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APPLICATION OF MULTIPHYSICS MODELING TO COMBINE ELECTROMAGNETIC THEORY, TISSUE BIOMECHANICS, AND CLINICAL IMAGING FOR NEXT-GENERATION MEDICAL DIAGNOSTIC AND THERAPEUTIC DEVICES

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Abstract:

Multiphysics modeling combines electromagnetic theory and tissue biomechanics for applications in medical diagnostics and therapeutic device design. Future medical devices will incorporate embedded sensors and actuators that measurably interact with the patient, thereby requiring anticipation of coupled interactions between electromagnetic fields and biological structures. Understandings of sensing and therapeutic implementations support new medical device designs, allowing guidance, control, and landmarking to facilitate next-generation therapies. Diagnostic applications include virtually all clinically established imaging techniques, and validation methods for targeted therapies rapidly improve patient outcomes. The development of therapeutic techniques explores low-level direct applicator-to-tissue couplings that hold promise for tissue regeneration and enhancement.

Keywords: Multiphysics Modeling, Electromagnetic-Tissue Interaction, Medical Imaging, Therapeutic Device Design, Biomechanics Simulation

1. Introduction

Multiphysics modeling describes computational techniques used to simulate multiple physical processes and their interactions. When extended beyond physics, it provides insights into coupled physical and biological systems. Coupling electromagnetic theory with tissue biomechanics is highly pertinent in medical devices used in diagnostic imaging and therapeutic procedures.

Continuous advances in computer power and algorithms have enabled increasingly complex multiphysics models, particularly in the medical device sector, facilitating novel methods of diagnostic imaging and therapeutic treatment. However, developing high-fidelity multiphysics models remains a significant challenge due to the complexity of the underlying multiphysics and computational requirements. The integration of physics with clinical imaging offers clinically useful information about tissue biomechanics. The combined use of magnetic resonance imaging (MRI), computed tomography (CT), and ultrasound compliments the approach by providing diagnostic information about a variety of pathological processes resulting in altered tissue mechanical properties [1][2][3][4].

2. Fundamentals of Electromagnetic Theory

Electromagnetic theory provides the foundation for the design of many medical devices. Electromagnetic waves diagnostically provide imagery and tissue characterization, while applied electromagnetic fields can provide novel therapeutic modalities. For such applications, a comprehensive examination of the related governing equations, physical implications, and practical applications is beneficial. Maxwell’s curl equations, integral expressions, divergence theorems, Lorentz force law, energy conservation relations, and the principle of reciprocity constitute this analysis.

Many inhomogeneous media in fact do not comply with the prescribed constitutive equations. When modeling complex media, it is often more appropriate to impose the relations of the physical properties at the microscopic scale where they are homogeneous and known to be true, and then one can effectively relate the distribution of charge, current, polarization, and magnetization sources at the micro scale. From these, the physical properties can be derived. It is important to understand the principles of microwaves as applied in diagnosing human disease and also the role of microwaves in producing therapeutic agents. In addition, the interactions of their fields with biological tissues are crucial [5][6][7].

2.1. Maxwell's Equations

Electromagnetic theory facilitates antennas and waveguides for wireless communication, establishes guidelines for electromagnetic compatibility, and enables the initial extrapolation of Maxwell’s classical linear partial differential equations of the electromagnetic field to a nonlinear universe [8]. Maxwell’s equations are a set of four partial differential equations that govern electromagnetic phenomena. The equations describe how the electric and magnetic fields relate to each other and to their sources, the electric charges, and currents, and they form the fundamental equations of classical electromagnetism, classical optics, and electric circuits. The current density is often expressed in the form $J=\sigma E$

2.2. Electromagnetic Waves in Biological Tissues

Since devices in medicine can be made smaller, faster, and with more functionality than ever before, modeling the underlying physics and physiology is also increasing in importance as a guide to innovation of new medical devices and clinical protocols. This chapter presents multiphysics modeling of electromagnetic waves in biological tissues, tissue biomechanics, and clinical imaging (magnetic resonance imaging, computer tomography, and ultrasound). The multiphysics model, which integrates biology, medicine, and engineering physics, can lead to new diagnostic modalities and devices, and an understanding of physiological mechanism of tissues. The fundamental equations and key concepts of the electromagnetic waves–tissue biomechanics–clinical imaging multiphysics modeling—relevant to magnetic resonance imaging, microwave tomography, thermography, radiothermometry, ultrasound, microwave heating, electromagnetic hyperthermia, and devices from magnetic resonance imaging to follow on devices and applications—are described [9][10][11].

3. Overview of Tissue Biomechanics

The accurate quantification of mechanical properties of soft tissues, especially malignant lesions, remains a significant challenge. Mechanical properties undergo marked changes in various pathological conditions such as carcinoma, fibrous hyperplasia, fibrosis, and scleroderma [12]. These changes occur as malignant cells grow and invade the surrounding complex three-dimensional extracellular matrix architecture. Biological tissues exhibit inherently nonlinear, anisotropic, inhomogeneous, dispersive, and viscoelastic mechanical behavior. Establishing the direct relationship between pathology and disease progression with tissue properties provides an index for diagnosis.

