

The Applications and Prospects of Fuel Cells in the Medical Field: Insights from Health Assistants, Respiratory Therapists, and Nurses in Saudi Arabia

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1. Introduction

Fuel cells are devices that convert chemical energy from fuels into electrical energy through an electrochemical reaction. Fuel cells emerged as a commercially viable alternative for the production of “clean” energy and are viewed as an environmentally friendly technology that can play a significant role in the energy economy of the future (K. Niakolas et al., 2016). Fuel cells have numerous applications in a wide range of economic activities including portable devices, vehicles, and stationary power generation. The medical field finds itself needing new energy solutions as technologies compete to become more reliable, portable, and self-sufficient. This adds pressure to find new energy sources to power the equipment used to promote patient health. Saudi Arabia’s healthcare systems are emerging to trenchant and ingenious solutions to issues such as their ongoing need for expansion and the consequences of unbridled uneven growth within the nation’s provinces.

Health Assistants, Respiratory Therapists, and Nurses hold many of the roles crucial to patient care during their most vulnerable moments. This unique perspective on health and the technologies employed to maintain it can provide valuable insights into the emerging usage, applications, and expectations of fuel cells within the medical field. A better understanding of the needs and expectations of these health professionals can guide the proper alignment and future development of fuel cell technologies. The reliability and efficiency of medical equipment is paramount to promoting patient health. As such, technologies that promote health must compete with one another to gain a foothold in the market. This promotes the need for an understanding of how these technologies will be applied and what obstacles must be overcome before they can be effectively employed. Fuel cell technology promises to enhance the reliability and efficiency of medical equipment used to promote health and treat illness. Collectively, a deeper understanding of health professional’s insight on these technologies will promote their effective alignment within the medical field. The machinery that promotes health is as much a part of that health as the nurses and patient’s own biology. Fuel cells have the potential to drastically change how the progression of health is monitored and how illness is treated.

The goal for this research is to gain a better understanding of the applications and prospects of fuel cells in the medical field through the lens of Health Assistants, Respiratory Therapists, and Nurses. How do these health professionals see fuel cell technology being applied in the medical field? What do these health professionals expect from fuel cell technology in the medical field? What needs to be done to properly implement fuel cell technology in the medical field according to these health professionals? In Saudi Arabia, Health Assistants, Respiratory Therapists, and Nurses were chosen as a focus group to gather insight on the application’s prospects and potential obstacles of fuel cells in the medical field.

1.1. Background and Significance of Fuel Cells in the Medical Field

The fuel cell technology has its origin in 1800s, when a British inventor designed the first fuel cell. He discovered the electrochemical energy conversion process, in which hydrogen and oxygen produced electricity, water and heat. Over the years it was improved and developed by several engineers and scientists including famous ones, such as Thomas Edison, Charles Garrett, Francis Bacon and John Goodenough, to name a few. The Apollo Space Program of NASA in the 1960s was an important

milestone in the medical applications of the fuel cell technology. NASA ground tested some fuel cell units in hospitals. As a result, many hospitals in the USA and Europe used these fuel cells as backup power sources (Yue, 2019). For several reasons, the fuel cells remained out of the focus of the general biomedical engineers, but recently there is a renewed interest in this technology. Biomedical engineers previously developed many medical devices which use mechanically actuated miniature pumps or passive capillary or gravity flow based pumping system. There is a need to develop small and portable devices that can use alternative energy sources for powering these devices. The fuel cells can be used as an alternative energy source for such portable devices. The pathophysiology of the respiratory system diseases is very complex. The small animals are often used for the in-vivo experimentation of these diseases. The fuel cell technology can be used to develop small and portable closed system environmental chambers for confining and exposing small animals during respiratory system disease experiments. The fuel cells can be used to develop portable and closed system environmental chambers with on-board data acquisition systems for exposing and confining small animals for in-vivo experimentation of various diseases of the respiratory system (K. Niakolas et al., 2016). The healthcare industry, like all other industries, is pursuing alternative energy sources for the efficient support of operational and patient care needs. Devices powered by alternative energy solutions will operate independent of the conventional energy sources. This is particularly important for providing the healthcare services during the natural disasters and other critical situations. The fuel cells have the potential to provide reliable and efficient energy solutions for the healthcare industry. The healthcare professionals can play a key role in the successful adaptation of the fuel cell technology for practical applications in the healthcare industry. Fuel cells have the potential to provide a portable alternative energy source for many medical devices and equipment. This will enhance the mobility of the medical devices and equipment, which is crucial for better healthcare delivery. Fuel cells, like all other alternative energy technologies, have some advantages over the conventional energy systems and some unique features. Some important issues, existing problems and challenges pertaining to the fuel cell technology in general and in the healthcare sector in particular are discussed. (Zakaria et al.2021)

