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Preparing the Clinical Engineers of the Next Millennium*

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Academic clinical engineering programs should be designed to provide students with the technical skills and critical thinking abilities necessary to become successful professionals. The success of clinical engineers depends not only on their ability to solve current problems, but also to anticipate their future needs. Employers today demand professionals with a broad knowledge, not limited only to technical aspects. The role of clinical engineers in the healthcare system is continuously changing, and consequently, academic programs should also change accordingly. This paper describes the current academic requirements and approaches of clinical engineering and how these may change in the near future.

INTRODUCTION

EDUCATION in clinical engineering is aimed at training future professionals in the maintenance, repair, acquisition and management of clinical and medical equipment. Over the last few years, the dependence of the healthcare system on technology has grown continuously. Today, almost all healthcare professionals depend on technology for diagnosis, imaging, therapy, rehabilitation, healthcare administration, and education among others. This technology has opened the door to cost-efficient and safe methods for physicians to explore, test and interact with their patients. Clinical engineering has become a discipline in itself, branching from the wider and broader concept of biomedical engineering.

However, clinical engineering is continuously undergoing major changes [1]. The origins of clinical engineering can be found in the increasing concerns for patient safety that arose in the 1960s because of the proliferation of clinical equipment in the medical arena. The functions of clinical engineers were at that time mainly focused on repair of equipment and carrying out routine electrical safety inspections. As equipment became more complex and grew in number, it became obvious that electrical safety failures represented only a small part of the overall safety problem. Investigators of accidents found that the users of clinical equipment did not completely understand its operation and most of the instruments were not properly maintained. Furthermore, they found that many devices did not perform as specified by the manufacturer [2]. As clinical engineers entered the hospital environment, they took care of these problems, developing routine programs for integral safety and performance inspections. These actions made hospitals consider clinical engineering departments as a tool to provide the hospital with solutions to safety problems. The clinical engineers of today play a multifaceted role in the clinical environment, as the result of their continuous and growing involvement with the management of clinical equipment. They regularly interact with the clinical staff, the administrators of the hospital, vendors and manufacturers, the clinical engineers at other healthcare institutions and regulatory agencies.

It is in this continuously changing scenario that we need to revise how we approach the education and training of future clinical engineers. As we prepare to enter the next millennium, we need to create academic programs that are in consonance with the industry needs of today as well as to anticipate the needs of the future professionals. This paper will explore academic activities and tools that can be developed to serve the professional needs of future graduates in clinical engineering programs. Although the experiences presented and discussed in this paper are based on clinical engineering in the United States, they can be easily embraced by other countries. The issues addressed in this paper to clinical engineers also affect biomedical engineering technologists, as they work in the same environment and have similar roles and responsibilities. One of the differentiating factors from the International Certification Commission for Clinical Engineering and Biomedical Technology to provide certification for clinical engineers and biomedical technicians is based on the education of these professionals (http://www.aami.org). Currently, certification is not required in the United States for clinical engineers, although achieving this certification is positively viewed by employers and healthcare institutions.

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THE NEW CLINICAL ENGINEERING SCENARIO

The job responsibilities of clinical engineers are continuously increasing. Their traditional roles of maintaining and repairing medical equipment, and performing safety analysis of the equipment are still valid today. However, these traditional roles need to be redefined accordingly with the changes in technology. Newer medical equipment is becoming more reliable, thus diminishing the need for repairs. New technologies, such as integrated circuit custom design and surface-mount components, make the repair of the equipment more difficult and challenging. Most of the equipment today also contains microprocessors and is computer-driven, which adds additional complexity. A common trend in most clinical engineering departments is to move from a component-level troubleshooting approach to a board- or system-level troubleshooting and repair approach. As systems become more complex, more powerful and with more options, the number of possibilities for malfunctions and erroneous configurations also increases.

The maintenance of medical equipment is still not only a very important part in the jobs of clinical engineers, but it becomes a critical issue for risk management. Risk management was first introduced by the Joint Commission for Accreditation of Healthcare Organizations (JCAHO) in 1988. The concept of risk management is based on the fact that the work done in a hospital will always have a certain risk associated. Consequently, the hospital administration must establish an acceptable risk for their institution in order to minimize possible injuries or death to patients and employers or property damage. Today, risk management requires communication, teamwork and sharing of information among the clinical staff, manufacturers and other healthcare providers. The function of the clinical engineers in this environment is to develop proactive risk management techniques within their areas of expertise. Clinical engineers evaluate the risk of an instrument assigning a static risk factor and a dynamic risk factor to the instrument. The static risk factor classifies new equipment by its type and function, assigning to them two parameters. The first one defines the application and environment where the equipment will operate and the second one measures the physical risk category, that is the worst-case scenario in the event of a malfunction.