Recent advances in computational methods have facilitated multiphysical approaches to quantify and predict tissue biomechanics across different length scales, which is critical given the hierarchical and heterogeneous nature of biological tissues [13]. The primary modelling strategies include traditional structural mechanics and mechanobiological frameworks that incorporate the effects of tissue microstructures and the biological environment.

3.1. Mechanical Properties of Biological Tissues

Mechanical properties define how materials respond to forces, displacements, or changes in temperature; in biomechanics they describe tissue response to external loadings or internal CD (current density) induced forces. Property selection depends on analysis type--e.g., solid or fluid mechanics. Biological tissues are predominantly solids supporting most diagnostic and therapeutic applications. Unlike simpler engineering materials, tissues exhibit nonlinear behavior and heterogeneous mechanical properties. Nonlinearity arises when stress is not proportional to strain, and heterogeneity shows that stiffness may vary with factors like strain level, location, loading direction, or velocity; a headline common to clinical imaging modalities.

Citizenship of this headline yields Monash University analysis of corresponding diagnostics in section 5, renderingindex Concealed_in in the Free Page [14][15][16].

3.2. Modeling Tissue Response to Electromagnetic Fields

In physics, multiphysics modeling combines two or more areas of physics to create a more broadly applicable model. These models are usually highly non-linear and study the effect that one system has on the other. They are especially important in medical device research and development, where the goal is to provide innovative tools for clinical diagnostics and therapeutic procedures.

Eleven different, closely related fields have been identified, ranging from fundamental theories of biodynamic interactions through the development of next-generation smart therapeutic medical devices. These are: electromagnetics interacting with tissue, tissue response to electromagnetic fields, clinical imaging, clinical imaging and tissue mechanics, next-generation therapeutic devices, principles of mechanics, regulatory and ethics considerations, computational methods, case studies in diagnostic devices, case studies in therapeutic devices, and future directions. The foundations of electromagnetics and tissue mechanics are each discussed in detail prior to their integration in section 3.2. An overview of clinical imaging completes the list of enabling technologies and is presented in section 5 [11][17].

4. Clinical Imaging Techniques

Clinical imaging techniques are essential in medical diagnostics, providing clinicians with insight for diagnosis and therapy and delivering essential information for the validation of multiphysics models. These models facilitate computational prototyping of medical devices used in healthcare. Commonly employed clinical imaging modalities with varied resolutions, acquisition times, and levels of tissue penetration include magnetic resonance imaging (MRI), computed tomography (CT), and ultrasound. MRI is based on nuclear magnetic resonance and exploits intrinsic magnetic properties within the body. CT employs X-rays to capture cross-sectional images of tissue. Ultrasound utilizes the piezoelectric effect to generate and receive high-frequency mechanical waves.

Clinical images generated by these modalities are consulted by radiologists to determine the presence of injury or disease. Furthermore, these images can be semiautomatically or automatically segmented to yield information about tissue health and condition. Examples include susceptibility-weighted imaging to observe hemorrhagic features in the brain and diffusion-weighted imaging combined with a mean diffusivity analysis to type cerebral abscess. Imaging outcomes such as first-pass myocardial perfusion imaging and noninvasive computed tomography angiography have proven capable of both diagnosing the presence and assessing the severity of coronary artery disease [18][19].

4.1. Magnetic Resonance Imaging (MRI)

Magnetic Resonance Imaging (MRI) is a widely applied non-invasive imaging modality based on non-ionizing radiation, which produces excellent images and soft tissue contrast of living tissues. The modified Bloch problem serves as a model of MRI for flowing spins in an incompressible flow field. After establishing the well-posedness of the corresponding evolution problem, the spatial semi-discretization using discontinuous Galerkin methods is analyzed. The high-frequency time evolution requires a proper explicit and adaptive temporal discretization; the applicability of the approach is demonstrated for basic examples [20].

MRI plays a crucial role in medical imaging by providing high-resolution images with excellent soft-tissue contrast. Techniques such as undersampled k-space data acquisitions, compressed sensing, and deep learning reconstructions have been developed to reduce scan times and mitigate artifacts. Magnetic Resonance Fingerprinting (MRF) has emerged as an efficient framework for acquiring and estimating multiple tissue properties simultaneously in a single fast MR acquisition. Although MRF is a relatively new technique, research interest has increased exponentially, with developments in pulse sequence structure, parameter optimization, and reconstruction, aiming for clinical usage. Despite advancements, challenges persist across different magnetic field strengths and body parts, presenting opportunities for further research. The combination of spin dynamics and undersampling makes MRF one of the best examples of effective quantitative mapping of the human body using MRI scanners [21].

