

Review Article

Bridging Biophysics and Medical Physics: Advancements and Applications

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A B S T R A C T

Biophysics and medical physics are interdisciplinary fields that play crucial roles in advancing healthcare through the application of physical principles to biological systems and medical technologies. Biophysics seeks to understand the fundamental physical processes within living organisms, while medical physics applies these principles to improve diagnostic tools, therapeutic procedures, and healthcare devices. This review explores key advancements in both fields, including structural biology, biomechanics, bioelectricity, medical imaging, radiation therapy, and nuclear medicine. The synergy between biophysics and medical physics has resulted in innovative solutions such as personalized medicine, targeted drug delivery systems, and functional imaging techniques, which have greatly enhanced clinical practice. Despite these advancements, challenges remain in ensuring safety, ethical considerations, and the accessibility of new technologies. The future of both biophysics and medical physics holds immense promise, with continued interdisciplinary collaboration and technological innovations driving the next generation of healthcare solutions.

Keywords: Biophysics, Medical Physics, Radiation Therapy, Personalized Medicine, Nanotechnology

Introduction

The integration of biophysics and medical physics has led to transformative advances in both basic biological research and clinical medicine. These two fields, though distinct in their primary focuses, are deeply interconnected in their quest to understand the physical principles that govern biological systems and apply this knowledge to improve healthcare. Biophysics applies the concepts and methods of physics to explore the molecular, cellular, and systemic processes within living organisms, seeking to uncover the underlying mechanisms of biological phenomena. On the other hand, medical physics focuses on the application of physics in the development and optimization of medical technologies, including diagnostic imaging, radiation therapy, and therapeutic devices.

In recent years, the collaboration between biophysicists and medical physicists has resulted in revolutionary progress across a wide range of healthcare applications. Biophysics has contributed to a deeper understanding of the structure and function of biological molecules and cells, while medical physics has played a pivotal role in enhancing clinical techniques, from medical imaging modalities like MRI and CT to advanced radiation treatments in oncology.¹

This review aims to provide a comprehensive overview of the current state of both biophysics and medical physics, highlighting their interconnectedness, key advancements, and their potential for further breakthroughs. We will examine how biophysical insights are being applied in the development of medical technologies, the role of medical physics in clinical practice, and the ongoing innovations

that are shaping the future of healthcare. As the fields continue to evolve, their collaboration promises to address some of the most pressing challenges in modern medicine, leading to more effective, personalized, and accessible healthcare solutions.

Biophysics: Foundations and Advances

Biophysics is the branch of science that applies principles and techniques from physics to understand the complex processes and mechanisms occurring in biological systems. This interdisciplinary field combines the rigor of physical theory with the intricacies of biological systems, enabling scientists to investigate the physical foundations of life. Through the exploration of molecular, cellular, and systemic biological processes, biophysics has provided crucial insights into the mechanics of biological structures and their behavior. In recent years, biophysics has made significant strides in several key areas, with important implications for medicine and healthcare.

Structural Biology and Molecular Biophysics

A major focus of biophysics is understanding the structure and dynamics of biological macromolecules such as proteins, nucleic acids, and lipids. Advances in techniques such as X-ray crystallography, nuclear magnetic resonance (NMR) spectroscopy, and cryo-electron microscopy (cryo-EM) have revolutionized our understanding of molecular structures. These techniques allow for the atomic-level resolution of biomolecular structures, providing deep insights into how these molecules interact, fold, and function.

One significant area of research has been protein folding and misfolding, which is essential for understanding diseases such as Alzheimer's and Parkinson's. The study of protein-protein and protein-DNA interactions is also central to drug design, helping to identify new therapeutic targets and guide the development of precision medicines. The ability to determine the 3D structures of complex proteins has also driven innovations in biotechnology and pharmacology, leading to the creation of biologics and monoclonal antibodies.