The dynamic risk factor also consists of two parameters. The first one looks at the maintenance history focusing on the average required manpower per year, planned and nonplanned. The second parameter assigns risk points to individual equipment for each risk occurrence. Because these parameters are based on events that change with the history of the instruments, they change dynamically. Clinical engineers assign a number in an arbitrary but consistent scale from 1 to 25 to each one of these four parameters. The sum of risk factors produces the risk priority for each instrument that is used to determine the priority on attempting to repair the instrument, execute preventive maintenance, user education, test the equipment, etc. [3].

Table 1 shows how risk points are distributed according to these parameters. Because of the critical function of risk assessment, clinical engineers need to know the basic working principles and possible effects of failures for all the equipment in the hospital. They also need to be familiar with the procedures for risk assessment and how these policies are implemented in their facilities. For example, a blood and plasma warming device can be classified with 5 points of equipment function and 5 points of equipment risk, while a pulse oximeter would have 18 points of equipment function and 15 points for equipment risk. The last components of the risk assessment, the dynamic factors depend on the particular history of each unit and cannot be generalized. It is then, the responsibility of clinical engineers to assign risk points to each one of these categories.

The newest approach to risk management differs from the previous points. They are based on classifying medical equipment in intrinsic device risks, that is, physical, clinical and technical. Then, the risk rating system is based on engineering endpoints such as clinical measurements or the energy that they deliver. This newer approach has the advantage that by classifying the equipment according to engineering endpoints allows us to monitor technical parameters during routine maintenance. It stills classifies the equipment as ordinal data, which allows us to establish priorities if it is necessary, and finally it assesses the type of risk more accurately [4].

In addition to their main duties of repairing and maintaining medical equipment, clinical engineers often assist clinical staff with their technical expertise in the purchase of new equipment, by interacting with the manufacturers and vendors. They are also involved in the preparation of the inspection visits that accreditation agencies regularly do to hospitals and other healthcare institutions. Other responsibilities include: inspection of all incoming new and repaired equipment, calibration of the medical equipment, equipment inventory control, coordination of the external services performed by manufacturers, training of clinical staff in the effective and safe use of the equipment, and input in the design of facilities where medical equipment will be used among others. In summary, they provide extensive engineering services to their healthcare institutions.

Clinical engineers are also actively involved in the testing to ensure that medical equipment will continue to work safely after January 1st, 2000 (Y2K issues). Because the new generations of equipment are computer controlled and software driven, it is imperative to ensure that they will continue operating as they were intended to do after the change of year, especially with critical equipment such as life-support systems. After reviewing the information available for medical instrumentation, the Food and Drug Administration (FDA) in the United States concluded that only the manufacturer had the intimate knowledge of the design of their instruments to effectively evaluate the potential risks for patients. The FDA determined that the most effective way of informing the public about the compliance of medical instruments with Y2K was the voluntary reporting by the manufacturers [5]. However, most clinical engineering departments go beyond the manufacturer's self-report on compliance with Y2K and have developed plans to test all the medical instruments in their hospital to ensure the safety of patients and clinical staff.

CAREER OPPORTUNITIES FOR CLINICAL ENGINEERS IN THE NEXT MILLENNIUM

Although the job responsibilities of clinical engineers are continuously changing and increasing, we can distinguish three main categories of employment as outlined below:

