Integration of Medical Physics, Optics and Laser, and Medical Device Engineering: Concepts and Applications in Modern Diagnosis and Therapy

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Contents

Abstract

The framework integrates medical physics, optics and laser science, and medical device engineering to explain their roles in the modern clinical workflow. Medical physics encompasses the application of radiation physics principles, including radiation-matter interactions, interactions of ionizing radiation with biological tissue, the related concepts of radiation dose and safety for patients and medical staff, dosimetry, calibration, quality assurance, and medical application standards. Optics and laser science covers light propagation, reflection, refraction, and absorption, principles of coherence and polarization, scattering, and concepts relevant to optical imaging and therapeutic procedures, including laser types and optical safety standards required for clinical application. Medical device engineering outlines the principles of instrument and device design in the fields of optics, radiation physics, sensor techniques, biochemistry, and computer science, the requirements of usability and user interfaces, consideration of error prevention, human factors, and biocompatibility.

Key functions within the integrated framework of medical diagnosis and therapy are identified, with a focus on the physical science, optics, laser science, and engineering knowledge related to diagnosis and treatment. These disciplines connect the patient with the diagnostic and therapeutic applications, enabling the necessary clinical results. In a patient-centric model, these functions fall along the complete patient diagnosis and treatment pathway: preparation, procedure performance, safety assessment, quality, confirmation, and effectiveness. The historical development of diagnosis and therapy by these methods is briefly

summarized, as are the current emerged trends leading to convergence and integration, with attention to control and precision medicine. Finally, the associated future challenges, opportunities, and translational pathways are introduced.

Part I - Foundations

The integration of medical physics principles, optics and laser technologies, and medical device engineering concepts enable a multitude of diagnostic and therapeutic modalities used in clinical practice. Medical physics provides and certifies the scientific basis for safety, efficacy, and quality control of those concepts, techniques, and systems. Optical and laser technologies directly utilize the connection of light with biological tissue to perform diagnosis or therapy. Finally, medical device engineering supports the design of safety and usable instruments for the application of radiation, with all their complexity of sensors, actuators, data acquisition, and user interface. Together, these disciplines cover all phases of the clinical pathway for the development of new diagnosis and therapy modalities, from instrumentation and medical imaging to therapy application.

Modern healthcare relies on a wide array of sophisticated diagnosis and therapy techniques, relying on the fusion of several medical specialties to ensure the integrated control of patients. Although some techniques have distinct origins—radiology, for example, has its foundations in medical physics, whereas laser surgery originated from optics and laser science—these methods are becoming increasingly interconnected. Optical systems can be integrated into a wide range of medical instruments for signal detection and processing, imaging, and monitoring. Implantable and wearable devices are now able to monitor physiological parameters and signals, allowing their transmission via the Internet of Things (IoT) to databases and health structures for operative analysis. The analysis of the complete process underlying the use of such diagnosis and therapy methods, together with the research of those components that can be integrated, leads to consider a new approach to precision medicine that integrates the three areas of medical physics, optics and laser, and medical device engineering [1, 2, 3, 4].

Chapter - 1

Introduction to Interdisciplinary Medical Technology

A growing body of research fosters convergence between the disciplines of medical physics and medical device engineering—both long-established fields—together with optics and laser science, which have evolved more recently, largely in response to demand from the fields of telecommunications and information technology. This integrated framework provides a lens through which to examine how both diagnosis and therapy exploit concepts from medical physics and optics/laser technology and deploy tools developed through the engineering of dedicated medical instruments. The close interplay of these three areas, together with artificial intelligence (AI) for treatment optimization, is at the heart of modern precision medicine.

The integration of medical physics, optics/laser technology, and medical device engineering into a coherent framework enables a comprehensive understanding of how clinical diagnosis and therapy have evolved and how they are becoming increasingly fused at an operational level. The underlying concepts also allow the identification of translational needs arising from advanced research in quantum imaging, optogenetics, or therapeutic photonics, as well as advances in informatics that encompass governance of critical issues such as data bias and patient protection. The first step is to establish definitions for the core concepts involved: medical physics principles that underpin safety and efficacy, optical and laser technologies that facilitate increasingly sophisticated imaging and treatment modalities, medical device engineering that develops the physical tools, and the interconnections between them. These elements map to a patient care pathway that spans initial diagnosis, consequences for treatment, and monitoring of patient wellness [5, 6, 7, 8].

Evolution of medical physics and biomedical engineering

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The integrated framework that encompasses core aspects of medical physics, optics/laser science, and medical device engineering can be synthesized to delineate the enabling principles, technologies, and devices used in diagnosis and therapy. As the concepts and applications in modern healthcare are explored, the critical importance of medical device engineering is emphasized.