4.2. Computed Tomography (CT)

Computed Tomography (CT) is a powerful diagnostic tool that employs short bursts of X-ray photons that are passed through the patient and recorded on the opposing side. X-rays exhibit relatively low absorption in regions with low density or low atomic number, such as soft tissues, while exhibiting strong absorption in regions with high density and atomic number, such as bones or injection contrast agent. Contrast agents can be injected into the patient to mark different types of vessels or tumors. The X-rays are typically projected onto an X-ray detector to form a shadow image (radiograph), which can be used to determine the position and shape of bones, implants, or foreign bodies. To create a CT image, a large number of radiographs are acquired while the source and detector rotate consecutively around the patient. A mathematical back-projection is then applied to generate a 3D radiograph, or CT scan. CT can achieve high resolutions and, depending on the X-ray source, the contrast agents, and the acquisition protocol, it is also sensitive to a wide range of organs and vessels. Nevertheless, the ionizing radiation of X-rays limits the number of radiograph images that can be acquired. More recently, in order to enable material differentiation, several clinical scanners have been equipped with several (mostly two) X-ray sources and detectors, referred to as dual-energy or spectral CT scanners.

In CT images, the different tissue properties modulate the line integral of the photon fluence, and therefore the medical images also contain additional medical information. When the images associated with a particular tissue or area-of-interest are registered, image-processing algorithms can be applied—such as integration of the difference between the reference and follow-up image—to create new maps that highlight the differences between those images. The so-called soft-tissue window (soft tissue) enhances structures in the organs, whereas the bone window highlights bony structures in the skull and the thorax of cancer patients. COVID-19 and influenza pneumonia can, for instance, be detected by highlighting the ground-glass opacities with a lung window and consideration of the overall pattern [22][23].

4.3. Ultrasound Imaging

Ultrasound imaging represents a crucial clinical modality for guiding and confirming the progress of diagnostic and therapeutic procedures in the human body. It complements modalities such as magnetic resonance imaging and computed tomography, thereby enhancing the capability for accurate diagnosis. Moreover, effective ultrasound imaging provides a powerful means to validate numerical studies of tissue biomechanics and contributes to the design of novel medical instruments for advanced therapeutics and diagnostics and for safeguarding the health and long-term development of vulnerable populations [24].

5. Integration of Electromagnetic Theory and Tissue Biomechanics

The rapid development of medical imaging and the ongoing technological advancement of medical instruments demand an integrated approach based on electromagnetic theory, tissue biomechanics, and clinical imaging to improve diagnostics and therapies. Existing computational models reveal that electromagnetic fields induce significant mechanical response in a wide range of soft biological tissues. Models based on Biot's theory for poroelastic media, a microscale approach connecting solid matrix deformation with ion and fluid transport, single-phase descriptions of porous media, and standard thermoelasticity can be adopted when the wavelength is much larger than the size of the microstructure to investigate this coupling and prepare applications in medical physics, e.g. for electromagnetic and electro-therapeutic devices. Coupled multiphysics formulations constitute the cornerstone of a new generation of medical devices enabling both diagnostic and therapeutic non-invasive medical procedures [25]. Available imaging modalities including MRI, CT scan, and ultrasound imaging provide important indications about the size and the location of critical soft tissue regions and can be incorporated into the development of such devices to overcome the limitations of pure waveguide cutting, thermo- or acoustic-based methods [26].

5.1. Coupled Electromagnetic-Tissue Models

Multiphysics modeling refers to computational approaches that integrate problem-specific physics to solve complex challenges, frequently encountered in the simulation of real-world phenomena. Such analytical modeling has gained attention in the medical field because it supports the development of diagnostic methods and medical implants capable of enhancing the quality of healthcare. Using a combination of biomechanical and electromagnetic principles, novel clinical imaging-based tissue characterization techniques and minimally invasive approaches for the treatment of cancers are explored in this work. The coupling between electromagnetic and tissue biomechanical models gives rise to smart magnetic resonance imaging-guided therapeutic systems that can leverage either therapeutically-induced thermal or mechanical tissue responses.

When interactions between clinical imaging and either electromagnetic or biomechanical principles are considered, new-generation diagnostic techniques producing high-quality multiparametric imaging of specific organs are subsequently developed. Biomedical applications have complex geometries and material properties, which require specialized computational approaches. The Finite Element Method (FEM) is an effective analysis technique for complex model geometries. The Boundary Element Method (BEM) of analysis, requiring discretization only of the model boundaries, provides a particularly attractive approach for electromagnetic analysis of prostates under movement. Meshless methods are well suited for biomechanics–clinical imaging applications because these methods compute tissue stress–strain distributions without introducing testing or integration points [27][28].

5.2. Applications in Therapeutic Device Design

Multiphysics modeling focuses on the integration of electromagnetic theory, tissue biomechanics, and clinical imaging, with the goal of advancing diagnostic and therapeutic medical devices. Therapeutic devices that leverage multiphysics modeling and simulation embody the theme of the book as a whole.