Biomechanics

Biomechanics focuses on the study of mechanical properties and behaviors of biological tissues and organisms. By applying principles of mechanics, biophysicists study how forces are generated and transmitted through biological systems. This includes examining the mechanical properties of tissues such as bones, muscles, cartilage, and ligaments, as well as the biomechanics of fluid dynamics in the cardiovascular and respiratory systems.

Advances in biomechanics have significant applications in medicine. Understanding the mechanical properties of tissues has contributed to the development of better

prosthetics, orthopedic implants, and rehabilitation devices. For example, more effective artificial joints and prosthetic limbs have been designed by considering the forces and stresses experienced by natural tissues. Additionally, biomechanical studies on the heart and vascular system have led to improved treatments for cardiovascular diseases and the development of better surgical procedures.²

Bioelectricity and Biophysical Signals

Bioelectricity refers to the electrical phenomena that occur in biological systems, particularly in the generation and propagation of electrical signals in nerve and muscle cells. These electrical signals are essential for processes such as muscle contraction, neural communication, and the overall functioning of the heart. Biophysicists have made great strides in understanding the mechanisms of action potentials, ion channels, and synaptic transmission.

This understanding has profound medical applications. Medical devices such as pacemakers, defibrillators, and deep brain stimulators rely on bioelectric principles to treat conditions like heart arrhythmias, epilepsy, and Parkinson's disease. Additionally, technologies such as electroencephalography (EEG) and electromyography (EMG) are used for diagnosing neurological and muscular disorders. Advancements in the understanding of bioelectric signals have also contributed to the development of non-invasive techniques for monitoring brain activity and neural responses, which is essential in the study of consciousness and the treatment of mental health disorders.

Biophysics of Membranes and Transport

Biophysics plays a critical role in understanding the transport mechanisms across biological membranes. The study of membrane biophysics involves understanding how molecules and ions pass through the lipid bilayers that separate the interior of cells from the external environment. This field is crucial for understanding processes such as nutrient uptake, waste elimination, and signal transduction.

Research in this area has led to a better understanding of how certain drugs and therapeutics can be delivered across cellular membranes to target specific areas of the body. This has implications for drug delivery systems, particularly in the context of cancer treatments, where targeted drug delivery can minimize side effects by focusing treatment on cancer cells. Biophysical principles are also used to design nanoparticles and liposomes for drug delivery, ensuring that therapeutic agents are transported efficiently and safely.

Systems Biology and Computational Biophysics

Systems biology is an emerging field that looks at the complex interactions between biological molecules and systems, including signaling networks, metabolic pathways, and gene regulation. Biophysicists use computational

models and simulations to analyze these interactions, often employing techniques like Monte Carlo simulations, molecular dynamics simulations, and statistical mechanics.

In recent years, the rise of computational biophysics has revolutionized our ability to predict and understand biological behavior. By modeling the interactions between biomolecules and predicting the outcomes of biological processes, researchers can gain insights into complex diseases like cancer, diabetes, and neurological disorders. These computational tools also help in drug discovery, where large-scale simulations are used to screen potential drug candidates and predict their efficacy before clinical testing.³

Nanobiophysics

Nanobiophysics is an emerging subfield of biophysics that applies the principles of nanotechnology to understand and manipulate biological systems at the nanoscale. By exploiting the unique properties of materials at the nanoscale, such as quantum effects, biophysicists are developing innovative solutions for drug delivery, biosensing, and imaging.

Nanotechnology has the potential to revolutionize healthcare. Nanoparticles can be engineered to target specific cells, tissues, or organs, allowing for more precise and effective therapies. For instance, in cancer treatment, nanoparticles can be used to deliver chemotherapy drugs directly to tumor cells, reducing side effects associated with traditional chemotherapy. Additionally, nanoscale biosensors are being developed to detect biomarkers at low concentrations, providing earlier and more accurate diagnoses of diseases such as cancer, infections, and neurological disorders.