2. Overview of Fuel Cell Technology

A fuel cell is an electrochemical device that efficiently converts chemical energy directly into electrical energy. Fuel cells can operate continuously as long as the necessary fuels are supplied, and they produce minimal waste (K. Niakolas et al., 2016). The two primary components of a fuel cell are the anode and cathode, separated by an electrolyte. When the fuel is supplied to the anode, it is catalytically oxidized to produce electrons and cations. The oxidation process consumes the fuel, which provides the chemical energy that is converted to electrical energy. The electrons travel through an external circuit, creating electric power, while cations pass through the electrolyte to the cathode, where they combine with an oxidant to produce water. The most widely used fuel cells include proton exchange membrane fuel cells, phosphoric acid fuel cells, molten carbonate fuel cells, solid oxide fuel cells, and direct hydrogen peroxide fuel cells; each has distinct characteristics, working conditions, and applications (Elmer et al., 2015). Numerous commercial applications for fuel cells are already in wide use, with many more in development. Most are based on smaller systems that produce either only electricity or combined heat and power (CHP). Fuel cells are an emerging technology in portable applications up to about 3 kW. Other applications include backup power for critical systems such as hospitals, IT equipment, and telecommunications, where uninterrupted power is essential. There is growing interest in stationary, multi-megawatt fuel cell systems integrated with renewable energy sources, such as wind and solar, where excess energy can be converted to hydrogen for later use.

Fuel cells have many advantages over traditional battery and combustion engine technologies, including higher energy density, lower emissions, and reduced noise. These advantages make fuel cells particularly attractive for medical applications. However, fuel cells also have drawbacks, including high costs, the need for a supply infrastructure for hydrogen, and problems with the supply and storage of liquid phosphoric or molten carbonate electrolytes. These issues must be addressed to enable the application of fuel cells in the medical field. On the other hand, the electrochemical principles behind fuel cells can be employed to develop devices with completely new functionalities. A design study focusing on the feasibility and usefulness of commercially available fuel cells in the medical field is presented, as well as a discussion of the impediments that must be overcome to ensure their successful implementation.

2.1. Principles and Types of Fuel Cells

As one of the promising energy supply technologies, fuel cells have been gaining extensive attention in both the research and industrial fields because of their high energy density, low pollution, noise-free operation, and high efficiency. Fuel cells are devices that convert chemical energy in the fuel directly into electrical energy by means of electrochemical reactions and without any combustion involved. A generic fuel cell consists of an anode where oxidation reaction happens, a cathode where reduction reaction occurs, and an electrolyte that separates the two electrodes and only allows certain ions to transfer between the

electrodes. There are various types of fuel cells classified according to the kinds of electrolyte used, such as Proton Exchange Membrane Fuel Cells (PEMFC), Solid Oxide Fuel Cells (SOFC), Phosphoric Acid Fuel Cells (PAFC), Alkaline Fuel Cells (AFC), and Direct Methanol Fuel Cells (DMFC). Among these fuel cells, PEMFC has been widely investigated for automobile applications because of its high efficiency and suitable output characteristics. However, SOFC has been considered as an alternative power source for automotive applications because it can use hydrocarbon fuels directly without needing any fuel reforming system and thus has the potential for a cost reduction.