Computational multiphysics modelling provides key capabilities in the design of therapy delivery devices. Physiological phenomena of great interest, such as tumour growth, are multiphysics problems; knowledge about these phenomena, permissions for hypothetical treatment strategies, and clinical intervention planning and monitoring are guided by the benchmarks referenced in Section 9.

6. Computational Methods for Multiphysics Modeling

Multiphysics modeling—which combines electromagnetic theory and tissue biomechanics—aims to contribute to the development of novel medical diagnostics and therapeutic techniques. These two bodies of physics refer, respectively, to phenomena associated with electrical currents, charges, and magnetic fields; and phenomena associated with the motions and deformations of matter. Clinical imaging techniques provide clinical context for multiphysics models and modern diagnostics, especially MRI, CT, and ultrasound.

Maxwell's equations describe essential phenomena in the human body, most notably bioelectric activity and electromagnetic wave propagation. Tissue biomechanics governs several mechanical properties of the human body, and is crucial in the design of therapeutic devices such as stents and implants. Although they deal with separate topics, these two fields can be combined by analysing the interaction between the governing equations. This coupling between the two fields can, in turn, be applied to improve existing clinical diagnostic tools or to design next-generation therapeutic devices. Computational modeling plays an essential role in guiding diagnostic assessments and in the design, optimization, and validation of therapeutic devices.

Multiphysics tissue properties and responses that involve electromagnetic and tissue-biomechanical phenomena are investigated in a broad spectrum of medical applications. Modeling approaches are broadly classified into domain-discretization methods, including finite-difference and finite-element methods, for which analysis is performed on a structured or unstructured mesh; an infinite-domain discretization method, the boundary-element method, for which analysis is performed on a mesh constructed on the domain boundary; and meshless methods, for which mesh construction is not required, offering flexibility in simulating a variety of physical systems [29][30].

6.1. Finite Element Analysis (FEA)

Finite element analysis (FEA) is a numerical technique used to find approximate solutions to boundary-value problems for differential equations usually encountered in engineering. It is also called finite element method (FEM). The essential idea is to divide a large problem into smaller, simpler parts that are called finite elements. Mathematical equations that model these finite elements are then assembled into a larger system of equations that models the entire problem. FEA then uses variational methods from the calculus of variations to approximate a solution by minimizing an associated error function. FEA for electromagnetic system analysis is discussed in principle 7.1.2.

Through advances in procedural automation and increased processing power of computers, FEA has become a popular tool for simulating physical phenomena. This makes it possible to quickly and easily simulate problems for which an analytical solution is not available. It can also be used in situations where only a very general solution is known, and a more specific solution important for the design of the actual device is desired. Typical examples are the Maxwell differential equations describing the electromagnetic field. Even in cases where analytical results are available, the complex model of the device can be taken into account in detail, without making any supporting assumptions. FEA is also applied to such problems as heat distribution, fluid flow, and stress analysis in structures.

6.2. Boundary Element Methods (BEM)

Numerical modeling of coupled electromagnetic and biomechanical phenomena often requires solution of the Helmholtz equation and Maxwell's equations for electromagnetic fields. Such problems can be represented by surface integral equations with field sources in the volume. Boundary element methods (BEM) offer an attractive approach to modeling these types of problems by describing the fields solely in terms of their surface values across the model geometries. In practical applications, the volume where the governing equations change is usually composed of multiple subdomains joined at common boundaries. In electromagnetic modeling, the subdomains typically consist of inhomogeneous and non-uniformly anisotropic volume conductors with different conductivity tensors, representing the biological tissues within the application. Each subvolume is associated with a constant conductivity or diffusion tensor. The solution of the electromagnetic field inside the tissue space follows from the continuity of potential and current across the surfaces separating these volumes; thus, the problem reduces to determining surface values satisfying the boundary conditions imposed by the tissue conductivity distribution. BEM approaches have been widely adopted in academic and industrial electromagnetic time-harmonic and static field simulators. For harmonic electromagnetic problems, BEM reduces the computational domain for the Green's function evaluation, thereby significantly decreasing the computational load compared to volumetric approaches [31].

6.3. Meshless Methods

Biomedical applications frequently involve complex moving boundary and large deformation problems. Volume meshing of the associated evolving geometric domain can be both time consuming and costly, especially when vessel volumes need to be frequently changed during simulations, as in haemodynamic studies or for scaling arterial branches during vascular tree growth. To facilitate biomedical modelling in such cases, meshless methods provide an attractive alternative to traditional mesh-based methods such as the finite element and finite volume methods [32]. Mesh-free formulations remove the overheads of mesh generation, and interface capturing and evolution algorithms from the numerical solution procedure. Meshless methods have been used in the bioheat applications, simulation of tumour ablation, non-linear Pennes' bioheat transfer, patient-specific modelling and non-rigid registration for hepatic metastasis, and nonrigid and coupled radiative and conductive heat transfer problems. They have also proved suitable for modeling soft tissue deformation via digital imaging and radial basis functions. Meshless methods are capable of accurately describing soft tissue deformation and interactions, including the treatment of penetration impacts and surgical grasping. They have been extended to real-time deformation analysis and large deformation simulation of soft tissues and organs.

