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Biomedical Engineering Education for Developing Countries

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Biomedical engineering (BME) finds itself at the intersection of the emerging disciplines of humanitarian engineering and global health, through its role in developing sustainable technological solutions to improve health and addressing health disparities. It provides a framework within which to educate future leaders to design and implement health technologies that are appropriate and useful in their social context, particularly because of its multidisciplinary and design-oriented nature [1]. Some universities in the United States have included an engineering component in their global health programs [1]–[3] or included global health and development components in their BME curricula [4].

Debates about the nature of development [5] form the background to the emergence of humanitarian engineering, which is also referred to as "engineering for development" [6], [7]. This new discipline represents a transition in engineering education in two directions [8]. First, engineers are being educated to address issues of human development and to regard engineering as a service to humanity. Second, they are being prepared to work in a global context to ensure global competitiveness, cultural inclusivity and sustainable design.

BME educators from developed and to a lesser extent from developing countries have described not only the content of their BME programs, but also the challenges and successes of their implementations. Published work on the broader area of humanitarian engineering education, however, has mainly originated in developed countries. Much of this literature is directed at preparing engineering students "to become facilitators of sustainable development, appropriate technology, and social and economic changes" [6] not only in their own but often in poorer countries [8].

Developing countries are typically societies in transition, often displaying large socioeconomic disparities and significant political tensions. They are not homogeneous societies: the richest often lead lives and have incomes comparable with those of the middle classes in the developed world, while the majority live in impoverished contexts. Moreover, many developing countries have capabilities in engineering education approaching those of developed countries. They may benefit from the lessons learned by the latter in implementing education in humanitarian engineering, and more particularly in BME for development, provided they respond to the concerns and needs of the marginalized.

This article summarizes research on these topics. A research synthesis rather than a traditional narrative review is presented, with the aim of deriving solution-oriented knowledge, or design propositions, for BME programs. The approach entails reviewing the literature with reference to a problem context, for which interventions are suggested; interventions produce, through particular mechanisms, intended outcomes [9]. The context describes engineering students, their educational environment, the social conditions and the communities in which engineering and BME practice takes place, and the relationships between engineers and the communities. The interventions refer to the types of educational activities engaged in, the mechanisms are the pathways through which the interventions are effected, and the outcomes are the actual or expected results of interventions. Components of different humanitarian engineering and BME programs are synthesized to represent what has been proposed or implemented to produce graduates able to address health problems in a contextually appropriate manner. General attributes of educational programs rather than specific curriculum topics are covered. The suitability of such educational programs for a developing country context is discussed.

BME in Developing Countries

Advances in health care and improved population health are driven by scientific and technological progress, and mediated by BME. Health in turn drives employment, innovation, sustainable development, and growth [10]. The improvements in living conditions and life expectancy enjoyed in the developed world result from achievements in medicine and engineering during the past 150 years. However, few of these benefits have reached developing countries, with the majority of engineering design efforts being targeted at the richest 10% of the world population [6].

Innovation, including medical device innovation, is generally considered a key contributor to progress in public health [11]. The term innovation covers the entire process from the generation of new ideas to their transformation into new or significantly technologically improved products, services, methods, manufacturing processes, and management structures or policies, to their implementation [12], [13].

Despite assertions of the potential of science, technology, and innovation to improve the fate of the global poor, the literature on innovation contains little reference to the poor and to mechanisms for poverty reduction [14]. Conventional measures of innovation, such as patents, show little evidence of biomedical engineering innovation in the developing world [15].

A systematic review of the social science literature on innovation in low-income countries revealed that 26% of papers accounted for health related innovations [14]. Issues of concern covered the entire pharmaceutical value chain from drug development to disbursement, innovative medical equipment, institutional arrangements for health service delivery, and contextual factors affecting the adoption of technologies developed elsewhere. The review found a relative neglect of contextual factors in publications on health innovation in low income countries. Most of the papers analyzed described innovative ways to address particular problems, with only a few addressing the influence of context on implementing solutions. This finding is attributed to a view of technology as a freely available public good which can be assimilated without cost. However, in the same way that society is not merely a collection of people, but also their interrelationships, technology includes the relationships among innovations and their relationships with people [16]. Therefore, contextual factors such as health systems and their capabilities should be considered [14].

