Med Biol Eng Comput (2010) 48:721–726
DOI 10.1007/s11517-010-0630-1

EDITORIAL

Evidence-based approach to the maintenance of laboratory and medical equipment in resource-poor settings

Robert Malkin · Allison Keane

Received: 28 January 2010 / Accepted: 23 April 2010 / Published online: 21 May 2010

Abstract Much of the laboratory and medical equipment in resource-poor settings is out-of-service. The most commonly cited reasons are (1) a lack of spare parts and (2) a lack of highly trained technicians. However, there is little data to support these hypotheses, or to generate evidence-based solutions to the problem. We studied 2,849 equipment-repair requests (of which 2,529 were out-of-service medical equipment) from 60 resource-poor hospitals located in 11 nations in Africa, Europe, Asia, and Central America. Each piece of equipment was analyzed by an engineer or an engineering student and a repair was attempted using only locally available materials. If the piece was placed back into service, we assumed that the engineer's problem analysis was correct. A total of 1,821 pieces of medical equipment were placed back into service, or 72%, without requiring the use of imported spare parts. Of those pieces repaired, 1,704 were sufficiently documented to determine what knowledge was required to place the equipment back into service. We found that six domains of knowledge were required to accomplish 99% of the repairs: electrical (18%), mechanical (18%), power supply (14%), plumbing (19%), motors (5%), and installation or user training (25%). A further analysis of the domains shows that 66% of the out-of-service equipment was placed back into service using only 107 skills covering basic knowledge in each domain; far less knowledge than that required of a biomedical engineer or biomedical engineering technician. We conclude that a great majority of laboratory and medical equipment can be put back into service without importing spare parts and using only basic knowledge. Capacity building in resource-poor settings should first focus on a limited set of knowledge; a body of knowledge that we call the biomedical technician's assistant (BTA). This data set suggests that a supported BTA could place 66% of the out-of-service laboratory and medical equipment in their hospital back into service.

Keywords Medical devices · Resource-poor settings · Clinical engineering · Biomedical engineering technicians

1 Introduction

More than 50% of the laboratory and medical equipment in resource-poor settings is not in service (WHO Guidelines for Donated Medical Equipment). The lack of working equipment has a devastating effect on healthcare in resource-poor settings. Certainly one of the most common causes for a piece of medical equipment being out-of-service is the lack of consumables [2], including reagent packs, electrodes, and other single use devices. However, a large quantity of out-of-service equipment does not require consumables. There is evidence [2] that much of this medical equipment is out-of-service because of the lack of trained professionals able to execute the needed repairs or maintenance, usually considered a lack of biomedical engineering technicians (BMET) or biomedical engineers. If the problem is the lack of professionals, then the solution would be training. But what training?

There are many programs in the US and Europe that focus on training high school graduates to become BMET, where the role of the BMET is often to repair, maintain, and manage laboratory and medical equipment in hospitals. But is training designed for a resource-rich setting appropriate for a resource-poor setting? We examined 2,849

R. Malkin (✉) · A. Keane
Department of Biomedical Engineering, Duke University, Hudson 136, #90281, Durham, NC 27708, USA
e-mail: robert.malkin@duke.edu

engineering requests (a.k.a work orders or tickets) from 60 resource-poor hospitals to determine what knowledge or skill was required to return the equipment to service, with particular emphasis on the knowledge typically included in BMET training. We concluded that a typical BMET curriculum is not required for most repairs in a resource-poor setting and we introduce an evidence-based curriculum that we call the biomedical technician's assistant (BTA) curriculum.

2 Methods

Between 2003 and 2008, approximately 100 engineering students, biomedical technicians, and engineers voluntarily gathered data on out-of-service medical equipment from 60 resource-poor hospitals located in 11 nations (nation, number of hospitals): China (1), The Dominican Republic (1), El Salvador (4), Ghana (17), Haiti (5), Honduras (10), Nicaragua (9), Sierra Leone (1), Sudan (1), Tanzania (10), and Ukraine (1). The hospitals varied in size (1–11 operating rooms, 10–772 beds) and technical staff (0–8), though 38 had zero or one technical staff, and most technical staff were not trained BMET's. A survey of the hospital administration reported 25–90% of the hospital's equipment working (survey average: 71.4%). However, physical inventories by the volunteers suggest that the administration was overestimating the percentage of working equipment, perhaps by ignoring closets, or even small warehouses, of donated, idle equipment. Only seven hospitals reported having some planned preventative maintenance programs and only three reported having complete planned preventative maintenance programs. Hospitals were a mixture of government-funded, private, and some faith based.