7. Case Studies in Medical Diagnostics

Medical diagnostics present a fertile testing ground for novel biomarkers, sensors and scanning modalities, where the emphasis lies in patient safety and improved image fidelity rather than novel therapy. Often there is a greater scope for combining modalities to mitigate one technique's shortfalls here (see Section 5). The use of computational modeling and simulation in the development of more accurate imaging techniques has grown significantly in recent years, with the goal always being to engineer a technique that can serve as a better diagnostic aid for clinicians.

In bone studies, the combination of sonography and MRI has been developed to provide insights into cortical bone health. Owing to low signal intensity on MRI, direct structural assessment of cortical bone has remained a challenge in applications; here, biomechanical modeling converts measurements made using supersonic shear imaging to the cortical bone Young's modulus. The validation of any diagnostic technique is paramount; clinical studies ascertaining the diagnostic quality of multi-modal imaging are crucial in appropriate contexts. For example, for breast cancer patients with invasive lobular carcinoma, a study was presented to test the hypothesis that co-registration of MRI and digital breast tomosynthetic information (along with DXA and menopausal data) would provide a more accurate and objective diagnostic model of skeletal health.

7.1. Electromagnetic Imaging Techniques

A wide bandwidth and no ionizing radiation make electromagnetic fields in the frequency range from 1 MHz to 50 GHz a noninvasive source for diagnostic imaging. Electromagnetic imaging obtains intensity images of electrical property distributions of the tissue under examination. These images provide information of biological and pathological conditions not otherwise available from physiological imaging. Techniques include electrical impedance tomography, electrical capacitance tomography, electrical resistance tomography, magnetic induction tomography, microwave imaging, tissue property tomography, tissue property concentration tomography, and tissue property tomography testing.

A diagnostic device and method based on electromagnetic tomography testing generate tomography images showing the differences in boson concentrations at the different areas inside a tissue specimen. These techniques can be used in diagnosis, such as differential diagnosis of cancer. Electromagnetic tomography testing also can be used to monitor the effects of therapeutic procedures such as chemotherapy or chemoprevention. Tomography images of the electrical property distribution of the breast also can be used in conjunction with other modalities (e.g., X-ray mammography) for increased accuracy in diagnosis. In every area of health care, there is a gap between the increasing demand for better service and the supply of available resources [33][34][35].

7.2. Biomechanical Assessment of Tissue Health

The geometry-based approach is illustrated for the multipolar formulation of BEM by following a systematic procedure that allows hierarchical building of different formulations from the potential formulation. The potential formulation demonstrates the efficiency of the formulation, where a reduction in computational complexity is seen once a particular hierarchy level is reached [12]. Advances in numerical methods have enhanced the computational efficiency of multiphysics modeling by facilitating the accurate representation of multiple physics with different characteristic wavelengths simultaneously [36].

Biomechanical investigation is crucial for understanding mechanical behaviour and contributes to differentiating healthy and diseased tissue states through assessment of local pathologies. Changes in tissue morphology due to tumours or fibrosis alter mechanical properties, providing diagnostic indices for differentiation. Commonly used techniques for assessing tissue differ mainly in the mechanobiological models employed to interpret pressure–deformation relationships, which cannot fully predict frequency-dependent viscoelastic responses. Material properties depend on numerous factors, including the structure and composition of tissues, loading amplitude, temperature, and initial state. Viscoelasticity originates from fluid movement in tissue matrix compartments, maintained by embedded cells. For correlation studies, characteristic histological and quantitative biological measurements are important for analysis with modulus coefficients.

8. Next-Generation Therapeutic Devices

Multiphysics modeling combines electromagnetic theory, tissue biomechanics, and clinical imaging to support the design of medical devices with novel diagnostic and therapeutic functionality. Such models have the potential to accelerate translation by improving understanding of tissue physics, biliary pathology, restraining development uncertainty, enhancing design iterations, reducing the number of design prototypes, providing in silico verification for planned measurements, and minimizing in vivo experimentation. Therapeutic fields represented in the literature include microwave ablation, magnetic resonance-guided focused ultrasound treatment, radiofrequency ablation, electroporation, and electromagnetic manipulation of tissue scaffolds. Devices under design draw on coupled physics to improve existing methods of diagnosis and treatment, such as radiofrequency ablation tools enhanced by tumor segmentation, active catheters, or biosensors; stretchable, wireless neonatal monitors for non-wired measurements; and novel electromagnetic-photonic implants intended to stimulate bone tissue repair. Micro- and meso-scale models under development include feature-level photonic models, expanded resonance models for metamaterial absorbers, and multiscale models for mechanobiology of bone regeneration. At larger scales, progress is reported for coupled electromagnetic-thermo-mechanical simulation of microwave ablation; multiscale radiofrequency ablation treatment models; thermal ablation; magnetic resonance-guided focused ultrasound; transient coupled fluid dynamics models of contrast agent dispersion combined with electromagnetic radiation models of sound propagation and reflection; and electromagnetic manipulation of tissue scaffolds to drive morphogenesis of tissue constructs [37].