Studies on the adoption and regulation of health technologies have predominantly targeted the developed world, while scant attention has been given to developing countries [17]. Over 95% of medical equipment in public hospitals in developing countries is imported, and much of it is of poor quality and does not meet the needs of the health care facilities using it [18], [19]. A significant gap exists between innovations in health, which usually originate in the developed world, and their delivery to communities in the developing world, largely because their implementation is "untested, unsuitable, or incomplete" [20]. Several reasons for the implementation gap have been identified [20]: the social constraints and health threats faced by impoverished communities make health care more difficult; scientists fail to pay attention to the complexities of implementation and neglect the analysis of health delivery schemes; and the planners of health delivery systems assume that innovations can be applied in the same manner in different settings. A study of the diffusion of CT scanners in Brazil found that technology adoption decisions are linked to the organizational strategies of health care providers rather than being based on public health needs or priorities defined by health policy [17].

The biological, social, and environmental factors impacting the implementation of health care innovations should be analyzed, and researchers should be trained to bridge the implementation gap between technology and health care delivery [20]. Design of medical technologies should consider factors in the business environment such as medical device registration, product standards, intellectual property, and import/export policies [21].

Innovation in health care has been contrasted with that in agriculture. The appropriateness of technology, its contextualization, and the involvement of its users in design and implementation are more evident in agriculture than in health research on innovation in low-income countries [14]. The mismatch between economic conditions surrounding agricultural product use in designer and user countries, has promoted a design process in which technological design is not considered complete until the product has been adopted [18].

The above suggests two important considerations for BME education and practice in developing countries: that the work that is likely to make the most impact may address different problems from those for which a developed country curriculum may have prepared graduates; and that local context impacts on problems in ways that affect the design of effective, implementable solutions.

Challenges in BME Education

A number of universities in developed countries have embarked on global health programs to train students in, and to develop solutions for, the health problems of the developing world. Some of these multidisciplinary education programs include a BME component. They attempt to prepare students for careers developing and disseminating interventions that advance global public health, and they produce researchers able to interact with governments, non-governmental organizations (NGOs), and communities to devise and implement sustainable health care solutions [1].

BME education and research rely on collaboration with health care providers. Engineers and clinical professionals tend to focus on different aspects of technology: clinicians are concerned with ease of use, while engineers are excited by innovation; this dichotomy results in a communication gap which may be bridged by acquainting BME graduates with the language of medicine and with the way in which clinicians think [22]. The same may be said for the gap between engineers and professionals that deal with the social and political aspects of medicine and health care.

Student exposure to social and political issues is often achieved through international humanitarian engineering placements, in which students from developed countries do service learning or work-study in developing countries. These have been criticized as a new form of colonialism, benefiting the visiting student more than the host community [8], [23], and focusing on students' educational benefit and their universities' philanthropic ambitions rather than on the welfare of the target communities [24]. The following concerns have been raised with regard to international placements in poor communities [8], but apply generally to attempts at engineering for development: social structures are difficult to understand across cultures; interventions by outsiders can create damaging dependencies in developing communities and undermine the self-determination of the hosts; external influence on cultural practices may be detrimental; technology transfer is difficult; and interference by outsiders can give rise to unequal power relationships. Despite the risks, however, such placements have the potential to promote social justice and development and inspire students towards further work with marginalized communities.

