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Bioethics in Biomedical Engineering

Bioética en Ingeniería Biomédica

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Abstract

Bioethics is essential for guiding the ethical practice of biomedical engineering, ensuring that technological innovations are developed and applied responsibly for individual and social well-being. As healthcare evolves, ethical considerations become crucial for addressing moral dilemmas and aligning technological advancements with ethical principles. This study explores the definition, trends, and application of bioethics in biomedical engineering, using real-world examples and ethical frameworks to demonstrate how bioethics influences decision-making, research practices, and the development of medical technologies to improve patient care and outcomes. Using a qualitative-documentary methodology, the research utilized databases such as ACS Publications, ScienceDirect, etc, focusing on bioethics and biomedical engineering. Information was organized using Mendeley, guided by principles of bioethics and biomedical engineering

Keywords: Bioethics, Biomedical Engineering, Bioethical principles, Bioengineering, Medical technology.

Resumen

La bioética es esencial para guiar la práctica ética de la ingeniería biomédica, garantizando que las innovaciones tecnológicas se desarrollen y apliquen de manera responsable para el bienestar individual y social. A medida que la atención médica evoluciona, las consideraciones éticas se vuelven cruciales para afrontar los dilemas morales, alineando los avances tecnológicos con los principios éticos. Este estudio explora la definición, las tendencias y la aplicación de la bioética en la ingeniería biomédica, empleando ejemplos del mundo real y marcos éticos para demostrar cómo la bioética influye en la toma de decisiones, las prácticas de investigación y el desarrollo de tecnologías médicas para mejorar la atención y los resultados del paciente. Utilizando una metodología cualitativa-documental, la investigación utilizó bases de datos como ACS Publications, ScienceDirect, etc, con foco en bioética e ingeniería biomédica. La información se organizó utilizando Mendeley, guiado por principios bioéticos y de ingeniería biomédica.

Palabras clave: Bioetica, Ingeniería biomédica, Principios bioéticos, Bioingeniería, Tecnología Médica.

1 Introduction

Bioethics in biomedical engineering is a fascinating discipline that sits at the intersection of ethics, technology, and medicine.

Bioethics plays a crucial role in guiding the ethical practice of biomedical engineering by ensuring that technological innovations are developed and applied responsibly. This approach promotes the well-being of individuals and society. In today's rapidly evolving healthcare landscape, ethical considerations are more important than ever, as they help navigate complex moral dilemmas prevalent in society and the medical industry. They also ensure that technological advancements are aligned with ethical principles and values.

This study aims to explore the definition, trends, and principles of bioethics and its application in biomedical engineering. Real-world examples and ethical frameworks are used to recognize how bioethics shapes decision-making processes, influences research practices, and guides the development of medical technologies to improve patient care and outcomes.

2 Methodology

For this research, a qualitative-documentary methodology was employed, relying on:

a. Search and data compilation: databases such as ACS Publications, ScienceDirect, Scopus, IEEE, SciELO, RedAlyC, and Google Scholar were utilized; key search terms included “Bioethics”, “Biomedical Engineering”, “Bioethical principles”, and “Bioengineering”.

b. Information selection and refinement: With a search period from 1970 to 2023, a comprehensive exploration was conducted. Utilizing Mendeley (Elsevier, 2021) as a bibliographic management tool, the data was organized based on their relevance to this study’s two foundational frameworks: the bioethical principles outlined in Lewis Vaughn’s “Bioethics: Principles, issues, and cases” (Vaughn, 2019), and the principles of biomedical engineering articulated in Professor William Mark Saltzman’s “Biomedical Engineering: Bridging medicine and technology” (Saltzman, 2015).

c. Selection of subtopics: the refined information facilitated the organization of the research structure and clarified the chosen subtopics related to the study.

d. Analysis of results: a critical analysis of the data was conducted, resulting in comprehensive conclusions found in this study (Rondón y cols., 2023).

3 Results and Discussion

3.1 Definition of bioethics

The term bioethics has a well-known etymological origin from the Greek language. Particularly, the word “bios” meaning life and “ethos” meaning ethics, with the combination commonly translated as “ethics of life” (Postigo, 2011). This term originated in the seventies, due to the need to address ethical challenges posed by scientific and technological advances concerning life and its survival on the planet.