1. The first type of employment is in the clinical engineering department of a hospital or healthcare institution, where clinical engineers are responsible for the maintenance, repair and management of the medical equipment that is not under warranty or service contract from the manufacturer. This has been the origin of the clinical engineering profession and it is still the category that employs most of the graduates. The actual responsibilities of these clinical engineers depend on their function and title. The *Journal of Clinical Engineering* publishes an annual report of salaries and responsibilities of clinical engineers employed in hospitals in the United States compiled from the information provided by 9,000 clinical engineers [6]. This report is widely used by hospital administrators to establish compensation packages for clinical engineers. The analysis divides clinical engineers into eight different categories depending on their experience and responsibilities, and in seven geographical areas throughout the United States. Clinical engineers in a hospital are also normally involved with the investigation of accidents and hazardous equipment recalls from regulatory agencies. Because of the complexity of the equipment and the large number of different instruments, professionals in this area of employment need to know how changes in technology and management will affect the future of clinical engineering. They need to be prepared to respond to changes in the profession. Consequently, educators need to incorporate into the curricula activities that, in addition to the technical aspects of clinical engineering, address their socio-economic issues. During their professional careers, clinical engineers also need to be continuously trained and updated on in-depth technical issues of equipment as well as management procedures and strategies.
2. The second category of employment is with manufacturers of medical equipment. Here clinical engineers provide technical service and support the equipment under contract with a hospital. Normally, these professionals, also known as field service engineers, become highly experienced with the products that they serve. They usually work with the high-tech end of medical equipment such as different imaging systems, surgical lasers, etc., which have a high economic cost to the healthcare institution that decides to buy service contracts or warranties. Because of the constant introduction of new equipment with more advanced technology, clinical engineers in these positions need to keep their knowledge and skills on the cutting edge. Other clinical engineers have the responsibility of providing technical support to the more difficult problems that field service

Table 1. Criteria for establishing static and dynamic risk factors in medical equipment: the equipment is classified according to static factors; its function and the potential hazards in case of a failure and dynamic factors; the history of maintenance requirements for each particular unit and an additional factor that depends on additional history factors.

Elements of risk analysis							
Equipment function		Physical risk		Maintenance requirement	Risk points	
Function/Risk Points		Function/Risk Points		Function/Risk Points	Function/Risk Points	
Life Support	25	Patient or operator death	25	25 divisions based on least to greatest Equipment Type annual unplanned maintenance requirements	Exceeds AHA useful life	+1
Surgical & IC	23	Patient or operator injury	20		Injury	+2
Physical therapy	20	Misdiagnosis	15		Equipment failure	+1
Surgical & IC monitoring	18	Patient discomfort	10		Exceeds MTBF	+1
Addtl. Monitoring & diagnostic	15	No significant risks	5		Repair redo	+1
Analytical laboratory	13				User operational error	+1
Laboratory accessories	10				PM inspection failure	+1
Computer & related	8				Physical damage	+1
Patient related & other	5				PM overdue	+1
Non-Patient	0					

engineers face. These professionals, who are known as technical support specialists, are also responsible for the technical publications that discuss common failures and malfunctions reported by field service engineers. Finally, some clinical engineers who work for a manufacturer of equipment specialize in the training of either customers (clinical staff) or field service engineers. It is critical that the experience of these clinical engineers includes working in the hospital environment or in field service, so they can better understand the needs and frustrations of their clients.

3. The final category of employment is with an Independent Service Organization (ISO) that offers its services to a healthcare institution to support either all their equipment or only specific instrumentation. ISOs act as a third party between the manufacturer and the healthcare organization, helping in most cases to reduce the cost of clinical engineering [7]. They normally serve hospitals that are too small to justify the presence of a clinical engineering department. Some other ISOs concentrate on working in areas where equipment is complex such as lasers or autoclave units or where the clinical engineers are less experienced due to the low number of units installed. In the mid-90s, ISOs appeared to be the largest growing source of employment for clinical engineers as a great number of companies appeared in the market. They were driven by the replacement in some hospitals of their in-house clinical engineering departments by independent providers. However, the situation today seems to have stabilized as most small and medium ISOs have been bought by larger companies [8].

There is currently in the profession a strong need to service healthcare institutions in the most cost-effective manner yet maintaining exceptional quality standards. ISOs have aggressively marketed their companies as an effective system to respond to the needs of preventive maintenance and repair of clinical equipment. However, they cannot totally replace the in-house service provided by clinical engineers employed by the hospital. We can imagine that the future will be built on the coexistence of both approaches. A new emerging opportunity for clinical engineers, and in particular ISOs is based on the growing home healthcare market. Because of the managed healthcare, home healthcare is a growing trend, as the number of healthcare and durable medical equipment vendors has increased logarithmically over the last 5 years. This increase originates equipment management and maintenance needs and a concomitant increase in the number of insurance claims and litigation related to medical equipment. We can expect clinical engineers becoming more involved in providing services to these companies, learning how to implement safety and quality standards and training home caregivers in the proper use of the equipment as well being involved in the management of device accidents and maintenance documentation [9].