Further barriers to effective engagement of engineers with communities are located in their beliefs and educational culture [24]. Engineers believe that a particular order defined by science and technology brings progress. Engineering problem solving and reliance on the scientific method emphasize the technical rather than the community, social justice, and the environment. Engineers tend to regard communities as homogeneous entities. In addition, engineers often disregard structural and political constraints to development and social justice, and the dependence of project sustainability on community engagement [7]. Engineering students and graduates as well as students entering university intending to study science, technology, engineering, or mathematics have been found to be less socially and politically engaged and culturally aware than their peers, and are inadequately prepared to deal with the ethical realities of engineering practice [25]. These limitations become more pronounced in a developmental context. The dynamic nature of BME practice and the regular emergence of new sub-disciplines [26] pose additional obstacles to the identification of and engagement with ethical issues. The inherent difficulties in applying engineering principles to biological data, such as high dimensionality and low signal to noise ratio, may lead to complex engineering solutions that are not practical in a clinical setting, if engineers disregard clinical context [27].

Research suggests that women and other underrepresented engineering student groups more readily enter fields that they recognize as having a broader impact on society [28], [29]. Despite the beliefs and culture described above, social context appears to have played a role in attracting women to engineering in some cases; a desire to contribute to society and the perceived role of engineers in the community have been identified as motivators for women entering engineering [30].

Interventions and Mechanisms

Key interventions found in the literature on education in humanitarian and biomedical engineering are described below.

Courses and Projects

Courses in humanitarian engineering have been introduced to develop in students "an understanding of the ethical, cultural, historical and technical dimensions of engineering work applied to community development" as well as "an ethical awareness and global understanding of the worldwide human condition but also a sense of responsibility to use their engineering knowledge to solve problems that address basic human needs" [28].

Design projects are a major component of humanitarian engineering and global health curricula and often take place at external sites [2], [3], [28]. Topics to support a design-based BME curriculum include [1]: current problems in health and how they differ in developed and developing countries; who pays to solve health problems; how technology can be used to solve global health problems; and how technologies move from the bench to the bedside.

Exposure to Real-World Situations

Pedagogies of transformation inform efforts to overcome the challenges of international student placements, by exposing students to situations that enable them to develop a willingness to accept uncertainty, engage in critical reflection, and use the larger social context as the starting point for humanitarian projects [31]. Disruptive learning takes place in an environment that challenges established patterns of experience and causes students to reassess the foundations of their experience and knowledge. Problem-oriented learning presents problems in real-world settings, enabling students to contextualize knowledge. Community service learning and community based research emphasize the role of the community in developing solutions.

Exposure to real-world situations in which BME problem-solving is required typically takes place through collaborative linkages and partnerships with governments, NGOs, clinical practices, communities, and industry. Partnerships between universities in developed countries and health care providers in developing countries [1] and public-private partnerships that extend from developed country universities and industry to developing country universities [2] have been reported. Student learning is enhanced through critical analysis of the organizations within which experiential learning takes place [23]. Furthermore, the following benefits are achieved through university-industry interaction in BME [32]: universities become aware of current technologies being used in industry and are able to prepare students to meet industry needs; universities obtain industry input into research projects and funding for projects; students become familiar with different aspects of industry and prepare for their careers.

Disease-based case studies are used to attune BME students to clinical context [22], while humanitarian case studies involving socio-technical problems promote attention to community and social complexity [31]. Student-initiated community engagement and peer-to-peer training events and seminars [33] broaden the student experience. Participation of social scientists, economists, and others with significant cultural knowledge increase the likelihood of successful involvement of the community in community-based projects [23].

Contextual Listening

Majoring in engineering has been negatively associated with listening skills [25], yet listening to the community has been emphasized as a factor that promotes successful socially responsible engineering for development assistance [34].Contextual listening has been suggested as a component of engineering education to promote effective student engagement in sustainable community development efforts [35]. Such listening goes beyond hearing and paying attention to verbal and non-verbal messages, and enables the engineer-listener to understand project context and facilitates social learning and shared meaning with communities [24].

Ethics and Policy

The implications of BME technologies must be considered within an ethical framework and with reference to public policy, which includes, among other things, policies on funding and intellectual property, and regulation impact on the practice of biomedical engineering. Student exposure to science policy and ethics can be facilitated by seminars and informal discussion groups [36].