8.1. Design of Electromagnetic Therapy Devices

The design of next-generation electromagnetic therapeutic devices relies heavily on multiphysics effects in the body. Each success in research activities with a new electromagnetic therapy strongly motivates industrial development and attracts the attention of other researchers to propose new devices. Multiphysics models can anticipate the performance of a therapeutic device and provide insights into new scientific directions. The effectiveness of such devices can ultimately be measured only by clinical evaluations, which involve the development of dedicated electromagnetic tissue–body models that include the patient's disease state and its progression after repeated treatments.

Next-generation therapeutic devices can, for example, be addressed by combining diagnostics and therapeutics, where clinical imaging data are used for accurate patient-specific therapy planning. Other research directions consider smart implants for disease treatment. These innovative devices could be inserted into the body similarly to a stent and stimulate nearby tissue at the end of the cardiac ablation procedure to initiate the automatic heart rhythm for a patient. The implants would have to be electromagnetically powered and communicate with the doctor for control and adjustment. Such challenging combinations of multiple sensors can be created for many pathophysiological conditions and, therefore, have the potential to open a new paradigm for therapy treatment [38][39][40].

8.2. Smart Implants and Biomechanical Devices

Biomechanical devices and implants utilize the natural mechanical functions of human tissues for diagnostic and therapeutic purposes. Examples of such devices include commercial cardiac assist pumps, artificial bone and cleaned blood vessels. Novel developments in this area include smart implants and biosensors. Smart implants operate in a manner analogous to biological tissues but also have the capacity to sense their environment. For instance, the mechanical properties of the surrounding tissue can be monitored as the tissue gets damaged or is repaired. The information collected by the smart implants can be relayed to the healthcare providers. Biosensors, on the other hand, require biochemical compatibility of the surrounding media in order to function properly. Their operation depends on the interactions of ionic charges and ions with the electric and magnetic signals generated by the surrounding tissues.

Design of medical devices commonly uses subject-specific clinical information. For example, image data from an individual patient can be used to model the patient's tissue architecture and biomechanical properties. In addition, major arteries such as the aorta are frequently imaged. Clinical magnetic resonance imaging (MRI), computed tomography (CT), X-ray and ultrasound provide useful insight into disease progression. Such information can be utilized for the early detection and monitoring of disease as well as for the analysis of the surgical and treatment outcomes. The advantage of clinical imaging for biomechanical modeling lies in the simultaneous geometric and property specifications from the same individual. Simplicity in modeling can also be achieved when complete images of the region of interest are generated [41][42][43].

9. Regulatory and Ethical Considerations

Multiphysics modeling and simulation, especially when integrated with medical imaging technologies, have engendered the introduction of novel working principles for medical diagnostics and next-generation medical treatments. Emerging technologies such as electromagnetic imaging and therapeutic devices leverage the interaction between electromagnetic fields and biological tissues within human-sized bodies. Mechanical assessment of diseased tissues through clinical imaging modalities like Magnetic Resonance Elastography (MRE) relies on the application of low-frequency mechanical vibrations to induce stress and strain in targeted tissues. Hybrid technologies encapsulate additional mechanical properties, particularly viscoelasticity, with examples including hybrid Electromagnetic-Acoustic Systems (EMAS).

The migration of post-processing, signal analysis, and inversion stages—integral to the diagnostic workflow—from laboratory settings to the clinic necessitates the development of dependable and accurate multiphysics computational models. Consequently, next-generation therapeutic devices are prioritized as a major area for research funding. Advances such as Electromagnetic–Acoustic Structural Stimulation (EASS) are designed to mechanically stimulate tissue, promising treatment benefits that range from pain management and tissue healing to tumor therapy. The transition of these technologies to clinical practice requires a comprehensive understanding of medical device regulations alongside the ethical considerations that accompany introducing multiphysics devices. [44][45][46]

9.1. Regulatory Frameworks for Medical Devices

The proliferation of technologies capable of delivering therapeutics through at-a-distance energy deposits has generated a new class of devices subjected to existing medical device regulations. All such devices must demonstrate compliance with appropriate regulations and standards in the areas of manufacturing, device safety and effectiveness, and quality control. Voluntary standards have been developed to demonstrate safety of medical devices designed to deliver energy through biological tissue; the accompanying electromagnetic and acoustic modeling techniques are often used in the evaluation process. In instances where technological innovation supports regulatory approval by demonstrating a device's ability to achieve either a new performance attribute or higher levels of existing performance attributes, multiphysics modeling is playing an increasing role [47][48][11].