Despite being new when compared to more traditional fields, bioethics has gained prominence in the biomedical sciences. It can be defined as a branch of philosophical ethics that encompasses appropriate concepts and behaviors aimed at safeguarding life and the environment. The field focuses on ethical arguments and addressing dilemmas when applying scientific advancements. Specifically, UNESCO defined bioethics as “the analysis of ethical issues raised by life-sciences, the application of technology, and medicine and health policies. It encompasses all fields of scientific development which affect human beings socially, judicially, and environmentally” (UNESCO, 2015).

The complexity of human experience highlights that of bioethics and underscores the need to establish an interdisciplinary environment. Currently, bioethics outlines the ethical questions raised by scientific facts within an environment of interdisciplinary and transdisciplinary discussion that professionals in the life sciences must reach.

When concerned with the human perspective, bioethics involves decisions, legal arguments, and morality. The objective is to understand the wide moral diversity of humanity from an anthropological perspective by developing values, norms, and criteria to understand moral responsibility (Rachels & Rachels, 2023). Additionally, it evaluates the consequences for patients when materials or technological devices are applied to them. Considering this argument, an ethical standpoint resonates in this field, asking “what should I do” in contrast to “what can I do” (Triana, 2000).

Fig 1. Bioethics, Points of View (Rondón, 2020).

1.2 The origins of bioethics

Bioethics arose in the seventies to confront ethical challenges presented by scientific and technological advances affecting life and its sustainability. Despite its recent emergence, the origins of bioethics are complex and widely debated. This emphasizes the importance of understanding its history and developmental context. Particularly, in topics including research involving human subjects, abortion, euthanasia, and related issues. Although, without a defined terminology, cultural efforts aimed to raise awareness and dedicate time to systematic examination.

In 1970, the scientific community was introduced to the term “bioethics” through the publication of “Bioethics, the science of survival” by Van Rensselaer Potter (1911-2011), a Dutch American biochemist, in the journal Perspectives in Biology and Medicine (Potter, 1970). Potter continued to use this term in subsequent works, including his 1971 book titled "Bioethics, Bridge the Future”. In these writings, Potter advocated for the development of a discipline focused on addressing humanity’s survival amidst ecological challenges, earning him recognition as the father of bioethics (Potter, 1970; Rosillo, 2000).

Before Van Rensselaer Potter popularized the term,” Fritz Jahr, a Protestant pastor, theologian, philosopher, and German educator, had already introduced it in 1927. Jahr’s (1927) use, in his article titled “Bio-Ethics: A review of the ethical relationships of humans to animals and plants” lacked the global application later proposed by Potter. Nevertheless, Jahr proposed a “bioethical imperative”, extending Kantian ethical principles from the 18th century to encompass all forms of life (Sass, 2007).

During that period, the global community witnessed alarming instances of science being exploited for nefarious purposes. Notably in atrocities including the atomic bombing in the cities of Hiroshima and Nagasaki, which demonstrated the capacity for destruction of humanity. Similarly, during the Nuremberg trial of the crimes of the Nazi regime, experiments on human beings were revealed related to euthanasia, eugenics, abortion, and more in the name of science and reductionism (Shuster, 1997; Ghooi, 2011). Additionally, during the Cold War era the United States conducted ethically questionable experiments, such as the Tuskegee Study of Untreated Syphilis (1932-1970) on Afro-descendants, the Jewish Chronic Disease Hospital (JCDH) cancer experiment (1964) on non-cancerous patients, and the Willowbrook State School hepatitis experiment (1956-1970) on children with Down Syndrome (Asnariz, 2001). These experiments further underscored the urgent need for society to reflect on the inherent value of human life (Ciccone, 2015) and the ethical responsibilities of scientific research.

Consequently, the relationship between science, medicine, and humanity underwent a significant transformation alongside advancements in biotechnology. A part of this change is attributed to obstetrician André Hellegers, founder of the “Joseph and Rose Kennedy Institute of Ethics for the Study of Human Reproduction and Bioethics,” established in 1972 with sponsorship from the Kennedy family and later renamed the “Kennedy Institute of Ethics” in 1979. Hellegers pioneered the integration of the term “bioethics” into the academic, biomedical, and public environment.