ACADEMIC GOALS AND OBJECTIVES FOR CLINICAL ENGINEERING EDUCATION

The key concept in preparing the clinical engineers of the next millennium is to combine the exceptionally good training given by traditional academic programs with the elements that will make the students aware of the industry demands in the upcoming years. The traditional components in clinical engineering education consisted of lectures and laboratory exercises focused on troubleshooting and repairing medical equipment and also performing preventive maintenance. This approach is still perfectly valid today as students need to know the basic working principles of medical equipment, and they need to be able to identify possible causes for its failure. What may be different are the actions taken by clinical engineers as a response to an equipment failure.

Table 2 shows the current academic sequence for Biomedical Engineering Technology at the Wilkes-Barre Campus of Penn State University. From this table it is possible to observe how the curriculum is designed to provide the future professionals with the skills to understand the basic working principles of analog and digital electronic systems as well as the special particularities of medical equipment. Because clinical engineers do not work isolated from the rest of the world and need to interact with other professionals, it is necessary to provide them with the tools to effectively write and communicate with other engineers and clinical staff.

We believe that the structure of the curriculum shown in Table 2 is perfectly adequate to the needs of our future professionals. This is also reinforced by the feedback obtained by the author from interviewing the managers of the clinical engineering departments where the students carry out their clinical internship. However, they also indicate that new directions in the contents of the courses would be desirable. For example, the changes of technology can make it too difficult and too costly to attempt to repair them at the component level. Most of the time it is more efficient to replace a defective board and send it to the manufacturer who can run customized diagnosis testing. As systems become more complex, with larger specialized boards, the communication and interconnection between them becomes an important issue to consider. Communication networks and communication protocols are expected to play a major role in the near future, as clinical equipment is built more in a computer-like basis. The front-end of the equipment, the acquisition circuits may be similar to the ones used so far, but the changes reside in how these systems communicate with host computers in a central station or even to remote locations. Clinical engineering then should consider incorporating elements of telecommunications within their curriculum. However, there is a limitation in the total number of academic credits and time that is imposed by the practical constraints of the universities.

Thus to introduce new concepts in a curriculum can only be done, in practice, by reducing the number of hours that the students spend learning other concepts. And here is where clinical engineering educators face their most critical problem: what part(s) of the current contents should be dropped in favor of the introduction of new ones? A possible answer to this question may come from the changes in technology. Is it still reasonable to spend so much time working in troubleshooting at a component level? Should we focus on giving our students a basic overview of how electronic components work and move towards a system approach, where they work by considering an electronic instrument made of different boards? After all, the managers of clinical engineering departments indicate that the response of the current professionals in case of equipment failure will be to replace one or more defective boards. Unfortunately, because the broad type of work performed by these professionals, it is not possible to find a single solution that will fit all the needs. However, the input from industry makes us move in this direction of a systemic approach.

The clinical engineering managers interviewed also responded that they would like future employers with a broad range of interpersonal and interprofessional skills. In particular, they appreciate professionals with time management and customer skills, professionals with the ability to write clear and coherent documents, professionals able to communicate with other engineers and clinical staff. Fortunately, this kind of knowledge can be built into the curriculum, not as a subject of study, but as a constant practice throughout the curriculum. The Guest Lecture Program that will be described in detail in the next section is an example of this approach. During one semester, professionals from the field come to the campus and talk to the students about their experiences, emphasizing the fact that they will need more than technical skills to become successful professionals.

Another approach to teach the reality of the profession taken by the author is to ask the students to critically analyze a series of articles provided by the instructor. These articles, summarized in Table 3, have been extracted from professional and trade journals in clinical engineering, and have been selected because they discuss critical aspects of the profession. The instructor then provides feedback and follows up on the comments of the students, engaging them in discussion. The pool of articles is expected to grow and change, as new and insightful articles are published. These article reviews are carried over the course of two semesters, which gives the students enough time to think of the problems and challenges that face the profession, but also on the personal rewards of becoming a clinical engineer.

Nevertheless, these changes in technology have deeper implications: equipment becomes more reliable and less prone to failure, most of the equipment is software-driven with self-test and autodiagnosis, and the management of preventive maintenance is easier to schedule, perform and document. The medical instruments of the new generation are computer controlled, can run a diagnosis test on power-up, and are networked to a central station, especially those designed to be used in intensive care units. Future clinical engineers need to have the technical skills to understand how this equipment works and to have the tools to diagnose a fault in very complex systems.