Medical Physics: Key Contributions to Healthcare

Medical physics is a discipline that applies the principles of physics to the field of medicine, with a primary focus on improving diagnosis, treatment, and patient care through the development and application of various medical technologies. Medical physicists play a crucial role in advancing healthcare, particularly in the areas of medical imaging, radiation therapy, and nuclear medicine. The combination of physical principles with cutting-edge technologies has led to innovations that have transformed patient care, improved clinical outcomes, and enabled the early detection and precise treatment of various diseases. This section discusses some of the key contributions of medical physics to modern healthcare.

Medical Imaging Techniques

Medical imaging is one of the most significant contributions of medical physics to healthcare, enabling non-invasive visualization of internal structures and functions of the

human body. Over the years, advancements in imaging technologies have improved the accuracy of diagnoses, facilitated early disease detection, and allowed for more precise treatment planning. Key imaging modalities include:

- **X-ray and Computed Tomography (CT):** X-ray imaging remains one of the most widely used diagnostic tools in healthcare. It enables the visualization of bones, soft tissues, and organs, aiding in the diagnosis of fractures, infections, and certain types of cancers. The evolution of CT scans, which combine multiple X-ray images to create cross-sectional images (or slices) of the body, has greatly enhanced the ability to detect conditions like tumors, cardiovascular disease, and lung disorders. Medical physicists are integral in optimizing imaging protocols, ensuring that the dose of radiation used is as low as possible while maintaining high image quality.
- **Magnetic Resonance Imaging (MRI):** MRI uses strong magnetic fields and radio waves to produce detailed images of internal structures, particularly soft tissues, such as the brain, muscles, and organs. It provides high-resolution, non-invasive images without the use of ionizing radiation. MRI has become an indispensable tool in the diagnosis and monitoring of neurological conditions (e.g., brain tumors, strokes, and multiple sclerosis), musculoskeletal disorders, and cancers. Medical physicists are involved in optimizing MRI hardware and software, improving image resolution, and ensuring safety in clinical environments.
- **Ultrasound Imaging:** Ultrasound uses high-frequency sound waves to generate images of internal organs and tissues. It is a commonly used technique in obstetrics, cardiology, and oncology. Ultrasound is non-invasive, real-time, and safe, making it particularly useful in prenatal care, monitoring the fetus, and detecting cardiovascular issues. Medical physicists contribute to the optimization of ultrasound equipment, improving image quality and ensuring its safe application in clinical settings.
- **Positron Emission Tomography (PET) and Single Photon Emission Computed Tomography (SPECT):** PET and SPECT are functional imaging techniques that allow clinicians to observe the metabolic activity and function of tissues and organs. PET scans are particularly useful in detecting cancers, assessing heart disease, and studying neurological disorders like Alzheimer's disease. These techniques rely on the use of radioactive tracers and require careful management of radiation doses, a key responsibility of medical physicists. By optimizing imaging protocols and ensuring proper calibration, medical physicists enhance the accuracy of functional imaging, aiding in early diagnosis and personalized treatment plans.⁴

Radiation Therapy

Radiation therapy is a cornerstone of cancer treatment, using high doses of radiation to kill or shrink tumors. Medical physicists play a crucial role in the planning, delivery, and quality assurance of radiation therapy treatments, ensuring that patients receive safe, effective, and precise care. Advances in radiation therapy techniques have significantly improved the precision of treatment, minimizing damage to surrounding healthy tissues while maximizing the destruction of cancerous cells. Key advancements in radiation therapy include:

- **Intensity-Modulated Radiation Therapy (IMRT):** IMRT is an advanced form of radiation therapy that uses computer-generated images to precisely target tumors with varying radiation intensities, allowing for highly tailored treatment plans. This technique enables clinicians to deliver radiation with great precision, reducing the risk of damage to surrounding healthy tissue and critical structures. Medical physicists ensure that IMRT is delivered accurately, verifying the treatment plans and performing regular quality assurance checks.
- **Stereotactic Radiosurgery (SRS) and Stereotactic Body Radiation Therapy (SBRT):** SRS and SBRT are non-invasive treatment options that use focused, high-dose radiation to treat small tumors or lesions in the brain or body. These techniques allow for precise targeting of tumors with minimal radiation exposure to surrounding healthy tissues. Medical physicists are essential in ensuring the accuracy of these treatments by performing complex calculations, simulations, and safety checks, thereby optimizing outcomes.
- **Proton Therapy:** Proton therapy is a type of radiation therapy that uses protons instead of X-rays to treat cancer. Protons have mass and charge, which enables them to deposit most of their energy directly in the tumor, minimizing damage to surrounding tissues. This makes proton therapy particularly useful in treating tumors located near critical structures, such as those in the brain or spine. Medical physicists are involved in the design, planning, and quality assurance of proton therapy systems, ensuring precise targeting and delivery of radiation.