In contrast to Potter’s environmental focus, Hellegers directed the field towards reproductive biology and medicine. The term gained official recognition with epistemological status in 1978, following its acknowledgement in Warren T. Reich’s publication, “Encyclopedia of Bioethics”. Where he defined bioethics as “the systematic study of human conduct in the area of the sciences of life and health, as this conduct is examined in the light of moral values and principles” (Reich, 1978). This definition highlights its scientific foundation, governed by fixed principles, and enriched by multidisciplinary dialogues in biosciences and human culture. In essence, bioethics encompasses all aspects of life and health sciences, including biological, psychological, mental, economic, commercial, legal, family, political, and social dimensions. Thus, emphasizing its ethical significance beyond mere scientific-technical considerations (González, 2017).

According to W. T Reich, Potter and Jahr are undoubtedly the originators of the term “bioethics”, while Hellegers played a crucial role in systematizing and popularizing it. However, philosopher Daniel Callahan of the “Hastings Center” in 1969 elucidated the goal of this emerging discipling by equipping professionals and the public with tools to comprehend ethical and social challenges stemming from bioscientific progress. Since then, it has been imperative to analyze facts ethically and explore decision-making methodologies with sensitivity, aiming for a balanced consideration of all variables (Contreras, 2004)

1.3 Ethics and bioethics

Ethics and bioethics are founded on the understanding of moral concepts, beginning with morality. Often linked to notions of goodness or righteousness, morality encompasses individuals’ beliefs, standards, and principles, guiding behavior and providing criteria for assessing moral value.

Ethics, also known as moral philosophy, goes beyond mere morality, employing methodologies like reflection and critical reasoning to systematically study morals. It provides a rational framework for exploring moral concepts and judgments, facilitating discussions on determining right and wrong actions, moral principles, virtues, personal objectives, and the definition of good and bad.

Ethics consists of three principal branches: normative ethics, metaethics, and applied ethics (Figure 2). Normative ethics concerns itself with establishing moral standards and principles that guide ethical decision-making. It addresses fundamental questions such as which moral principles should inform our judgments and the role of virtues in our lives. Debates in normative ethics often revolve around moral dilemmas, such as whether the principle of autonomy justifies certain actions or if there are exceptions to moral prohibitions, like the principle of “not killing”.

Fig 2. Branches of Ethics (Rondón, 2020).

In contrast, metaethics delves into the nature and validity of ethical concepts, exploring abstract questions about the foundations of morality. Unlike normative ethics, which focuses on practical ethical forms, metaethics investigates the meaning of ethical terms and the coherence of ethical arguments. It confronts questions about the existence of moral facts, the difference between moral and non-moral beliefs, the justification of moral standards, and the truth value of moral statements.

Finally, applied ethics addresses practical moral issues in specific contexts, such as healthcare and law. This branch of ethics seeks solutions to real-world ethical dilemmas faced by professionals in various fields. For example, science employs descriptive ethics to empirically study morality, focusing on behaviors, beliefs, and experiences that shape moral practices. This approach contrasts with normative ethics which address future-oriented questions about how we should live, whereas descriptive ethics focuses on present realities.

Thus, a subfield of applied ethics that employs the ideals of descriptive ethics must exist for ethical issues in healthcare, research, and technology. This branch is the field of biomedical ethics, or commonly referred to as bioethics. Bioethics confronts complex moral questions including those related to medical treatment decision, reproductive technologies, and end-of-life care.

Bioethics addresses a wide range of complex moral questions, such as end-of-life care, reproductive rights, genetic testing, organ transplantation, and animal research. These include considerations such as whether it is ethically justifiable for a woman to undergo abortion following the detection of a developmental defect in the fetus, whether parents should have the right to select embryos based on specific genetic traits, the ethical obligations of medical professionals regarding honesty with patients, whether doctors should remove a ventilator from an elderly person sick with COVID-19 and give it to a young person sick with the same disease due to equipment shortages, the role of doctors in assisting terminally ill patients in end-of-life decisions, and the ethical dilemmas surrounding the allocation of scarce organs for transplantation.

The complexity of bioethical analysis necessitates input from a diverse range of experts, including healthcare professionals, legal scholars, scientists, clergy, and policymakers, as well as non-experts such as patients and their families. While moral philosophy forms the core of bioethics, it relies on a comprehensive understanding of medical, scientific, technological, and legal realities to effectively address ethical challenges (Vaughn, 2019).