Table 2. Course work required for graduation with number of credits for each course in parenthesis: courses with specific biomedical engineering contents are indicated in bold

BET GRADUATION REQUIREMENTS	
1st SEMESTER	**2nd SEMESTER**
Electrical Circuits I (3)	Electrical Circuits II (4)
Electrical Circuits Laboratory I (1)	Electrical Circuits Laboratory II (1)
Engineering Orientation (1)	Digital Electronics (3)
Technical Math I (3)	Digital Electronics Laboratory (1)
Technical Drawing Fundamentals (1)	Experimental Methods (1)
Introduction to CAD (1)	Technical Math II (3)
Rhetoric & Composition (3)	Technical Physics (3)
Social/Arts/Humanities Elective I (3)	Social/Arts/Humanities Elective II (3)
3rd SEMESTER	**4th SEMESTER**
Biomedical Transducers (5)	Physiology (3)
Social/Arts/Humanities Elective III (3)	**Biomedical Instrumentation & Systems (5)**
Technical Elective (3)	**Medical & Clinical Equipment (3)**
Technical Calculus (4)	Introduction to Chemistry (3)
Fundamentals of Semiconductors (2)	Effective Speech (3)
Semiconductors Laboratory (1)	
5th SEMESTER (Summer)	
Clinical Internship (4)	

Furthermore, clinical engineers need to be familiar with specifications of equipment in order to predict the life expectancy of the instrumentation and to produce technical recommendations to the clinical staff when the hospital is considering the acquisition of new units. These aspects become critical to the management of the instrumental resources in the hospital.

Academic goals in modern clinical engineering programs should also put a strong emphasis on safety issues, for example the compliance of the institution with the Y2K issues, risk management and the advisories from the diverse regulatory agencies that will interact with a hospital. In addition to the basic knowledge of electrical safety of medical equipment, students should be familiar with other possible hazards in the hospital such as chemicals, gases, nuclear material, and mechanical malfunctions. Clinical engineering programs should also address the different safety standards and regulations issued by the corresponding regulatory agencies. Students need to be able to read and understand the different standards issued by the Association for the Advancement of Medical Instrumentation (AAMI) that address the requirements and specifications of medical instruments, and more important for clinical engineers, how these specifications are to be tested. Clinical engineering students should be also familiar with the documents issued by other regulatory agencies that are also involved with the safety of healthcare institutions, such as the National Fire Protection Association (NFPA) and the Occupational Safety and Health Administration (OSHA). In the United States, clinical engineering departments also play an important role in the accreditation visits taken by the Joint Commission for the Accreditation of Healthcare Organizations (JCAHO). In particular, they are responsible for demonstrating that the hospital is in compliance with the issues regarding the safety of the institution, risk inventory and management and preventive maintenance of equipment completed in the scheduled time, among others. Academic programs in other countries will surely have to develop classroom activities tailored to their specific regulatory agencies.

Electromagnetic interference

An emerging issue that is becoming increasingly important in clinical engineering is the Electromagnetic Compliance (EMC) of medical equipment and its immunity against Electromagnetic Interference (EMI). This is a relatively new aspect of medical instrumentation that is, in part, motivated by the increasing number of high-speed microprocessors and digital circuits in the instruments, as well as the increasing electromagnetic noise environment in which medical instrumentation operates. For these reasons, we can expect EMC to be an increasingly critical aspect in the design and maintenance of medical instrumentation. Clinical engineers will need to know and understand the multiple factors that contribute to the increase in the level of EMI. In first place, the sharp edges in digital signals are known to produce a wide range of harmonics that, together with the higher clock frequencies from their microprocessors, increase the electromagnetic radiation emitted by medical instruments. Digital links and communication between bed monitoring instruments and central stations and computers also radiate interfering energy that can interact with nearby instrumentation.