Every piece of equipment was analyzed to determine why it was out-of-service. If it was determined that the sole cause of the equipment not being used was the lack of a required consumable that the laboratory or medical staff could not replace, reuse or obtain locally, then that piece of equipment was returned to the staff and was not included in this study.

All other pieces of equipment were attempted to be repaired by the volunteer. Engineering volunteers had a basic toolkit, access to the internet, and US$50 or less for locally purchasing spare parts. Expert engineers were available to offer advice electronically and provide scanned copies of manuals when possible (both service and user). Engineering volunteers did not have access to imported spare parts and were not provided with specialized parts or tools. Volunteers were not permitted to order parts and have them shipped into the country. However, volunteers were encouraged to travel to obtain parts as long as the travel required only public transportation by surface transport.

Every piece of equipment was labeled as either repaired or not repaired by the volunteer. A piece was labeled as repaired only if that piece was returned to use. If the device was repaired by the volunteer, but the staff was still not using it, then it was considered out-of-service and not repaired. Testing at the bench was not considered sufficient evidence of repair. With this definition of repaired, we assumed that the engineering volunteer correctly identified the cause of the failure when they reported the equipment as repaired.

Upon returning to the US, every volunteer filed a complete report on each piece of equipment that they touched during their visit. Every report was read and the cause of the equipment failure reanalyzed by a second engineering volunteer possibly based on both the description and the categorization. Selected cases were read by a third or fourth engineer or an experienced, licensed engineer, as required to conclusively categorize the equipment, the problem, and the repair.

In addition, the panel reviewing the reports also attempted to identify what knowledge was required to complete the repair. This determination was based on the written descriptions provided by the volunteers.

3 Results

A total of 2,849 engineering requests were analyzed. Of those, 2,529 were determined to be laboratory or medical equipment (320 pieces were determined to be non-medical). In other words, 89% of engineering requests in resource-poor hospitals are for medical equipment.

Of the 2,529 pieces, 1,821 pieces were repaired. This is a remarkable result. Without the use of imported spare parts and without extraordinary financial resources or specialized tools, engineering volunteers were able to put 72% of the equipment back into service. This strongly contradicts the hypothesis that most medical equipment repairs require imported spare parts to be returned to service in resource-poor settings.

The occurrence of each device type was noted. There were 65 different types of laboratory or medical equipment that appeared more than once in the records, repaired or otherwise. The devices that were most often reported out-of-service (and the number of occurrences) were: blood pressure devices (294), bedside monitors (214), lamps (183), aspirators (136), nebulizers (123), pulse oximeters (104), electrocardiograms (86), incubators (80), electrosurgery devices (77), infusion pumps (77), autoclaves (74), microscopes (65), centrifuges (63), X-ray devices (57), and ventilators (57). The lack of seemingly critical pieces of equipment from this list, such as automated clinical laboratory equipment, reflects the lack of this type of equipment in resource-poor settings.

Of the 1,821 repaired pieces of medical devices, only 1,704 were sufficiently documented to identify what knowledge was required to complete the repair. We found that six domains of knowledge were required to accomplish 99% of the repairs: electrical, mechanical, power supply, plumbing, motors, and installation or user training. Example repairs for each knowledge domain are provided in Table 1. The distribution of the equipment repairs is shown in Fig. 1.

We wished to further determine how profoundly each domain needed to be mastered. In other words, what percentage of the repairs required only basic knowledge in a given domain, and what repairs required more advanced knowledge or skills. Therefore, each domain, except user training, was further subdivided into units. A unit was defined as a group of related concepts and skills needed to diagnose a problem and execute a repair with locally available materials. Units were categorized as basic or more advanced. The more advanced units were later grouped into one category (called “other”). A unit was considered basic if the repairs documented in that unit were accomplished using skills and tools that we felt a qualified person could have been taught in 1–2 h. A qualified person was considered someone who could read, write, and do math through fractions but does not necessarily have other prior knowledge of laboratory or medical equipment.

Each unit could be further subdivided into specific skills. A skill was defined as the steps required to diagnose and execute the repair. All skills were divided into multiple skills if we felt that more than 2 h would be required to learn the skill. Only basic units were divided into skills.