1.4 Trends in bioethics

In bioethics discussions, it is crucial to recognize its origins in the United States, reflecting the industrialized, technological, and globalized nature of modern society. This discipline rapidly expanded to similarly situated nations, each infusing its cultural nuances into the analysis. Common themes emerge across diverse contexts, including euthanasia, patient autonomy, reproductive rights, resuscitation, quality of life, honesty with patients, genetic studies, transplants, and medical research ethics. All these themes are framed within the broader scientific and technical landscape but have expanded to encompass ecological concerns and environmental pollution.

For instance, variations in views for organ transplantation illustrate these trends. Anglo-Saxon countries often lean towards a market-oriented approach, where organs may be bought and sold, reflecting a more commercialized stance. Conversely, in Europe, the emphasis tends to be on altruism, where organ donation is primarily motivated by a desire to benefit others without expecting financial gain in return.

Similarly, debates surrounding medically assisted reproduction, such as surrogacy and postmenopausal motherhood, reveal contrasting perspectives on issues like donor anonymity and the rights of the unborn. For example, in Europe, there is an ongoing debate regarding the right to anonymity of the donor in assisted reproduction procedures. In contrast, Anglo-Saxon countries often prioritize the rights of the unborn child over the rights of the donor, leading to stricter regulations and limitations on donor anonymity.

Moreover, regulatory approaches differ significantly between the United States and Europe. In the United States and other Anglo-Saxon countries, there is a prevailing individualistic or autonomous perspective when it comes to regulation in experiments with human beings, genetic engineering, or informed consent. This approach emphasizes individual rights and freedoms, often resulting in less stringent regulation. In contrast, Europe tends to impose more restrictions in these areas, prioritizing ethical considerations and social welfare over individual autonomy (Neves, 1996).

Differences in regulatory approaches reflect broader cultural outlooks. Anglo-Saxon countries prioritize individual autonomy in matters like informed consent and genetic engineering, often influenced by factors such as media coverage, legal frameworks, and high-profile cases. For example, in the United States, bioethical discourse is shaped by media representation, legal precedents, and publicized moral dilemmas arising from technological advancements and notable legal trials. This influence has extended to the healthcare system, where the proliferation of specialized medical fields has led to depersonalization and dehumanization of patient care. Traditional medical paternalism is increasingly giving way to a model that emphasizes patient autonomy, albeit amidst challenges related to the equitable distribution of resources and evolving social norms surrounding civil rights. In contrast, Europe tends to adopt more stringent regulations.

The evolution of bioethics in North America and Europe is influenced by historical, cultural, and economic factors. In North America, bioethics tend to prioritize pragmatism and utilitarianism, often adopting a normative, deontological approach to ethical action, which emphasizes adherence to moral rules or duties regardless of their consequences. Conversely, European bioethics is characterized by their transdisciplinary and philosophical nature, drawing from ancient Greek ethical traditions and legal frameworks that emphasize human rights and autonomy. These European traditions contribute to a distinct philosophical approach to bioethical issues, rooted in the medical tradition of doing good and seeking excellence. Additionally, European bioethics is influenced by the political custom of justice dating back to the 4th century BC and shaped by the legal practice of human rights and autonomy since the onset of the 17th century. These opposing approaches at times converge and clash within modern bioethical discourse (Triana, 2000).

In 1974 the National Commission for the Protection of Human Subjects of Biomedical and Behavioral Research, developed the principles of biomedical ethics, in what is known as the Belmont Report. These principles ensured proper conduct that followed basic ethical values: respect for persons, beneficence, and justice. From these three basic principles, American philosophers Beauchamp and Childress (2001) divided the concept of beneficence into two sections: nonmaleficence and beneficence. Their four principles – respect for autonomy, nonmaleficence, beneficence, and justice – provided the medical community with a framework for recognizing and considering moral problems (Iserson, 1999), while allowing room for judgment in specific cases.