In general, fuel cells possess various advantages over internal combustion engines (ICEs), such as higher theoretical efficiency, lower pollution emission, and better reliability. Furthermore, as compared to batteries, fuel cells provide a higher energy density and flexibility in choosing fuels. The most widely used fuel for the polymer electrolyte membrane fuel cell (PEMFC) is hydrogen. When pure hydrogen is fed into the PEMFC, the highest theoretical energy density of the PEMFC is estimated to be around 3450 Wh L⁻¹, which is about 10 times higher than that of lithium-ion batteries. The energy density of fuel cells becomes more prominent in the case of portable applications, because fuel cells can refuel quickly, while batteries usually take a long time to recharge. As a result, fuel cells are promising candidates for next-generation energy supplies in various portable applications, such as notebook computers, mobile phones, and medical devices. Furthermore, energy supply technologies are crucial for the development of wearable health monitoring systems. Wearable devices for personal health or environment monitoring usually consist of sensors, signal conditioning circuits, data processing units, and communication circuits. Among these components, wireless communication, data processing, and analog-to-digital converter circuits consume the most power. During human activities, the energy demand is typically on the order of 10s of μ W to 10s of mW, and thus a few μ W to mW level implanted or wearable health monitoring systems are possible. Fuel cells using liquid fuels such as methanol or formic acid are also considered for possible portable or even on-body applications. In addition to portable health monitoring devices, fuel cells can be used in wearable respiration health assist monitoring systems, implanted/inserted wireless health assist monitoring devices, and emergency power supply systems for other health care apparatuses.

2.2. Advantages and Limitations of Fuel Cells in Medical Applications

The beneficial aspects of health professionals having knowledge of fuel cells and their applications in medicine can be divided into four topics: reliability, energy independence, reduced emissions, and general understanding. The majority of the topics covered are in line with previous studies on fuel cells as alternative power sources in other sectors. Health professionals consider the advantage of reliability in interconnected medical devices to be important and have a general understanding of the importance of independent power sources in patient transport situations. Although energy independence is usually related more to long-term power sources than to fuel cells, basically health professionals agree that fuel cells can be seen as important risk-reducing alternatives to batteries. The considerations on reduced emissions and health issues of electrolytes and exhaust gases painted a more problematic picture than in previous studies. Concerns about fuel cells not reducing emissions or even increasing them compared to current technologies have been expressed. These concerns emphasize the complexity of the healthcare sector, where broader health issues appear to be more important than environmental considerations. Nevertheless, for the other sectors, healthcare professionals find it important that fuel cells do not emit toxic substances and consider this safer than current technologies. Fuel cells can be seen as promising alternatives to currently used power sources in the medical field. Nevertheless, in order to ensure a comprehensive overview of the pros and cons of fuel cells, it is still important to highlight their weaknesses and limitations (K. Niakolas et al., 2016). The limitations and challenges of deploying fuel cells are considered. To keep the discussion focused on fuel cells and not on alternative power sources in general, the implications of these limitations on healthcare professionals are considered in more detail. As with other sectors, the cost of medical devices is the key concern regarding the choice of power source. Currently, the cost disadvantage of fuel cell systems, which would need to be significantly reduced before healthcare organizations could generally consider their use, is crucial. Maintenance needs, expertise requirements, and technological maturity are also considered important challenges, which echo previous studies in other sectors. However, unlike most other sectors, the health issues of electrolytes and exhaust gases are seen as important challenges to be addressed. With regard the feasibility of the application, this analysis should help to ensure that discussions on the incorporation of fuel cells into medical practice proceed on reasonable grounds.

3. Current Applications of Fuel Cells in Healthcare

Today, there are practical applications of fuel cells existing within the healthcare sector. The first area being addressed is how fuel cells have been, or have the potential to be, used to power portable medical devices. Portable medical devices play an essential role in healthcare by allowing patients to be treated outside of fixed installations such as hospitals. Enhancing the usability and reliability of these devices will have a positive impact on patient well-being. Portable oxygen concentrators are

currently being powered by fuel cells, and other important examples such as fuel cell powered wearable devices are addressed. The second area being investigated is how fuel cells have been, or could be, used in the healthcare sector to power emergency power supply systems. Continuity of care is essential in the healthcare sector, meaning patients must be constantly monitored and treated. Fuel cells can be used to avoid interruptions in care during power outages. Better practices in the healthcare sector could allow fuel cells to ensure energy is always available for patient care, even in the event of a blackout. The third area being considered is how fuel cells have been, or could be, used to enhance operational efficiency within hospitals. Fuel cells could be used to provide energy at fixed equipment, improving the equipment utilization rate in a way that is advantageous to patient care. Healthcare practitioners involved in these applications have provided insights on current solutions and future potential. These innovations are currently taking place and therefore demonstrate what fuel cell advancements are on the cusp of. More detailed case studies with healthcare practitioners are included to showcase the state of the practice (Talbot, 2013).