Clinical engineers need to know how to deal with these causes of EMI that originate inside the

Table 3. Articles presented for critical review by the students: these articles are selected to give them a realistic overview of the problems and challenges of clinical engineering professionals

	TITLE OF THE ARTICLE FOR REVIEW	SOURCE
1	*Think about it: A patient lay dead in the intensive care unit*	*24 × 7 For technical service and support professionals in Healthcare. July 1998*
2	Medical instruments come home. But who keeps then running?	*24 × 7 For technical service and support professionals in Healthcare.* September 1998
3	Is preventive maintenance still a core of clinical engineering?	*Biomedical Instrumentation & Technology.* July 1997
4	Interview: Gail Robinson. Biomed is no longer a man's world	*24 × 7 For technical service and support professionals in Healthcare.* June 1998
5	Frustrating and flicking: when calling your vendor becomes a pain	*24 × 7 For technical service and support professionals in Healthcare.* January 1998
6	Solving technical challenges in difficult conditions	*Biomedical Instrumentation & Technology.* July 1998
7	Human errors and human factors engineering in healthcare	*Biomedical Instrumentation & Technology.* November 1997
8	Don't scare the patients!	*24 × 7 For technical service and support professionals in Healthcare.* December 1997
9	The art and science of troubleshooting medical equipment: a model for troubleshooting medical equipment down to the component level	*Biomedical Instrumentation & Technology* March 1997
9	A survey of the clinical engineer's role within the hospital	*Journal of Clinical Engineering.* November 1997
10	Current healthcare trends and their impact on clinical engineering	*Biomedical Instrumentation & Technology.* May 1997

instruments [9]. They can measure the levels of radiation for offending external instrumentation and use engineering techniques to minimize their effects on other equipment. But because we don't normally have control over the external sources of EMI, they become a more complex problem. The increasing popularity of cellular telephones has caused some hospitals to limit their use in restricted areas with sensitive instrumentation. Although this approach solves the problem of their possible interference, it does not address its origins or make the design of instrumentation immune to this source of radiation. It is not unreasonable to expect that future personal communication systems that will be used inside the grounds of the hospital by clinical staff and emergency response personnel will cause similar problems that will need to be addressed by clinical engineers and manufacturers of medical instrumentation.

The possible interaction of cellular telephones with implanted therapy systems, mostly pacemakers and defibrillators, has also been a source of controversy [11]. Although the technical community agrees that there is little possibility of interaction between cellular phones and pacemakers, they also recognize that it is necessary to carry out further investigations. In the meantime, users of these implanted devices are instructed to follow certain guidelines based on separating as much as possible the antenna of their cell phone from the region of the body where the unit is implanted. Another important source of external interference in the clinical environment is the use of two-way radios, especially in the ambulance bays of the hospitals. These radios may affect the instrumentation in the nearby services, normally their emergency room. In this case, because it is not possible to eliminate the source of interference, clinical engineers must use their knowledge of EMC/EMI in order to shield these rooms from the high power radiation coming from the ambulances and two-way radios [12].

In the last few months, clinical engineers in some large cities have found a new source of EMI: the tests from some television stations of High-Definition Television (HDTV) broadcasting. They have severely interfered with telemetry systems used to monitor the status of patients inside the hospital. This has originated because some of the newer frequency bands for patient telemetry are assigned as a secondary service shared with television stations [13]. In the past, these television channels were empty or transmitted relatively low-power analog television signals. As the stations started to use them for HDTV, their high-power digital signals totally interfered with the low-powered telemetry systems. The immediate solution to this problem was to change the frequency band of the patient telemetry systems, although it is reasonable to expect additional problems when HDTV systems are used normally in the near future. Clinical engineers need to evaluate the immunity of their telemetry systems to HDTV and eventually be involved in their redesign.

Some portable video game systems have also been banned from critical areas of hospitals because the radio-frequency leakage that they produce has interfered with critical care and life-support systems.

All these examples and recollections show the need for clinical engineers to have a solid technical background of today's technology as well as technologies that will be used in the future.

Clinical engineers need to have not only good technical skills, but also strong interprofessional and interpersonal skills. Academic programs should always stress the importance of correct writing and especially the consequences that ineffective writing can have on the careers of clinical engineers. Students in clinical engineering programs normally have a strong interest in electronics and technology, and in some cases may view writing as a chore instead of a vehicle to communicate the results of their work. Students should be familiar with writing service and operating manuals, technical memorandums and documenting the work they carry out in the laboratory [14]. Clinical engineers need then to have the ability to translate their opinions and experiences with this equipment into technical specifications to be used in future equipment acquisitions. In addition to having strong writing skills, clinical engineers need to have good interpersonal skills. They normally interact on a constant basis with nursing staff that reports malfunctions of equipment, provide feedback on how other medical instrumentation is performing, or simply let them know what features they would like to have in a certain piece of equipment [15]. Although not very common, sometimes clinical engineers need to work on equipment connected to a patient. In these cases it is imperative that they exhibit a strong professional conduct to decrease the anxiety that such work can produce in the patients and their families.