9.2. Ethical Implications of Multiphysics Applications

The exploration of multiphysics models for developing clinical devices employing new imaging techniques or creating innovative treatments brings about various new ethical questions for the medical and research community, especially when patient-specific information is used. For instance, while

CAD systems help reduce human error concerning device design and usage, the responsibility of a product's failure remains a topic for discussion.

Medical devices are supposed to provide additional benefits to patients and the healthcare system but cannot fully replace expert knowledge and recommendations. Nevertheless, modeling is an excellent tool to aid diagnosis, increase reliability, and design more efficient treatments and devices. As a result, patients might be exposed to facilities or therapies that would not have been considered without these tools, and scientists might believe that a treatment is feasible when it can only work under controlled modeling conditions. An additional concern arises when the created device requires invasive surgery; patient-specific models should at least reduce surgical risks by providing a clear vision of the procedure and interaction with deformed tissues [49][50][51][52].

10. Future Directions in Multiphysics Research

The future of multiphysics research is intimately tied to ongoing advances in computational multi-physics and the utilization of clinical imaging data for personalized problem generation and model calibration [53]. Current research explores novel applications of multi-physics models to cancer therapies, organ-specific laser diagnostics, and ventricular assist devices. Specific projects involve combining tissue biomechanics with acoustic, magnetic resonance, and nuclear imaging modalities to deduce material properties—experiments critical for model validation. Additional investigations focus on magnetic-hyperthermia cancer treatment, mechanical therapies for glaucoma, glucose homeostasis models for diabetes, and multi-physics-assisted tissue engineering. Envisioned next-generation devices will harness data from multiple physical systems, formulating inverse problems that integrate electromagnetic theory, tissue biomechanics, and clinical imaging to deliver unparalleled capabilities in both diagnostics and therapeutics [54].

10.1. Advancements in Computational Techniques

Multiphysics modeling is emphasized in the context of medical-device design. Key advances in computational techniques are considered, and the focus is on two complementary areas of physics. The first relates to electromagnetic theory applied to bioelectromagnetic–physics-based diagnostics, such as MRI and CT scans, and in proposed new imaging techniques based on scattering theory or in physiological interaction mechanisms such as cardiac defibrillators, emergency room devices, or transcranial magnetic stimulation. The second relates to the biomechanics of soft tissue and bones, including the evaluation of pathological tissue such as breast tumours, brain ventricle swelling or bone decalcification, and therapeutic methods. These are not isolated effects but must be dealt with concurrently and combined in the next generation of smart diagnostic and therapeutic medical devices.

A detailed account is presented of the fundamentals of electromagnetic theory, of tissue biomechanics, and of clinical diagnostic imaging. The clinical imaging section highlights MRI, CT scanning and ultrasound because these currently provide the bulk of the diagnostic data; the discussion is, however, aimed more broadly at the diagnostic power of any imaging technique and the crucial role of imaging in isolating the shape and properties of the subject. The results of these three sections can be brought together using the concept of multiphysics models of medical diagnostics.

10.2. Emerging Applications in Personalized Medicine

After a 2500-year development, electromagnetic theory and Maxwell's equations still generate innovative medical diagnostic and therapeutic devices. Tissue biomechanics enhances predictive capability for medical devices and comprehends health and disease. Clinical imaging advances diagnostic capability, offering solutions for clinical translation of multiphysics modeling. These three elements form a foundation for multiphysics in personalized clinical care; their effective combination, with clinical imaging serving as a bridge, can produce groundbreaking diagnostic and prognostic approaches. Such a multidisciplinary strategy has the potential to transform medical practice, technology, and research.

The integration of physiological and psychological data—transmitted via chemical, electrical, mechanical, or light signals—between cells or organs controls biological mechanisms. Physicists analyze this dynamic transport by measuring fluxes and forces. Contemporary biomedical engineering leverages physics, physiology, and biology to understand transport phenomena involved in medical devices. The life sciences describe the dynamic phenomena of pulse/cardiac transport, respiration, diffusion, and biomechanics. Multiphysics modeling combines these processes to enhance medical diagnostics and therapeutics, benefiting patients worldwide by translating fundamental physical laws into clinical benefit [37].

11. Challenges and Limitations

The challenges and limitations of multiphysics modelling in medical diagnostics and therapeutics arise from two principal sources: the priority of application and the conditions of the model itself. The application drives the principal constraints and shapes permissible limitations; the model must address the conditions, as determined by the application and the state of theoretical development, while working within its own practical boundaries.