Medical Physics applies the fundamental principles of physics—including X-ray and magnetic resonance imaging operations—as well as the physics of ionizing and non-ionizing radiation. Such applications ensure safety during patient examination, diagnostic efficacy, and adequate calibration for instrument operation. Optical technology comprises different types of imaging (e.g., OCT), spectroscopic analysis (e.g., fluorescence and Raman) for diagnostics, laser-assisted surgery (including precision-engineered devices), and laser-induced photothermal and photodynamic therapy. For optical and laser techniques to be clinically effective and feasible, proper device prototyping is essential. Successful incorporation of optical methods into hybrid modalities requires strategies for data synchronization, software development, and human factors consideration. Optical, Raman, and infrared-based biosensors enable continuous monitoring of blood glucose, heart rate, and SpO2 through easily wearable devices. Safety of these diagnostic, therapeutic, and monitoring methods is critically enhanced by the incorporation of Artificial Intelligence [6, 7, 9, 10].

The role of optics and laser technologies in medicine

Diagnosing and treating diseases with radiation (ionizing or non-ionizing) requires the associated Medical Physics knowledge, which includes, but is not limited to, fundamental concepts on radiation-matter interaction, physics principles of dosimetry, and technical safety standards. Optical diagnostics and therapy methods exploit light interactions with tissue as a non-contact probe, with the potential for high resolution, being inherently safe, or being native to the investigated medium; however, appropriate optical standards and testing conditions must be strictly followed. Optical imaging modalities, such as fluorescence spectroscopy, Raman spectroscopy, Optical Coherence Tomography, and Diffuse Optical Tomography, have become essential tools for dermatology, ophthalmology, oncology, and other areas. Optical Radiation sources, particularly Lasers, possess unique properties that permit the formation of novel therapy modalities (e.g., Laser-Tissue Interaction and Therapeutic Mechanisms, Photodynamic Therapy, Photothermal Therapy) with many clinical applications.

Furthermore, unlike other optical imaging techniques, optical modalities suffer from limited depth penetration. Thus, various optical Radiological Imaging Systems, mainly X-ray, Computed Tomography, Magnetic Resonance Imaging, Positron Emission Tomography, and hybrid systems, have been developed with the aim of allowing whole-body imaging, at lower doses, whilst presenting higher contrast. Recent developments of direct combination of Optical and Radiological Imaging modalities, supported by Artificial Intelligence-based algorithms, have allowed the overcoming of these limitations [11, 12, 13, 14].

Integration paradigm: from physics to patient care

Medical-device engineering shares with medical physics the modelling of radiation fields, design of safety interlocks, and definition of dosimetric data for protecting personnel and patients. Optical instruments, with their high sensitivity, resolution, and feasibility for non-invasive procedures, enable preclinical cancer diagnosis. Their integration with radiation imaging opens exciting paths for risk stratification, therapy planning, and response evaluation. Recently introduced biosensors, capable of continuous, long-term, and non-invasive physiological monitoring, can - when incorporated in IoT ecosystems - help to prevent or predict dangerous conditions. In parallel, the field of photomedicine resorts to integrated low/medium-power laser-light sources - now miniaturized and diffused in many hospitals - for an increasing number of therapeutic applications, endorsed by a comprehensive set of guidelines for qualified use.

Ethical framework, clinical indications, and dosimetric parameters for pulsed laser sources employed in skin therapies are well defined, whereas emerging uses of photponential-absorbing nanoparticles are still being explored. Similar integration is observed for photodynamic therapy, where diagnosis and treatment can now be correlated in an accurate and personalized manner by exploiting the same optical-active principle. The integration of medicine with opto-electronics, artificial intelligence, and nanomaterials also provides exciting and still largely unexploited opportunities along other hospital paths. Indeed, the convergence on a systemic definition of precision medicine implies that all the specialty areas involved in patient diagnosis and therapy should ultimately merge into a coherent whole oriented to the optimization of individual health management [15, 16, 17, 18].

Future trends and challenges

Development trends in modern diagnosis and therapy emerge from different paths—physicists, engineers, biologists, medical doctors, and industry until the economic crisis of 2008 acted in their own fields of expertise and scientific challenges. A recent trend is to establish multi-disciplinary teams that utilize different backgrounds, prepare instruments essentially driven by physics principles, and apply them to recent biomedical discoveries. A specific example is the development of external engineered devices that interact with hospitals (optical biosensors), while advances in optics, or physics involved in a specific area of optics and laser, emerge from the universities of the countries—the most advanced and scientific information highways always projected by the USA and the open access system in Europe. An application of an introduction of Optical-Afocal-Microscope devices in hospitals makes use of AAI and ICD-2—crucial for volcanic conditions—an MS- reveal research in early diabetes diagnostics.