Our approach is notably different than some approaches to determining knowledge domains. For example, we did not assume any theoretical knowledge of the principles of operation of the machine. In fact, in most cases, the definitions of domain, unit, and skill excluded diagnoses and repairs requiring theoretical knowledge of the equipment. Also, we made no attempt to be comprehensive in our coverage of topics. Rather, we intended to find only the most useful skills. Therefore, every domain, unit, and skill was required to be populated by multiple repairs. In other words, every listed skill had to be supported by evidence that it was used in more than one successful repair. Any unit for which only one repair was documented, was moved to “other.”

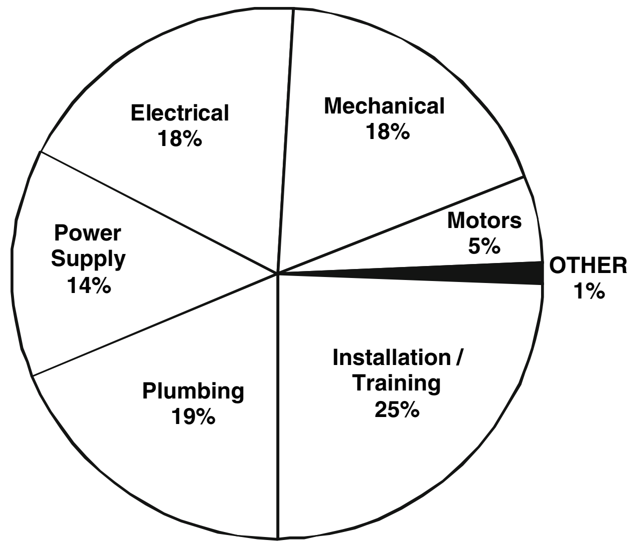

Fig. 1 The evidence presented here shows that six areas of knowledge were required to accomplish 99% of the repairs recorded here. Without the use of imported spare parts and without extraordinary financial resources or specialized tools, engineering volunteers were able to put 72% of the equipment back into service using these six domains of knowledge

A total of 26 basic units were identified. Only 107 skills were documented in more than one repair in a basic unit. Units ranged in complexity from cleaning to fuses or batteries. Due to space constraints, the 107 skills are not listed here, but are available upon request.

Table 1 Examples from the body of knowledge required to repair the out-of-service equipment in resource-poor settings

Knowledge domains	Repair examples
Plumbing	Valves, tubes, leaks, sponges, filters, flow adjustments and inflating bulbs and bladders, descaling. plumbing applies to both liquid and gas
Motors	Rotors, carbon brushes, drum bearings, motor fans, bearings, bearing lubrication, motor couplings, electric/mechanical breaks
Electrical	Patient ESU plates, contacts, light bulbs, switches, cables, temperature meters, relays, simple wiring, wall outlets
Mechanical	Screws or adjustments, mechanical lamp adjustments, lubrication, rusted parts, cases, boxes and enclosures
Power supply	Circuit breakers, fuses, wall plugs, transformers, batteries, battery chargers, battery backup, power resistors, power regulators
Installation/training	Devices that were never installed, user error, user training or working but not in service
Other	Descriptions did not fall under any of the above categories

Table 2 The body of knowledge (across the top) required to repair the studied equipment is further broken down into knowledge units shown in each column

Plumbing	Electrical	Mechanical	Power supply	Motors
Leaks (50)	Connections (21)	Attachments (42)	Batteries	Cleaning/lubricants (55)
Connections (18)	Lights/indicators (20)	Cleaning (21)	Plug/cable (24)	Carbon brushes (13)
Filters (10)	Fabrications (14)	Calibration (10)	Fuses (21)	Tightening (12)
Blockages (8)	Connectors (10)	Cashing (9)	Transformers (15)	Belts/gears (7)
Seals/gaskets (7)	Switches (10)	Fabrications (6)		
	Heating elements (6)	Lubrication (4)		
Other (7)	Other (19)	Other (8)	Other (8)	Other (13)

The percentage of equipment repaired from that domain using that unit of knowledge is shown in *parentheses*. Significantly, all the listed units can be accomplished using only 107 skills, each skill requiring only 2 h to teach to a secondary school graduate. These 107 skills were sufficient to repair 66% of all the out-of-service medical equipment in this study. The "other" entry shows the percentage of equipment (in *parentheses*) from that domain that required knowledge beyond the 107 skills

Because all of the analysis is based on the evidence presented by the work orders, the units are not only not comprehensive, they do not represent a classically, thematically organized body of knowledge. For example, in the mechanical domain "cleaning" was identified as a basic unit with only five skills: cloth and solvent, cleaning inside, sanding to remove rust, cleaning lenses, and using compressed air to clean. A classical approach to a body of knowledge would be unlikely to select those particular skills. Table 2 shows the units under each knowledge domain.