Nuclear Medicine

Nuclear medicine is a specialized area of medical physics that involves the use of radioactive materials (radiopharmaceuticals) for both diagnostic and therapeutic purposes. Nuclear medicine enables the assessment of physiological processes, making it possible to detect diseases at an early stage when they are most treatable. Key contributions of nuclear medicine include:

- **Diagnostic Imaging with Radiopharmaceuticals:** Radiopharmaceuticals are injected into the body, where they emit gamma radiation that can be detected by imaging devices like gamma cameras. This allows for the visualization of organ function, blood flow, and metabolic activity. PET and SPECT are two prominent imaging techniques used in nuclear medicine to assess conditions such as cancer, heart disease, and neurological disorders. Medical physicists play a critical role in optimizing imaging protocols, ensuring the correct dose of radiopharmaceuticals, and maintaining radiation safety standards.
- **Therapeutic Applications:** Nuclear medicine is also used for targeted therapy, particularly in the treatment of certain types of cancers and thyroid conditions. Radioactive isotopes, such as iodine-131, are used to deliver localized radiation to tumor cells or overactive thyroid tissue. Medical physicists are responsible for ensuring that the radiation dose delivered to the patient is precise and within safe limits, while also minimizing exposure to healthy tissues.

Radiation Protection and Safety

One of the primary roles of medical physicists is to ensure the safety of patients, healthcare workers, and the public in environments where radiation is used. Medical physicists are involved in radiation safety protocols, ensuring that diagnostic imaging procedures, radiation therapies, and nuclear medicine applications are carried out with minimal risk. This includes performing routine quality assurance checks, calibrating equipment, and ensuring that appropriate shielding is in place.

Medical physicists also work with regulatory agencies to ensure compliance with safety standards, and they contribute to the development of new technologies that reduce radiation exposure. For example, the development of low-dose CT scans has made it possible to detect conditions like lung cancer with significantly reduced radiation exposure, an area in which medical physicists have played a key role.

Synergy Between Biophysics and Medical Physics

The collaboration between biophysics and medical physics has led to transformative innovations in healthcare, with both disciplines benefiting from each other's advancements. While biophysics focuses on understanding the physical principles underlying biological systems at the molecular and cellular levels, medical physics applies these principles in clinical settings to improve patient care. The synergy between these fields has paved the way for more precise diagnostic tools, more effective treatments, and the development of cutting-edge technologies that have

significantly improved healthcare outcomes. This section discusses key areas where biophysics and medical physics intersect, highlighting their joint contributions to modern medicine.

Personalized Medicine and Targeted Drug Delivery

One of the most exciting areas of synergy between biophysics and medical physics is the development of personalized medicine and targeted drug delivery systems. Biophysics has provided a deeper understanding of the molecular mechanisms of diseases, such as cancer, at the level of proteins, genes, and cellular interactions. These insights have paved the way for the creation of drugs that can precisely target specific molecular pathways or cellular structures.