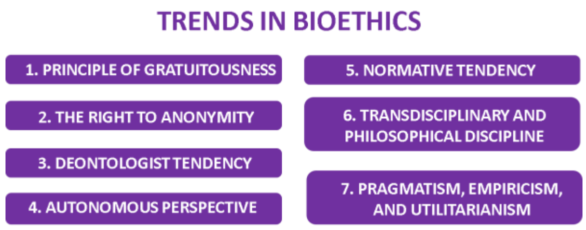

Fig 3. Trends in Bioethics (Rondón, 2020).

In their 1985 book “Principles of Biomedical Ethics”, Beauchamp and Childress highlight their intent behind the “four-principles approach” as a foundation from where detailed rules and policies could be produced. In this work, the first principle, respect for autonomy is defined as a person’s capacity “to rationally accept, identify with, or repudiate a lower-order desire or preference in a manner that is independent of the manipulation of desires” (Beauchamp & Childress, 2001). Additionally, they define an autonomous person as one who decides based on their chosen plan without lacking proper understanding. The latter has led to the implementation of informed consent as a fundamental practice in medical care.

The second principle, nonmaleficence, is defined as an obligation not to inflict harm or injury intentionally. The 1985 book further establishes the connection between this principle and the Hippocratic oath which emphasizes that medical professionals will use treatment to help the sick without injury or fallacy (Beauchamp & Childress, 2001). The intent behind nonmaleficence is to establish a framework that permits patients, caregivers, and medical practitioners to assess and decide on pursuing or denying treatments after considering the potential benefits and risks involved. This principle applies to both competent and incompetent patients, allowing for considerations of quality of life rather than ignoring them. In contrast, beneficence encompasses two doctrines: positive beneficence and utility. Positive beneficence highlights the provision of benefits, while utility involves balancing benefits and drawbacks in different forms of care.

Beauchamp and Childress distinguished the concepts of beneficence and nonmaleficence, despite their common use under a single principle in moral philosophy, to clarify pertinent differences. For instance, consider a surgical procedure. The principle of nonmaleficence ensures that a surgeon carefully assesses potential risks, such as infection, bleeding, or adverse reactions to anesthesia, and takes appropriate measures to minimize harm while achieving the desired outcome. Conversely, beneficence prompts surgeons to evaluate the potential benefits of the surgery, such as pain relief, improving function, or saving the patient’s life, against these risks and align the decision with the patient’s overall well-being and medical goals.

The fourth principle, justice, emphasizes fairness, equitable, and appropriate distribution of goods and benefits in a society (Beauchamp & Childress, 2001). It necessitates a thorough examination of the selection process for research subjects to ensure that certain groups, such as welfare recipients, specific racial or ethnic minorities, or those in institutional settings, are not chosen because of their easy availability, compromised status, or susceptibility to manipulation, but rather based on their relevance to the research problem. Moreover, in research supported by public funds which subsequently lead to therapeutic advancements, justice requires these benefits to be accessible to all, regardless of financial means. Throughout history, injustices have been observed in various research endeavors, as evidenced by the previously discussed cases such as the Tuskegee Study of Untreated Syphilis, the Jewish Chronic Disease Hospital cancer experiment, or the acts highlighted during the Nuremberg trial of the crimes of the Nazi regime (Shuster, 1997).

1.5 Biomedical Engineering

Defined as the application of engineering principles to human biology or medicine, biomedical engineering serves to enhance patient care through technological advancements (Moffatt, 2017). This interdisciplinary field encompasses various domains, including physiology, human biology, molecular imaging, and tissue reconstruction. With the objective to develop technologies designed for monitoring physiological functions and aiding in diagnosis and treatments. Originally rooted in electrical engineering, biomedical engineering shares a close connection with engineering principles while addressing healthcare challenges. Its curriculum integrates subjects such as mathematics, physics, programming, medicine, chemistry, and mechanics to (Aguilar & Gaibor, 2022) to develop tools and systems that contribute to healthcare improvements. While often associated with bioengineering and biological engineering, biomedical engineering has a more specialized focus, centering on medical applications (García, 2020).

Biomedical engineering plays a crucial role in medical practice by providing innovative solutions to clinical challenges, including the design and manufacture of medical equipment and technologies for diagnosis, therapy, and rehabilitation (Pineda, 2010). Despite its distinct focus, biomedical engineering, shares ethical responsibilities with medical professionals and engineers, ensuring adherence to their respective ethical standards. Biomedical engineering follows the principle of justice when addressing healthcare disparities in the fair selection of research subjects in respective specialties (Moffatt, 2017). Furthermore, its interdisciplinary nature fosters collaboration between different fields, such as computer science, leading to groundbreaking advancements in healthcare technology and delivery.