EDUCATIONAL TOOLS FOR THE CLINICAL ENGINEERS OF THE NEXT MILLENNIUM

New goals and approaches in clinical engineering education demand academic tools that, combined with the traditional ones, can create a learner-centered approach. This kind of approach shifts the learning process to the student, which makes the students more understanding of the global issues of their profession. This section discusses tools that have been experimented with by the author in his clinical engineering program. They should not be considered as the only available resources, as other academic institutions have successfully employed different methods in similar academic programs. When we incorporate in academia educational tools that are based on new technologies, we must carefully evaluate not only their benefits, but also their possible drawbacks [16].

Academic programs are still solidly based on theoretical lectures and experimental work in the laboratory. Lectures in the classroom should address the basic knowledge of electricity and electronics, physiological transducers, the basic origins of biopotentials and biological signals, and the interaction between living tissues and electricity. Because of the nature of the clinical engineering jobs, lectures should put a strong emphasis on the safety of technology users and patients. On the other hand, the laboratory is used to visualize the concepts previously developed in the classroom as well as to encourage the curiosity in the students in new areas not yet covered. Experimental activities should have a component of troubleshooting medical instrumentation, not only at the component level, but especially examining the interaction between different subsystems. The clinical engineering students need also to be familiar with the correct use of medical instrumentation, as it has been shown that a large number of service calls in a hospital are due to an erroneous configuration [17]. Clinical engineers need to quickly assess whether the instrument needs a change of configuration parameters or has a problem that requires further investigation. Modern systems have extensive configuration possibilities, normally through a series of menus and submenus that can confuse inexperienced users. In some other cases, the memory of the instrument will remember the previous configuration that may not be the most appropriate for a new patient. The experimental laboratory work needs to use different patient simulators that produce different signals (normal and abnormal ECG, blood pressure, pulse wave, etc.) in order for the students to recognize them easily. The author uses an approach that balances laboratory experiments with a strong electronic and transducer content with other experiments designed to show the correct operation of instruments and the expected signals in different operation modes.

New activities in clinical engineering education should be designed to move industry closer to the classroom. Students need to be aware of the current needs and demands of industry in their respective fields. This contact with industry is more effective if introduced into the curriculum early, as it will allow students to have a clearer vision and understanding of roles and responsibilities of clinical engineers and how they fit into the healthcare system.

There are several useful ways to effectively bring industry closer to the students. The Guest Lecture Program used in the author's curricula is a series of presentations given by professionals from the clinical engineering field that runs for two hours a week during one semester. This program gives the students the opportunity to learn about the different kind of industries and jobs in the field and their current important issues. The lectures are balanced between some with high technical content where the speakers talk in detail about specific medical instrumentation and some others aimed at providing them with a breadth of perspective. They focus on the aspects of clinical engineering profession that have been traditionally forgotten from academia, but have a strong impact in their careers, such as the importance of effective writing, interaction with different clinical staff, and safety in the workplace among others. Because the two campuses of Penn State University that offer this academic program are more than 300 miles apart, the speakers go to one of the campuses and their lecture is transmitted to the other campus by interactive videoconferencing. The use of this technology allows for reaching a higher number of students while limiting the costs and problems associated with travel and speaker coordination. However, the use of compressed videoconferencing is not exempt from problems such as image degradation, audio delays and losses of the carrier signal between campuses what can cause frustration to the students [18].

The concepts explored during these lectures are elaborated upon by a series of articles that the students are required to critically review as described in the previous section. Finally, distribution lists through e-mail that carry discussions between clinical engineers are another very important tool to move academia close to industry. By subscribing to these lists, students experience an open window on the day-to-day topics that are important to professionals in the field that cannot be achieved during regular lectures or laboratory experiments, and experience a sense of belonging to a professional community. Some of the topics that are discussed in the list are worth further discussing in the classroom, thus giving the students a complete perspective on the topics of interest.