Medical physics plays a crucial role in translating these advances into clinical applications. For example, radiation therapy can be personalized to target tumor cells based on their molecular characteristics, which are identified using biophysical techniques such as molecular imaging and genomics. Additionally, biophysics informs the design of nanotechnology-based drug delivery systems, where nanoparticles or liposomes are engineered to deliver drugs directly to disease sites, minimizing damage to surrounding healthy tissue. Medical physicists ensure the precision and effectiveness of these drug delivery systems by utilizing imaging technologies and radiation-based therapies to monitor drug distribution and optimize treatment protocols.⁵

Functional Imaging and Biophysical Modeling

Functional imaging techniques such as functional MRI (fMRI) and positron emission tomography (PET) are essential for monitoring real-time biological processes in the body. These imaging techniques often rely on principles of biophysics to interpret biological signals and understand how tissues and organs are functioning.

Biophysics contributes by providing a detailed understanding of the biophysical processes that underlie the signals observed in functional imaging. For example, biophysical models are used to interpret the neural activity detected by fMRI, enabling the study of brain functions such as cognition, movement, and sensory processing. In cancer treatment, PET scans can be used to observe tumor metabolism and track the effectiveness of therapy. By applying biophysical principles to the interpretation of these signals, medical physicists help clinicians obtain more accurate data that guide treatment decisions.

Additionally, computational biophysics, including modeling techniques such as finite element analysis (FEA) and Monte Carlo simulations, is increasingly being used to simulate biological processes and medical treatments. These models help predict how biological systems will respond

to therapies like radiation or drug delivery, which in turn allows for more effective and tailored treatment plans. Medical physicists use these models in clinical practice to optimize therapies, particularly in complex cases like cancer or neurological disorders.

Radiation Therapy and Biophysical Principles of Tumor Response

Radiation therapy, one of the most common treatments for cancer, benefits immensely from the insights provided by biophysics. Understanding the physical principles governing cellular responses to radiation—such as DNA damage, repair mechanisms, and apoptosis—is essential for improving radiation therapy techniques. Biophysicists study how different types of radiation interact with biological tissues, which informs the development of new radiation treatment strategies that maximize tumor cell death while minimizing damage to healthy tissue.

Medical physics applies these biophysical principles by designing and implementing advanced radiation therapies such as intensity-modulated radiation therapy (IMRT), stereotactic radiosurgery (SRS), and proton therapy. Each of these therapies relies on an understanding of how radiation doses affect the biological tissues at a cellular level. By combining the expertise of biophysics with sophisticated treatment planning and delivery systems, medical physicists are able to provide more effective, targeted therapies for cancer patients. These innovations are particularly beneficial for treating tumors near critical structures, such as in the brain or spine, where the precision of radiation delivery is crucial.⁶

Bioelectromagnetism and Diagnostic Technologies

The field of bioelectromagnetism, which studies the electrical and magnetic properties of biological systems, has significantly advanced both biophysics and medical physics. For instance, biophysicists study the electrical signals generated by neurons, muscles, and the heart, leading to a better understanding of diseases such as epilepsy, arrhythmias, and neurological disorders.⁷

Medical physics applies these biophysical insights through the development of diagnostic technologies like electroencephalography (EEG), electrocardiography (ECG), and magnetoencephalography (MEG). These non-invasive techniques allow for the monitoring of electrical activity in the brain, heart, and muscles, providing critical information for the diagnosis and treatment of various disorders. By applying biophysical principles to the interpretation of electrical signals, medical physicists can enhance the accuracy of these diagnostic tools, improving patient outcomes.

Moreover, advances in bioelectromagnetic technology are enabling the development of new treatments such as

deep brain stimulation (DBS) for Parkinson's disease and transcranial magnetic stimulation (TMS) for depression. These therapies, which rely on the application of magnetic fields or electrical currents to the brain, have been made possible by the intersection of biophysics and medical physics, offering non-invasive alternatives to traditional treatments.⁸

Computational Models for Disease Progression and Treatment Planning

Computational models of biological systems are becoming increasingly important in both biophysics and medical physics, particularly in understanding disease progression and optimizing treatment plans. Biophysical modeling techniques allow researchers to simulate the behavior of cells, tissues, and organs under various conditions, such as during cancer progression or after radiation therapy.