Of the total of 1,704 documented, repaired pieces, 1,132 were put back into service using one of the 107 identified skills. In other words, 66% of the medical equipment placed back into service here, required only knowledge of the identified 107 skills and all of those without importing spare parts.

The most common repairs that required more than basic unit knowledge were electrical repairs, where 18% required more advanced knowledge. Most of those repairs required knowledge of circuits or electronics. The motor domain was the next most common repair that required more than basic knowledge, where 13% required advanced knowledge or tools, including some wiring and shaft repair.

4 Discussion

4.1 The role of spare parts

Previous work has stated that the lack of spare parts is a primary cause of otherwise usable equipment being out-of-service in resource-poor settings [2]. But, this conclusion was based on interviews with technicians from the developing world. Our data contradicts the survey data. We find that the majority (72%) of the broken equipment encountered by our volunteer engineers could be repaired without importing parts and without great expense. The contradiction most likely arises from the fact that surveys of technicians are necessarily limited to hospitals with technical staff, whereas the data presented here are more comprehensive.

4.2 Towards a new curriculum

We have found that a body of knowledge encompassing only 26 units is sufficient to repair 66% of the laboratory and medical equipment repaired in this study. Each unit could be divided into just a handful of simple skills. With the knowledge of these simple skills, tools, modest financial resources, and electronic access to experts, individuals with only a secondary school education could make an enormous contribution to a resource-poor hospital.

This finding presents a problem. At this time there is no profession with a body of knowledge overlapping but not exceeding the 26 units presented here. At this time, there are only three relevant bodies of knowledge. There are two ABET accredited (www.abet.org), relevant university programs leading to diplomas in The United States: biomedical engineering (BME) and biomedical technology (BMET). These are sometimes known by somewhat different names. And, there is also one relevant professional licensure in The United States: certified clinical engineer (CCE) offered by the American College of Clinical Engineers (www.accenet.org).

There are also a few programs or textbooks that can be considered to represent bodies of knowledge specifically for the developing world such as the Medical Equipment Training program (MET) sponsored by International Aid (www.internationalaid.org), the Biomedical Equipment Training Program (EWH-BMET) sponsored by Engineering World Health, www.ewh.org), the Medical Instrumentation for the Developing World textbook developed and published by EWH (EWH-MIDW) [1], and The

Biomedical Equipment Repair Training program (BMT) supported by MediSend (www.medisend.org).

However, an analysis of these bodies of knowledge shows significant differences from the 26 units presented here. One body of knowledge does not include medical equipment repair (BME). All of these bodies of knowledge require or assume basic electronics (EWH-MIDW, EWH-BMET, BMT, CCE, BME, BMET). Several include a basic knowledge of physiology and anatomy (BME, MET, BMET, CCE). Some of the programs explicitly include theoretical approaches to finding the underlying cause of a malfunction abstracted from any particular piece of equipment (EWH-MIDW, CCE). Some bodies of knowledge focus entirely or significantly on specific problems for specific pieces of equipment (EWH-MIDW, EWH-BMET, MET). Most of the curricula significantly exceed the 26 units (MET, EWH-BMET, EWH-MIDW, BME, BMET, BMT, CCE), while some units may be missing. Significantly, most of these bodies of knowledge are considered attainable only after years of post-secondary training (EWH-MIDW, BME, BMET, CCE, BMT).

Requiring lengthy post-secondary training presents two barriers for direct implementation of curricula based on these bodies of knowledge in resource-poor settings. First, lengthy post-secondary training is most commonly delivered in a university or college. This creates a barrier for entry as seats for students in universities and colleges are very limited in resource-poor settings. Second, students who are educated through the university or college systems are often recruited out of the public health sector, or even out of the country. The education itself presents a barrier to retention.

The body of knowledge presented here presents the possibility of an alternative curriculum. The evidence presented here suggests that only 107 basic skills need to be mastered to accomplish 66% of the repairs. Since each of these skills requires approximately 1–2 h to teach (by definition), only approximately 5 weeks of classroom training would be required to teach the body of knowledge presented here.