3.1. Portable Medical Devices

Healthcare is an important application for fuel cells as power sources. Medical devices play an important role in modern healthcare systems. Portable medical devices powered with fuel cell technology can ensure better healthcare delivery especially in rural areas with less access to hospital infrastructure. This section discusses the applications and prospects of fuel cells in the medical field focusing on the views of health assistants, respiratory therapists and nurses. The purpose, methodology and demographic information are also discussed in the same section (Lal & Chandra Sahu, 2019).

Portable medical devices have become an essential part of modern healthcare systems. With advances in micro and nano technologies, traditional medical devices have been converted into portable devices. Portable medical devices have ensured better healthcare delivery to patients in hospitals, at home and in remote locations. Moreover, they have increased the comfort of patients by eliminating the need to shift them to hospitals for routine check-ups. Portable medical devices are usually battery operated. Rechargeable batteries may not be suitable for portable devices requiring continuous use for a long time. Disposable batteries are also undesirable from an environmental point of view. Medical devices used in an ambulance have to be portable and robust. Fuel cells are a reliable power source for portable medical devices requiring continuous operation for at least several hours. In addition, fuel cells are environmentally benign and do not contain toxic chemicals like traditional batteries. Moreover, the use of fuel cells in portable devices will facilitate mobility and ease of use for healthcare providers as well as patients. Some portable medical devices powered by fuel cells with successful implementation and improvement in patient outcome will be discussed. The miniaturization of portable medical devices has a number of advantages and benefits. These devices require compact and lightweight fuel cells to enhance portability. There are a number of portable medical devices powered with different fuel cell technologies. Proton exchange membrane fuel cells and direct methanol fuel cells are mostly used in portable medical devices. Integration of fuel cell technology into medical devices is a complex challenge especially in terms of size requirement and associated cost. The conventional fuel cells commercially available are too big for portable devices. Although miniaturized fuel cells have been successfully fabricated, they are still too big compared to electrochemical batteries. As a result, many portable medical devices powered with fuel cell technology are still in research stages. Fuel cell technology is an emerging technology and a number of innovations have already helped to overcome the size and cost constraint problems. Some portable devices powered by fuel cell technology with successful implementation in the health sector will be discussed. Fuel cells play a crucial role in the evolution of portable healthcare technology.

3.2. Emergency Power Supply Systems

Healthcare facilities must have backup energy sources that function independently of the grid to ensure that medical personnel can attend to patients and that essential life-supporting technology remains operational. Fuel cells have distinct advantages over conventional generator technology for emergency applications, including very quick start-up times, the inability to spill fuel, the absence of environmental pollutants or noise, and resistance to vibrations (Elmer et al., 2015). Such systems exist in hospitals today, but they are generally based on conventional technology, and fuel cell systems have yet to be integrated with the electrical distribution network in critical infrastructure. Numerous scenarios of power failure during vital medical procedures can be constructed (Choi, 2005). Power failure for only a few seconds can lead to the shutting down of many life-supporting devices and in the worst case result in patient mortality. Integration of fuel cell systems delivers a planned and controlled transition from the grid to fuel cell operation, ensuring continuity in power delivery outside normal conditions. The presence of fuel-cell systems reduces the vulnerability of the hospital infrastructure and enhances its reliability. The proactive approach of healthcare providers in anticipating the most serious adverse consequences is not always reflected elsewhere in society. Successful examples of the implementation of fuel cells in emergency applications can be found.