Medical physicists apply these models in clinical settings to predict the effects of treatments, evaluate the response of tumors to radiation, and plan personalized therapies. For example, in radiation therapy, computational models are used to simulate the distribution of radiation doses within the body, ensuring that the tumor receives the maximum dose while minimizing exposure to surrounding healthy tissues. In oncology, these models help predict how a tumor will respond to various treatment modalities, including chemotherapy, radiation therapy, and immunotherapy.^{9, 10}

Additionally, the integration of biophysical and medical physics models allows for the development of multi-modal treatment plans, which combine various therapeutic approaches (e.g., radiation therapy, surgery, and immunotherapy) to achieve the best possible outcome for the patient. These models also help track disease progression over time, enabling clinicians to adjust treatment plans based on real-time data.

Nanotechnology and Cancer Treatment

Nanotechnology, a field that heavily relies on principles of biophysics, is rapidly advancing in cancer treatment. Biophysics helps to understand the interactions between nanoparticles and biological systems, including how nanoparticles can be engineered to target specific types of cancer cells. These insights have led to the development of nano-based drug delivery systems, where drugs are delivered directly to tumor cells, minimizing side effects and improving the efficacy of treatment.¹¹

Medical physics plays a critical role in the application of nanotechnology to cancer therapy by ensuring the safe and precise delivery of nanoparticle-based drugs. Through advanced imaging techniques like MRI and PET, medical physicists can track the distribution of nanoparticles in the body, ensuring that the drug reaches the target site and is delivered effectively. Additionally, medical physicists

use radiation therapy in conjunction with nanoparticles to enhance the effectiveness of treatment, leveraging the unique physical properties of nanoparticles to sensitize cancer cells to radiation.^{12, 13}

Challenges and Future Directions

While the intersection of biophysics and medical physics has led to remarkable advancements, several challenges remain:

- **Safety and Ethical Considerations:** As radiation-based therapies and imaging techniques become more sophisticated, ensuring patient safety remains a top priority. Advances in radiation protection, imaging safety, and ethical guidelines for the use of biophysical technologies will be essential for future developments in both fields.
- **Interdisciplinary Collaboration:** The complexity of biological systems and medical technologies requires ongoing collaboration between physicists, biologists, engineers, and clinicians. Promoting interdisciplinary training and collaboration will be key to solving complex problems in healthcare and ensuring the successful application of biophysical principles in medicine.
- **Technological Innovation and Access:** As new technologies emerge, ensuring that they are accessible to patients in diverse healthcare settings is crucial. The challenge lies in balancing cutting-edge technological advancements with the need for affordable and widely available treatments and diagnostic tools.^{14, 15}

Conclusion

The synergy between biophysics and medical physics has led to numerous groundbreaking advancements in healthcare, from personalized medicine and imaging technologies to targeted therapies and radiation treatments. By combining the molecular insights of biophysics with the practical applications of medical physics, these fields have significantly improved diagnostic accuracy, treatment precision, and patient outcomes. As both fields continue to evolve, their collaboration will undoubtedly play a key role in addressing some of the most challenging medical conditions, ultimately leading to more effective, tailored, and less invasive treatments.

The continued development of computational models, nanotechnology, and bioelectromagnetic therapies promises to open new frontiers in treatment and diagnosis. As biophysicists gain deeper insights into the behavior of biological systems at the molecular and cellular levels, and medical physicists apply these principles to create more sophisticated and effective medical technologies, the gap between basic science and clinical practice continues to shrink. This partnership has already made significant strides in areas like cancer therapy, neurological disorders, and

cardiovascular disease, and is poised to revolutionize how we approach complex diseases in the future.

Moreover, as both fields continue to innovate, their combined expertise can help mitigate the risks of new technologies, ensuring the safety and effectiveness of treatments and diagnostic procedures. For example, with the increasing use of artificial intelligence (AI) and machine learning in both biophysics and medical physics, there will be even more potential to predict disease progression, optimize treatment plans, and automate diagnostic processes. This will further enhance the precision of medical practices, making healthcare more accessible and efficient.

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