While it may be possible to teach the body of knowledge in 5 weeks, it should be considered that there are significant differences between the volunteers who contributed to this study and future, potential students. For example, the volunteers in this study were already familiar with the names of the tools and the medical equipment before arriving at their hospitals. Also, those interested in learning this body of knowledge are unlikely to be strong classroom learners (otherwise they would already be pursuing a degree from the BME or BMET body of knowledge).

4.3 Recommendations

Most attempts at medical equipment maintenance and management capacity building for resource-poor settings have focused on traditional approaches. That is to say, adapting curricula developed in and for resource-rich settings, such as The United States or Europe, to resource-poor settings. However, this approach assumes that the problems faced by technicians in a resource-poor setting are comparable to those faced by technicians in a resource-rich setting. They are not.

As an example, 25% of the equipment reported out-of-service in this study was, in fact, working. The only repair required was the installation or, more frequently, the training of the user in the operation of the equipment. In a resource-rich setting, such problems are always approached with the aid of the manufacturer's representative, the manufacturer-supplied user's manual, or perhaps the service manual. None of the hospitals surveyed here had reliable access to a manufacturer's representative, nor did they have extensive manual libraries and most had no manuals at all, as their medical equipment had been donated used and without manuals. In such a setting, the most important skill is the ability to obtain a user's manual—challenging when the manufacturer has long since stopped supporting the equipment, or possibly existing—or to determine the operation of the equipment without the manual. Neither skill is typically taught in a BMET curriculum.

Another example might be that 14% of the equipment reported out-of-service in this paper required only power supply repairs such as plugs, batteries, and fuses. Unlike technicians in the United States, technicians in a resource-poor setting must be familiar with their local voltage, frequency, and outlet configuration, as well as that of the origins of their equipment; perhaps requiring them to know the voltage, frequency, and outlet configurations for several European countries, the US and Japan. Replacing fuses nearly universally required substituting a fuse available in the local market for the part recommended by the manufacturer. Neither outlet configurations nor fuse replacement are covered in a typical BME curriculum.

The evidence provided here suggests that a new approach is required to develop curricula for resource-poor settings. Our evidence suggests the creation of a new curriculum and accompanying profession: the BTA. The BTA would be trained with adequate preparation in tools and medical equipment, perhaps accomplished with 6 months of part-time, on-the-job training. This would be followed by 5 weeks of classroom training to learn the basic procedures. Finally, 1–2 years of on-the-job, documented, relevant work, supported by electronic access to experts would be required. Upon completing the training, we would recommend an international certification.

The limited classroom training would reduce the cost and therefore the barrier to entry for the BTA profession when compared to a BME or BMET curriculum. The BTA profession would only require a secondary education. Significantly, the majority of a BTA education could be completed, in fact would be required to be completed, while working at a healthcare facility. This minimizes the barrier to schooling associated with the loss of income. The loss of income while studying can be a larger financial barrier than the cost of tuition.

However, the profession would also lower barriers to retention. Since the majority of the time would be spent at relevant work, by definition, graduates would have to have a job in a hospital or clinic. They would be less likely to leave a job they already have. In addition, because it is a more restricted body of knowledge, the BTA would be less mobile than a BME or BMET.

The BTA need not be considered a terminal degree. BTA could be used as an entry for a more extensive BMET course of study, or perhaps as a companion curriculum to a BMET curriculum. At this writing, this approach has begun implementation in Rwanda. We are anticipating implementation in Cambodia and perhaps Ethiopia soon. In time, we will be able to report a prospective analysis of the improvements achieved.

Despite the limited investments of time and money, the evidence presented here suggests that a BTA would be able to repair 66% of the out-of-service equipment in their hospital if provided with a complete toolkit, modest financial resources, and electronic access to technical expertise.

5 Conclusions

We conclude that it is possible to return the majority of medical equipment to service using only a relatively small set of skills, without importing spare parts and using only limited financial resources. A BMET or BME curriculum is not required, and the time and money required to pursue one may be counterproductive. We recommend that when resources are scarce, they are best spent on an evidence-based, BTA curriculum.

References

1. Malkin RA (2005) Medical instrumentation in the developing world. Engineering World Health, Memphis, TN
2. Malkin RA (2007) Design of healthcare technology for the developing world. Annu Rev Biomed Eng 9:567–587