The most effective method to expose students to the world of clinical engineering is by immersing them into a professional setting. We accomplish this by two means: field trips to hospitals during the regular courses and a clinical internship that the students need to take after finishing the regular courses. Field trips to hospitals always have a positive impact on the students as they can experience first-hand a real work environment. These trips are, for most of the students, their first view of the healthcare system as a professional rather than being just a patient. Students can observe the equipment in the hospital that is the responsibility of the clinical engineers, from the unique imaging machines to the most common diagnosis tools. In the hospital, the students have the opportunity to see state-of-the-art medical instrumentation that is not available in the academic laboratories, familiarize themselves with this working environment and start to understand the role of clinical engineers in the institution.

After they finish the regular courses, we require our students to take a 400 h internship in a hospital. This clinical internship provides the students with the opportunity to acquire actual work experience before graduation. They are exposed to the different departments in the hospital and their medical instrumentation, learning not only the technical aspects of their work, but also the culture of the workplace and how to interact with other professionals. During the internship, the students are assigned different supervised tasks, starting from basic preventive maintenance to taking on more complex and challenging tasks. These activities increase their self-confidence as they have the opportunity to work without the pressures associated with new employment and realize that they can complete their assignments satisfactorily. During this period, the students are required to complete a daily log that summarizes their activities in the hospital. This daily log can be used by the faculty to assess in which areas the students feel more and less prepared and consequently, to modify the curricular contents of the program. When the internship is finished, their supervisors at the hospital are required to evaluate the students in different areas of their technical competencies. The students have always valued the internship as a very positive experience that taught them the reality of the profession, as well as opened to them doors for their future employment as clinical engineers.

CONCLUSIONS

The clinical engineering profession is undergoing major transformations as the result of technological advances and socio-economic changes. The increasing complexity of the new equipment units requires that clinical engineers, both in-house and from independent organizations, become more specialized. On the institutional side, the higher cost of specialized equipment does not allow for redundant units to act as a back-up in case of failure, which increases the pressure on clinical engineers to solve problems faster to keep units down to as short a time as possible.

Clinical equipment is today safer and more reliable than in the past, contributing to the overall safety of patients and clinical staff [19]:

> In the 1970s truly dangerous pieces of medical equipment were in daily use. There was little protection for operators or patients from electrical shock if a device failed. Grounding was not widespread and current-limiting devices were rare . . . This is not true today. The mean time between failures claimed by manufacturers of medical equipment is in the range from 7 to 10 years. Given the average life span of medical equipment in daily clinical use, the equipment will be replaced before a failure occurs.

Medical equipment is more powerful, yet more complex to use, having multiple configurations and possibilities. Clinical engineers are in the transition from a basic task of repairing and maintaining medical instrumentation, to becoming technology managers in the healthcare industry. They are involved in assisting the primary users of the instrumentation such as physicians and nursing staff. They also act as technical experts in future purchase decisions and are involved in safety and risk management. All of these changes in the profession need to be reflected in the academic programs that train future clinical engineers. These programs will produce highly qualified professionals that are able to carry out the tasks demanded in their industry today, as well as what will be demanded from them in the future [20]. Clinical engineers have also the support of local, regional and national organizations that act as a forum to discuss the problems faced in the profession. In the United States the main national organizations are the Association for the Advancement of Medical Instrumentation (http://www.aami.org) and the American College of Clinical Engineers (http://accenet.org/).

The approaches in clinical engineering education that have been presented in this paper focus on two main aspects. First, the contents of academic programs need to be in consonance with the skills that hospitals and industry demands from professionals. In the second place, the technological tools that we have available today such professional distribution lists by e-mail, Internet, interactive videoconference, etc., play a critical role, giving students a broader and more complete vision of the clinical engineering profession. We believe that clinical engineering programs should be presented as a set of knowledge that the students are required to master to become successful professionals instead of a series of independent courses that they need to take in order to graduate. It is important to put a strong emphasis on the interrelations between different subjects of study to achieve a common goal. Obviously, the education of clinical engineers is not a process that is finished when they first graduate from college, but it is an uninterrupted process where they learn continuously about the human and technical resources that surround them. The earlier students are introduced to the clinical engineering profession, the better they will understand its demands and requirements.

It is without doubt that all these approaches put additional work on the faculty, as they need to create new ways of instruction delivery and experiment with new technologies. However, the positive effects that these methods will have on the professional performance of graduates clearly counterbalance any inconveniences. These new academic approaches, based on shifting some of the academic activities from a teacher-centered approach to a learner-centered approach, allow the students to observe the reality of the profession at an earlier stage and consequently to become more interested and involved in the academic program, thus working synergistically to produce better professionals.

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