1.6 Origins of Biomedical Engineering

Biomedical engineering finds its roots in ancient Egypt, where rudimentary prostheses were crafted, and in the visionary works of Leonardo da Vinci's sketches which hinted at the fusion of anatomy and engineering. These early endeavors, while modest, laid the groundwork for more sophisticated techniques and technologies.

The late 19th century heralded significant advancements with figures like Lovett Garceau and Alfred Grass, whose pioneering work in electronic instrumentation paved the way for biomedical engineering. Garceau's utilization of vacuum tube-based amplifiers and Grass's creation of the first Electroencephalograph marked crucial milestones, illuminating the intricate workings of the human body with unprecedented clarity. Meanwhile, the mid-20th century witnessed a shift with the advent of cybernetics, as luminaries like Arturo Rosenblueth, Walter B. Cannon, and Norbert Weiner solidified the relationship between the two fields, fostering interdisciplinary collaboration (Pineda, 2010).

The evolution of the modern healthcare system reflects a transition from mystical explanations of illness to evidence-based medicine. Pioneers like Hippocrates revolutionized medical practice, emphasizing the body's inherent healing capabilities and documenting diseases with precision. The Renaissance saw a resurgence of intellectual curiosity, with figures like Leonardo da Vinci and Galileo Galilei advancing anatomical knowledge and promoting observation-based therapies. Despite these strides, hospitals in the Renaissance remained custodial institutions with limited efficacy. It was not until the 18th century that hospitals actively engaged in curative care, coinciding with broader humanitarian movements. However, early hospitals still faced challenges, with high mortality rates persisting into the 19th century.

A breakthrough in modern medicine came in the mid-nineteenth century with the development of the Germ Theory, stating that microorganisms cause infectious diseases. This theory, championed by figures like John Snow and Louis Pasteur, revolutionized medical understanding and paved the way for advancements in diagnostics and treatment. Florence Nightingale's contributions to nursing practices during the Industrial Era further improved patient outcomes by emphasizing the importance of hospital conditions. This period also witnessed the emergence of hospitals as comprehensive care centers, spurred by advancements in medical technology such as the electrocardiograph and x-rays, marking the integration of engineering and medical disciplines and the emerging stages of the biomedical engineering field.

Following the World War II, rapid technological innovations in electronics and medicine propelled the healthcare system into the modern era, with developments like telemetry devices, medical imaging techniques, and artificial organs transforming patient care (Enderle & Bronzino, 2012). For instance, in Colombia, engineer Jorge Reynolds Pombo's development of the pacemaker and biotelemetry in the 1960s underscored the country's early contribution to biomedical innovation (Pineda, 2010). This milestone, though regional in space, echoed the global trajectory towards the integration of engineering and medicine.

During the 20th century, the development of new medical technologies erupted. One of the most impactful included the first whole-organ transplant in 1967, when surgeons successfully completed the first heart transplant. A procedure that was successful because of the availability of medical tools and devices, allowing for sustaining of life and organ transportation. However, more minute changes are also important such as the development of automated machines which paved the way for DNA sequencing which in turn has made the Human Genome Project possible. Additionally, the development of thermometers, pregnancy tests, blood glucose tests, glucose sensors, and blood pressure monitors have made it so continuous monitoring of our vitals is possible from the comfort of our home. Furthermore, the design, manufacturing, and implantation of artificial joints, limbs, and heart valves have been possible through the study of biomaterials and other synthetic components including metals and polymers (Saltzman, 2009).

These recent advancements in medicine and biomedical engineering continue to push the boundaries of medical innovation. Current research efforts, including the Human Genome Project and stem cell research, are paving the way for the possibility of personalized medicine, and regenerative therapies for the future (Enderle & Bronzino, 2012).

1.7 The role of a biomedical engineer

According to Mark Saltzman (2009) in his book "Biomedical Engineering: Bridging Medicine and Technology", biomedical engineering, in a broad sense, entails the education and training of individuals across three distinct roles: "the clinical engineer" specializing in healthcare, "the biomedical design engineer" focusing on industrial applications, and "the research scientist" exploring scientific inquiry.

