e.g. LCA) could apply to examination of any other hospital process or equipment anywhere in any hospital, 2. the results could be generalisable to many Australian and overseas hospitals, and 3. the behaviour of hospital staff can be shown to be influenced by sustainability research.

What is the future research agenda for hospital sustainability and what advice could be given to someone interested in this field of research? There is a need to concentrate upon multiple areas; from the macro, i.e. the prevention of unnecessary healthcare events and avoidable diseases, through to improving a nation's healthcare financial and environmental footprint, and thus to the micro, i.e. examining the effects of individual equipment and procedures.

This thesis has remained focussed upon research that could improve the environmental effects of OR and ICU equipment and activities as the primary aim. There are many other highly important research projects that would have improved environmental outcomes that are beyond the scope of this thesis.

The bigger picture could be thought of thus: that prevention is better than cure, both for the patient that never was and the avoidance of an associated environmental footprint. The role of public health in reducing the environmental (and financial) effects of healthcare will become increasingly important. Studies are required to examine avoiding hospital admission in the first place. For example, it is possible that through encouraging just one smoker to quit, a general practitioner may have a greater effect upon healthcare dollars saved, reduced hospital admissions and environmental benefits than all of the hospital recycling performed in our hospital for a year. Of course, the patient will benefit from smoking cessation also, which remains the primary aim. Life cycle assessment research of the environmental effects of avoiding smoking, alcohol, obesity and diabetes could add to patient centred reasons to avoid such risk factors and diseases.

Systematic research of healthcare's total environmental footprint for an entire nation is under way in only the UK currently(4). Although a carbon footprint is rarely indicative of the total environmental footprint it serves as a useful framework and one that has been studied in some detail. Healthcare's carbon footprint could be subdivided in descending importance into: procurement, direct energy use, and travel. For procurement there is much scope for careful analyses of the environmental effects of different models of patient care as well as carbon hotspots for procurement of medications and devices(48). Study of the environmental and financial effects of the hospital building fabric is at a more mature stage than other aspects of healthcare sustainability(36). There are collaborative research opportunities with engineers to examine hospital equipment and how they are used by staff, e.g. radiology machines, OR ventilation and air-conditioning. Hospital staff attitudes to more sustainable transport options could be surveyed and trials of more environmentally friendly approaches piloted.

This thesis has aimed to explore the micro of hospital sustainability, i.e. what are the environmental benefits of reducing, reusing and recycling individual equipment and simple processes? Just as prevention is better than cure, so too is it better environmentally in most cases to follow the waste hierarchy and reduce then reuse then finally consider recycling(14).

A large research agenda is immediately apparent within each field of Reduce, Reuse and Recycle. For Reduce, avoidance of unnecessary procedures and superfluous devices, methods to reduce the packaging of drugs and devices, and reduction in idle periods for large equipment could be examined.

For Reuse, the field of life cycle assessment within healthcare is ready to enter a new phase of research. There are opportunities from the macro to examine input-output LCA studies of the environmental footprint of national healthcare systems right down to the micro LCAs of individual devices or drugs. As an example of the current state of play, several authors have recently completed LCAs of entire operations. The CO_2 emissions for three different procedures have been estimated at: (i) 180 kg CO_2 for an input-output LCA of cataract surgery(113), (ii) an average 240 kg CO_2 for a hybrid process based/input-output LCA for hysterectomy (robotic, laparoscopic and laparotomy)(35), and (iii) a range of 22- 40 kg CO_2 for a process based LCA of gynaecological cancer staging surgery (robot, laparoscopy and laparotomy)(188). Such variability in the CO_2 emissions for surgery indicates differing methods such as – input-output versus process based LCAs (detailed in Chapter 2.3), anaesthetic gas inclusion(35) or exclusion(188) (which have high direct global warming potentials,(122)) and uncertainties such as whether the electricity and water requirements for decontamination and steam sterilisation of reusable devices were included. Future LCAs could considerably guide device and drug selection and allow clear comparisons between equipment and procedures.

For Recycle, research opportunities probably have smaller potential than studies of reducing and reusing. For example, there are potentially hundreds of different devices and procedures to research Reuse with LCA for example, but only a few different recycling streams for all of these hundreds of devices. Nevertheless, recycling strategies on different wards, why different recycling streams have markedly different financial costs(214), and surveys of why groups of clinicians recycle would be valuable.

There are considerable differences between equipment used in the OR and ICU. In our hospital the OR has a majority of reusable equipment, linen, metal ware and plastic used, whereas within the ICU there are very few reusable devices. Most single use ICU equipment is inexpensive, thus even if research indicated that a reusable version had a lower environmental footprint, unless the financial savings were at least moderate, there may be no practice change. In the OR there are more expensive devices which would have research priority.

This thesis gives greater understanding to the environmental effects of hospital activities. Examples are given of improvements in OR and ICU sustainability occurring as a result of the thesis research. The methods used in this study are generalisable to many hospitals nationally and internationally. The studies within and future research could guide future policy makers, clinicians, engineers and others to make rational, informed decisions to improve hospital environmental sustainability, improve efficiency and reduce energy, water and pollution in an increasingly resource constrained world.

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