Suggested topics for formal ethics in BME education that provide a foundation for sophisticated thinking about ethical dilemmas, include fundamental, research, professional, and social ethics [26]. Professional codes of ethics in engineering have been proposed as a framework for formulating the goals of engineering education in ethics and professional responsibility [25]. A case study approach for introducing basic engineering and medical ethics principles for use in constructing ethical arguments and making ethical judgments has been well received by students [37].

Outcomes

Education in BME and in humanitarian engineering aims to produce graduates who [1], [6], [25], [28], [38]: understand the role of engineering in supporting basic human needs; have a mixture of skills to address global problems; are able to work in interdisciplinary teams in which they are able to communicate effectively with collaborators; are able to operate in developing communities; are able to operate in the face of uncertainty and in unfamiliar contexts; are systems thinkers able to consider the social, environmental, economic, and political context of engineering decisions and to discuss the broader impact of engineering research; are able to recognize ethical dilemmas and view them from multiple perspectives; and are humble in their approach to developing communities. Students are also expected to emerge with a career interest in global health technology, research, or policy [1]. The humanitarian component of the curriculum is expected to make it more appealing to some women and members of other underrepresented groups [28], [29], who might otherwise find the perceived engineering culture uninviting.

Awareness of Context

The public health and other crises experienced by developing countries have inspired developed-world engineering schools to offer programs in global health and humanitarian engineering. But many developing countries also have the facilities to educate engineers in the manner of the developed world and are able to address their health challenges directly through BME.

Literature on preparing students in BME for development and in humanitarian engineering has originated primarily in developed countries, and is informed by the perspective of universities in developed countries engaging with marginalized communities in either their own or developing countries. Developing country students with access to higher education in engineering are more likely to come from the developed rather than the developing sectors of such countries and may face socioeconomic and cultural gaps when working in marginalized communities.

Developing countries may benefit from the design propositions synthesized here from educational research and practice in developed countries, as the target students as well as the application domains in the two situations have common characteristics. Thus the same educational interventions used in developed countries to nurture a global perspective in students of BME and humanitarian engineering can also be used in developing countries to emphasize the needs of local communities, towards the ultimate production of graduates who are able to address these needs. These interventions include experiential training through partnerships, teamwork, case studies, and exposure to policy and ethics, as well as increasing the diversity of the student population and the engineering work force and thereby contributing multiple perspectives to engineering practice. Exposing BME students to industry through internships would improve the ability of graduates to contribute to medical device industries in developing countries.

Effective engineering education in developing countries would, however, have to exceed these interventions. While humanitarian engineering strives to address questions retained from the appropriate technology movement of the 1970s, such as the roles that technology should play in development, the mechanisms that should be employed for knowledge and skills transfer, and the relationship between the producer and the recipient of technology [7], it should acknowledge that technology is not always neutral and equally deployable in all settings [16].

Although awareness of context and exposure to real-world situations are emphasized in the educational interventions surveyed, the literature often fails to explain how equitable engagement with communities in marginalized and impoverished settings may be achieved. Partnerships are a key component of the interventions implemented, yet are not interrogated in great depth. Not all partnerships are equally developmental. A partnership with a private hospital in an urban setting in a developing country would provide a vastly different student experience than one with a community organization in a rural area in the same country. Partnerships with governments may address the "needs" of the elite 10% of a developing country or those of the impoverished 90%. Disaggregation of partner groupings will reveal those partners able to provide access to communities in need and enable context-specific development and education in an enriched and enriching partnership.

Engineering programs in developing countries have an opportunity to engage in close long-term partnerships with local communities and community-based organizations and co-evolve their curricula in humanitarian and biomedical engineering with changing community needs so that student involvement benefits not only the student but also the community. This may lead to a different type of "world class" research, which does not rely on imitating developed world solutions, but rather draws on the unique experiences and needs of developing communities, and the intellectual specificity that exists in them, to devise distinctive, contextually appropriate solutions. These solutions may well be adapted for application in developed countries, forging a new path for technology transfer. Similarly, the educational solutions designed in the developing world may enhance the engineering curricula of the developed world. In this sense, contextual relevance may enable world class status for biomedical engineering education in developing country universities.

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