At a more specific level biomedical engineering encompasses various subdisciplines, each addressing distinct challenges in human health. While the overarching roles of biomedical engineers encompass physiology and mathematical analysis, delving deeper reveals a multitude of specialized fields. These subdisciplines highlight the diverse applications of biomedical engineering and underscore the intricate roles they play in advancing medical technology and improving patient care.

Saltzman identifies physiological modeling as a subdiscipline of biomedical engineering, where mathematical models of biological systems are developed to understand and predict their behavior. For instance, engineers designing prosthetic hips use mathematical models to predict stresses and strains on artificial hips. This subdiscipline of biomedical engineering has far-reaching impacts, including analyzing blood flow in small vessels for the development of medical devices that treat diseases or ailments affecting the circulatory system, such as stents. By incorporating mathematical analysis, engineers in physiological modeling have successfully understood the functions of the human body with mathematical support. The Hagen-Poiseuille law is one of these models used to explain vessel constriction and pressure los. However, the Hagen-Poiseuille equation is also applied in fluid dynamics to understand non-biological systems.

Another subdiscipline is biomedical instrumentation, where engineers develop medical devices for medical use. These instruments range from heart monitors to pacemakers, and all play a vital role in patient care by providing feedback on the health of patients. This discipline has incorporated nanotechnology and microelectronics for miniaturization and improved functionality, allowing for the transplantation, like neural stimulators or drug delivery devices. Biomedical engineers in this field ensure that medical devices are dependable and safe.

Biomedical imaging is a revolutionary field led by biomedical engineers that has allowed physicians to collect medical images through machines. Biomedical engineers have successfully designed and constructed imaging equipment such as the computed tomography (CT) scan, magnetic resonance imaging (MRI), ultrasound, and X-Rays. Additionally, they incorporate continuous improvement by analyzing imaging data to enhance diagnostic accuracy, improving treatment outcomes.

The subdiscipline of biomechanics focuses on understanding the mechanical aspects of human physiology. Biomedical engineers in this field study the effects of mechanical forces on tissues and organs, design protective gear, and develop mechanical replacements for damaged body parts. In contrast, biomolecular engineering integrates chemical engineering principles with biology to design and analyze biological systems. In this field, biomedical engineers develop drug delivery systems, tissue engineering techniques, and diagnostic tools.

Continuously, biomedical engineers design artificial organs using synthetic materials combined with biological components. These artificial organs, such as vascular grafts, provide life-saving solutions for patients awaiting organ transplantation. Current methods focus on developing synthetic materials to improve the design of artificial organs to one day incorporate living cells leading “to implantable replacement cartilage, liver, or nervous tissue” (Saltzman, 2009). Biomedical engineers in this field have designed extracorporeal systems that simulate the function of real organs. For example, the process of hemodialysis incorporates an extracorporeal device that simulates the process conducted by the kidneys to filter the blood. Patients with kidney failure are able to undergo hemodialysis, having a machine function as their organ temporarily. Another example is the extracorporeal membrane oxygenation (ECMO) machine used during cardiac surgery. This machine allows the heart to rest during surgery, by taking over the function of the heart and lungs. Thus, the patient still receives the necessary nutrients to maintain their organs while surgeons operate on the heart (Fournier, 2017).

Biomedical engineers also play a role in molecular and cellular analysis of biological systems. In systems biology, biomedical engineers develop computational models, analyze biological data, and design experimental techniques. Their success in this field has contributed to new methods for cellular manipulation used for genetic engineering. Biomedical engineering’s interdisciplinary approach in systems biology drives advancements in understanding biological processes and developing personalized medical interventions.

Professionals in biomedical engineering are interdisciplinary experts who apply engineering principles to healthcare challenges, contributing to the improvement and advancement of healthcare through sustainable technological solutions. They play integral roles in diagnostic, treatment, and control processes, including patient information management and policy development for healthcare services (García, 2020).