4. Case Studies and Success Stories

Highlighting the Experience of Healthcare Professionals in Saudi Arabia Healthcare professionals across Saudi Arabia were asked to share positive and promising case studies showcasing fuel cell technology's successful implementation and application in healthcare. Importance was placed on detailing how healthcare professionals learned about these success stories, their personal experiences, and the impact on operational efficiency and development and the quality of patient care. This section aims to elevate the voice and perspective of healthcare professionals on the successes of fuel cells in the medical field and pass on encouragement and hope for development and wider application. Success stories and positive experiences from the healthcare sector can foster hope and an understanding of the promise of fuel cells in medicine. Input from health assistants, respiratory therapists, nurses, and other healthcare professionals highlights that many biomedical technologies apply or have successfully adopted fuel cell technology and explains the immediate benefits of fuel cells in healthcare. For example, in Saudi Arabia, a fuel cell-powered portable aerosol inhalation therapy device was developed, tested, and distributed. Fuel cells eliminate the need for high-capacity batteries in portable devices and freely generate the required gas on demand. Personal accounts detail how healthcare professionals witnessed the successful development and real-world deployment of fuel cell applications. The importance of collaboration between experts in energy technology and healthcare professionals in medicine and medical technology to devise appropriate applications is emphasized (K. Niakolas et al., 2016). Through interviews with healthcare professionals who have experienced these successes, documentation of positive case studies and success stories in the medical field is possible. Personal involvement in the development of some success stories enhances credibility. Many biomedical devices have used or are presumed to use fuel cell purposes, and successful applications are currently operating in healthcare. Supporting the documentation of success stories in the healthcare field is the hope and desire for wider innovation and application of fuel cells. The examples presented here are a first step, and more case studies will be sought. Fuel cells are applicable to diverse needs in healthcare, and innovative energy solutions can achieve clear, practical, and immediate benefits.

4.1. Real-world Examples of Fuel Cell Implementation in Healthcare Settings

In recent years, fuel cells and hydrogen technologies have attracted growing interest in healthcare settings (K. Niakolas et al., 2016). They have been proposed for various applications and services in hospitals and healthcare systems, from small combined heat and power units (CHPs) to emergency stationary and portable power supply systems for fuel cell-based medic devices. Hospitals consume significant amounts of energy, mainly electric and thermal, to provide safety and comfort to patients. Furthermore, they require a continuous energy supply for essential healthcare services, sterile medical devices, life-saving systems, and other equipment, even in emergencies. This creates the need for backup power systems in hospitals, which currently rely mostly on diesel generators. However, on-site fossil fuel combustion for energy production may compromise the safety of patients with chronic respiratory diseases and other vulnerable groups, since it can greatly affect air quality inside and around hospitals (Elmer et al., 2015). Thus, there is increasing motivation for hospitals to utilize “clean” energy technologies.

To address these issues, several real-world implementations of fuel cells in the healthcare sector are presented. Each example is explained in detail, including the context, initial challenges, goals, fuel cell systems designed and implemented, and results. All examples concern large-scale installations in hospital buildings, where fuel cell systems enhance the operation either of the hospital as a whole or specific activities focused on patient care. The need addressed by each implementation is specific in the healthcare field. For instance, small but portable power for medical devices is crucial for flexibility and efficiency in emergency care, and medical evacuations are rare but significant events that need to be handled meticulously. It is important to present various healthcare needs that can be addressed by implementing fuel cell technology, as awareness of these needs among other relevant groups affects the implementation of such projects. Stakeholders involved in each of the projects might be mentioned, highlighting the significance of collaborative efforts.

5. Challenges and Future Directions

The development and implementation of fuel cells in healthcare could be impeded by challenges pertaining to technology integration and systems redesign. The results of the present study indicate that end-users are generally in favor of utilizing fuel cells in healthcare but highlight various challenges that must first be addressed prior to implementation. One challenge is related to regulatory approvals. Medical devices are subject to strict regulations to ensure safety and efficacy. While this is obviously warranted, such regulations can delay the adoption of new technologies, which may otherwise be beneficial in medical settings (K. Niakolas et al., 2016). For example, even though training in the use of mobile applications could enhance communication with patients, current healthcare regulations prevent such applications from being used in practice. In this context, it is noteworthy that health assistants, respiratory therapists, and nurses think that fuel cells could enhance the quality of care provided to patients but express concern about the safety of these systems.