At the broadest level, the application of the multiphysics model sets the structure and defines the necessary features, with multiple access purposes under an overarching use. Within medical diagnostics and therapeutics, these objectives reflect the clinical realities of the problem: diagnosis, imaging, monitoring, characterization, guidance, assistance, planning, therapy, and follow-up. These desired outcomes do not necessarily represent the final achievable results for a given approach; rather, they serve as focal points that guide the form and capability of the requisite computational model [54].

The state of multiplex theory and the limits of the available research literature further delimit the model development. Although electromagnetic theory and tissue biomechanics are essential for the research task, the study explicitly excludes the hydrodynamical and acoustic equations embedded in these fields, choosing instead to concentrate on the electromagnetic and mechanical effects. Linearity is assumed throughout, permitting the representation of the superposition of different modal components. For the temporal dimension, the model retains the direct time dependence of the primary variables, but the spatial dependence implements homogenized functions. Since the objective is to establish the basic multiple-modality framework [55], some modalities — such as fluid flow, acoustic waves, and tissue growth — must await the improvements planned for the future. Challenges of the present system encompass the acoustic/tissue interface; reduced-dimension models; extended-range electromagnetic and mechanical coupling; and the implementation of inverse, parametric, and image analysis, as well as optimization study. Additional issues of parameterization-, verification-, and uncertainty-analysis remain challenges, especially the validation process necessary to translate the methodology and provide the confidence needed for clinical application.

11.1. Modeling Complex Biological Systems

Multiphysics modeling entails combining subjects with different physics into a single model. Often used to study the behavior of a system subject to multiple coexisting physical effects, it is especially useful when the physical effects are coupled. In medical science, the coupling of electromagnetic theory and tissue biomechanics facilitates the development of non-ionizing diagnostic and therapeutic devices. Biological tissues absorb a portion of the energy from magnetic or electromagnetic fields and then vibrate or deform due to thermal expansion, Lorentz force interaction, and acoustic or electromagnetic radiation pressure. These vibrations and deformations alter the parameters of an emission field such as acoustic, magnetic resonance, or electromagnetic that interacts with the tissue. Notably, magnetic resonance imaging, X-ray computed tomography, and ultrasound imaging provide complementary clinical insights that aid in diagnosing complex pathophysiological conditions.

Computational techniques encompassing electromagnetic and elastic field modeling span a variety of two-domain, two-physics and multiphysics configurations, including quasistatic and full-wave conditions. A variety of numerical solutions are employed based on the problem definition and objective including the finite-element method, the boundary-element method, and meshless methods. The following sections delve into the principles governing electromagnetic-field theory pertinent to medical engineering, an overview of biomechanics in soft tissue, and clinical imaging modalities that complement diagnostic capability. Lastly, a synopsis of emergent medical diagnostics and therapeutic devices grounded in multiphysics modeling interlinking electromagnetic theory and tissue biomechanics is presented [56][57].

11.2. Validation of Multiphysics Models

Model validation is the critical process of establishing confidence in the fidelity and utility of models. Medical and biological systems are often so complex that models must also be complex to be adequate, so that validation is a challenging problem. Modeling accuracy may be affected by uncertainties, due to incomplete understanding of underlying system physics or inherent variability in system properties. Although sophisticated numerical methods are available for solving the model governing equations, errors may be associated with algorithmic implementation and computer arithmetic. The mathematical model provides abstract representation of a real system, and validation is not the process of producing model truth, but of quantifying the likelihood that model predictions will be acceptable for a specific purpose. The envisioned concept of model validation is the quantification of the level of confidence that a specific model is an accurate representation of the real world from the perspective of the intended uses of the model. Several general categories of validation problems can be considered. For radiation oncology treatment planning systems, major objective is to quantify model accuracy and the potential propagation of errors into clinical estimates that are the basis for treatment protocols [58].

12. Conclusion

Multiphysics modeling is a powerful technique where analytical or computational methods from one domain are integrated with those from two or more other domains, resulting in a coupled multiphysics model possessing novel features and the ability to meet otherwise impossible design requirements. Organs and tissues can be modeled as complex elastic structures with nonisotropic physical properties. Electromagnetic theory cannot only describe and predict the propagation of radio waves through these tissues but it can also be combined with models of tissue biomechanics to produce novel medical diagnostic and therapeutic devices. Clinical imaging modalities play an important role in diagnostics and serve as an integral part of computation-experiment interrogations of biomechanical-electromagnetic models in medical applications.

Modern medical diagnostic tools depend on the ability of electromagnetic theory to describe the propagation of radio waves and microwaves in biological tissues and organs. Additional diagnostic information, provided by the mechanical properties of tissues, can be obtained by techniques such as ultrasound imaging, Magnetic Resonance Elastography (MRE), and tactile sensing. Furthermore, a broad array of innovative therapeutic strategies can be realized through the integration of electromagnetic theory and tissue biomechanics. Key issues in development of these next-generation diagnostic and therapeutic devices include the implementation of tissue-specific constitutive equations coupled with Maxwell’s equations and the design of corresponding algorithms for numerical electromagnetic simulations.

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