1.8 Applications of bioethics in Biomedical Engineering

In biomedical engineering, the integration of bioethical principles is of great significance. These ethical considerations are imperative for biomedical engineers engaged in innovative research and innovation. Just as medical professionals adhere to ethical guidelines set forth by the American Medical Association (AMA) in 1980, biomedical engineers must operate under a code of ethics. For instance, the American College of Clinical Engineers established a distinct code aimed at fostering ethical conduct among its members. This code mandates various principles, including the accurate representation of one’s level of responsibility, authority, experience, knowledge, and education. Additionally, it emphasizes the importance of disclosing conflicts of interest, respecting the confidentiality of information, and working towards the improvement of healthcare delivery. While this code underscores the profession’s commitment to minimizing harm, it may not comprehensively address ethical dilemmas in every scenario (Enderle & Bronzino, 2012) and other biomedical engineering specialties. Hence, the incorporation of bioethical considerations is crucial.

Consider the principle of respect for humans, which resonates deeply in the field. Consider the biomedical engineering subspecialty, bioinformatics, which focuses on studying the human genome. According to the NIH’s National Human Genome Research Institute (2024), bioinformatics incorporates the use of computer software to collect and study biological data, particularly DNA and amino acid sequences, to aid in diagnosis, treatment, and the understanding of diseases. When intervening in somatic cells to treat diseases, biomedical engineers must uphold the dignity of individuals. It is imperative that research subjects are not treated as objects of study but recognized as autonomous beings deserving of respect and protection. This principle underscores the ethical imperative to prioritize the well-being and autonomy of patients (Pineda, 2010).

Similarly, the principle of beneficence highlights the ethical obligation of biomedical engineers to prioritize transparency and safety. By openly communicating their research findings and proposed technological advancements, biomedical engineers ensure that patients, healthcare providers, and policymakers are well-informed. This transparency facilitates the discussion and resolution of potential implications and ethical considerations within the realm of biomedical engineering disciplines.

Consider the field of biomaterials where biomedical engineers develop materials for a variety of medical devices. These devices include artificial ligaments and tendons, heart valves, hearing loss implants, dental implants, and contact lenses. They offer innovative solutions to address medical challenges, by implementing non-biological materials "to interface with biological systems to replace, treat, or support functions of the body" (Moffatt, 2017). However, it requires ethical responsibility to ensure safety, efficacy, and compatibility for their use in patients. For example, consider the development of a new biomaterial for use in artificial heart valves. Biomedical engineers must adhere to the principle of beneficence by conducting comprehensive testing to assess potential dangers and estimate the risks associated with the product. This testing regimen may encompass a wide range of parameters, including resistance to mechanical stress, durability under physiological conditions, biocompatibility, possibility of corrosion, electrical conductivity, and other factors that could impact its compatibility within the patient's body. Complimentary to this, the principle of nonmaleficence must be considered, as any potential harm or adverse effects resulting from its use should be minimized or eliminated to the greatest extent possible.

Another area of interest in biomedical engineering concerning bioethics is tissue engineering. This discipline focuses on "integrating biology with engineering to create tissues or cellular products outside the body (ex vivo) or to use the gained knowledge to better manage the repair of tissues within the body (in vivo)" (Enderle & Bronzino, 2012). One of its objectives is to develop artificial organs for transplantation, which raises ethical concerns, particularly regarding the use of embryonic stem and germ cells. While these cells hold promise for regenerative medicine, their use is controversial due to ethical considerations surrounding the destruction of human embryos (Moffatt, 2017). Ensuring that research and applications in tissue engineering do not cause harm to human embryos aligns with the bioethical principle of nonmaleficence.

4 Conclusions

Bioethics serves as a guiding framework for the ethical practice and advancement of biomedical engineering, ensuring that technological innovations are developed and applied responsibly to benefit individuals and society. By upholding principles such as respect for autonomy, nonmaleficence, beneficence, and justice, biomedical engineers can navigate complex moral dilemmas, promote ethical awareness, and foster interdisciplinary collaboration to address pressing healthcare challenges. Additionally, the understanding of past and present trends in bioethics worldwide will continue the dialogue of ethical standards. However, ethical considerations in biomedical engineering are ever evolving, requiring ongoing dialogue to adapt to emerging technologies and dilemmas. As the biomedical engineering discipline continues to push the boundaries of medical innovation, integrating bioethical principles will be essential in promoting ethical integrity, safeguarding patient well-being, and advancing the collective pursuit of healthcare excellence.

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