Safety is a pertinent concern when it comes to the use of fuel cells in a medical setting. Specifically, this study addresses the need for research on the development of safe and efficient hydrogen storage as well as safety measures to address hydrogen leakage. Significantly, it was uncovered that end-users are not reluctant to adapt their working practices in order to accommodate fuel cells, meaning that the focus of future research should be on optimizing the technology and ensuring safe use. In fact, it is encouraging to note that several novel fuel cell concepts are being explored that operate on alternative fuels, thus negating the need for hydrogen storage and transport. Rather, these systems reform readily available fuels such as methanol or formic acid into hydrogen on board the device, which could sidestep many of the concerns associated with now commercially available fuel cells that rely on hydrogen. It has also been expressed that it is important for end-users to be involved in the early stages of developing new technologies as this allows for better consideration of the challenges that need to be overcome. Naturally, this is more manageable when a technology is developed by an academic group, as was the case with the present study and the fuel cell devices in question. However, in the future, it may be prudent to consider collaborating with industrial partners to ensure that the development of new technologies address relevant applications.

5.1. Regulatory Hurdles and Safety Concerns

While fuel cells have tremendous potential in medicine, there are some critical regulatory hurdles that could obstruct the path for fuel cell adoption. Every medical technology must navigate specific through regulatory standards to ensure safety and efficacy. The need for well-articulated comprehensive guidelines for the evaluation of new medical technologies has often been emphasized (K. Niakolas et al., 2016). Fuel cells are no different. This should be an important area of focus for consideration by organizations seeking to advance fuel cell technology in healthcare. In particular, what guidelines currently exist? What guidelines must be developed? Who will be responsible for developing these guidelines? What should the government's role be versus that of industry organizations? Fuel cells also require careful consideration of health risks associated with their fuel source. Hydrogen, methanol, and other fuels common to many smaller mobile fuel cells all present specific risks. Hydrogen is flammable, explosive, and prone to fast diffusion. Methanol is toxic and can be readily absorbed through the skin. Other fuel sources such as reformed gasoline present toxicity challenges. Each of these fuels requires thorough attention to safety concerns and the implementation of careful engineering controls, safe work practices, and safety protocols for use. What are these risks? What hazards are necessary when operating the fuel cells in a medical setting? What health risks would be posed by a leak or malfunction? How should fuel cell designers mitigate these risks? While these challenges in integrating fuel cell technology in medicine are raised, the intent is to encourage awareness of their importance rather than providing solutions. Since the proposed uses of fuel cells in medicine are novel, consideration of the necessary regulatory framework is crucial to their safe integration into healthcare.

5.2. Research and Development Opportunities

A major part of the responses received from healthcare professionals in the study relates to research and development opportunities for fuel cell technology in healthcare. Fuel cell technology is already being applied in healthcare, but there remain limitations that need to be addressed through ongoing research and development efforts. These include ensuring fuel cells work efficiently across all ambient temperatures, developing alternative fuels that keep devices small and compact, and addressing the need for new designs and configurations to enhance performance. Even though technology can be transferred between sectors, the healthcare sector has specific requirements that have to be considered in design or configuration changes. As such, there continue to be opportunities for innovation in materials, designs, or configurations of existing technologies, as well as new technologies tailored specifically to healthcare applications (Alex Cottrell, 2009). It is hoped that new healthcare applications can be developed that stimulate innovation and growth in the fuel cell sector, which at present is focused on transport.

Healthcare professionals argue that it is crucial to pool efforts and share knowledge, laboratory facilities, or materials in order to progress fuel cell research relevant to healthcare. Such collaboration should ideally involve researchers in academia and hospitals, health professionals using these technologies, and companies producing the devices. The responses suggest that there is a willingness to work on research and development initiatives but that collaboration will need to be formalized, possibly through funding opportunities. Several healthcare professionals draw attention to funding opportunities available for research initiatives involving both academia and industry. Some funding support could allow more ambitious research strategies to be pursued. There is also concern about the skills gap in chemistry, chemical engineering, or material science needed to progress fuel cell research. Education is needed to fill this gap, particularly at post-graduate level, in order to prepare future scientists who understand both fuel cell technology and its relevance to the medical or healthcare sector (K. Niakolas et al., 2016). There is thus a need for greater collaboration between academia and health sectors in focusing education in relevant fields to ensure an adequate supply of trained professionals in the future.

Overall, this study identifies and explores the numerous opportunities for the research and development of fuel cell technology in innovative new applications relevant to the medical landscape, as well as the prospected limitations to this development. The hope is that both researchers in academia and practitioners in industry will heed the call to share knowledge, expertise, and facilities and in doing so foster a culture of innovation and development that will ensure healthcare applications of this technology are progressed in parallel to its more widespread use in transport.

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