A trend that emerged years ago is the involvement of non-expert researchers in Physics, Optics, and Laser topics such as the design, optimization, and use of laser in therapy and diagnosis. Medical doctors or researchers aware of specific aspects of laser-tissue interactions have published without referring the laser principles and the effects induced on tissue. Medical doctors are introducing radiation and optics inside hospitals for therapeutic purposes without basic know-how in both required fields. Hospital management relies on slightly aware staff; radiation safety in a combination of strengths produces a radiation-naïve hospital environment [5, 19, 20, 6].

Chapter - 2

Fundamentals of Medical Physics

Many physical principles relevant to medical diagnostics and therapy originate from radiation physics, although only part of these deal with the efficacious use of ionizing radiation. A consistent understanding of radiation interaction with matter is essential for the safe and successful application of any physics-based technology in the clinic. Medical imaging with ionizing radiation or magnetic resonance uses radiation principles in the opposite sense, where state-of-the-art algorithms allow reconstruction of internal structures based on concepts of projection and diffusion. The specific aspects of image formation and the different pathology contrast mechanisms are discussed in the relevant chapters.

Two main groups of effects need to be considered when dealing with radiation safety. The first one concerns the unintended application of high doses of ionizing radiation and its damaging effects, especially at cellular level, while the second one deals with non-ionizing radiation of any nature and the accidental or controlled laser-tissue interactions leading to harmful effects. Procedures, standards, and concepts foreseen for the safe application of laser systems are described, as well as the physical basis for definitions and limit values for laser safety in medicine [21, 22, 23, 24].

Radiation physics and interaction with matter

Radiation describes a physical phenomenon of energy that is transferred from one point to another in space and time, in the form of particles (protons, photons, etc.) or waves (EM waves, sound, etc.) and induces an effect on matter. Radiation physics is the study of a special type of radiation known as radioactive radiation, which is emitted by radionuclides. These radionuclides contain excess energy within their nuclei, so they tend to decay spontaneously and transmit a part of this energy in the form of radioactivity, namely α-, β- and γ-radiation. X-ray and neutron radiation are artificially produced, but the principles of radiation physics still apply. The interaction of radiation with matter is a central topic in radiological imaging. All types of radiation studied in radiology produce changes in the matter they interact with; however, the consequences of these interactions depend on the specific type of radiation and its energy relative to matter. Ionizing radiation (α-, β-, X-ray, γ-ray and neutron radiation) produces changes that have a significance for radiotherapy, while non-ionizing radiation (radiofrequency fields, microwaves, infrared laser light and visible light) is used for other methods.

Radiation can be considered to be made up of particles or packets of energy known as quanta, which travel in an electromagnetic field. X-ray and γ-ray radiation consists of photons of short wavelength (high frequency) and can be considered as being composed of particle quanta. The ionizing radiations have sufficient energy to produce ionisation in matter. The particle radiations (α, β and neutrons) produce ionisation directly. The electromagnetic radiations (X-ray and γ-ray) produce ionisation indirectly by producing secondary electrons in the medium through which they pass. Ionizing and non-ionizing radiation differ mainly in terms of their energy. Ionizing radiation has enough energy to displace electrons from the atomic shells, leading to the formation of ions; non-ionizing radiation does not possess sufficient energy to produce ionisation. Safety limits have been set for exposure to both ionizing and non-ionizing radiation, testing laboratories have been established in different countries and protocols are in place for the testing of optical instruments for safety [25, 26, 27, 28, 29].

Ionizing vs non-ionizing radiation

Radiation in general is classified into two main categories: ionizing and non-ionizing radiation. Ionizing radiation has sufficient energy to liberate charges in the medium and cause chemical reactions, while non-ionizing radiation does not. Ionizing radiation includes ultraviolet rays, X-rays and gamma rays emitting photons with high energy. Radiation from radioactive sources such as alpha and beta rays is also classified as ionizing radiation. Non-ionizing radiation includes electromagnetic waves propagating through vacuum or air as well as acoustic waves and other forms of particles without sufficient energy to cause the liberation of electronic charges in the medium. The permeation of ionizing radiation generates a significant amount of energy in the absorbing medium during its passage, which may be hazardous to living beings. This hazard increases as the total absorbed dose (in gray) increases. Dosimetry aims to quantify the deposited energy by monitoring the radiation intensity (in gray dose rate) and the cumulative absorbed dose.

Medical and high-energy physics principles and standards provide the proper basis for safe, efficient, and clinically rational use of radiation in medicine; a safe working environment for patients and health personnel as well as sound clinical results. Safety, that is, which relies on the prevention of accidents and the proper management of accidental exposure; quality assurance, involving the continuous monitoring of the whole clinical and operation procedures through systematic tests on the diagnostic and therapeutic processes; dosimetry in general, aiming at measuring, calibrating and periodically controlling the radiation source output; and finally efficacy, defining the capacity of the medical radiation device to provide a proper diagnosis or therapy [30, 31, 32, 33].

Dosimetry, calibration, and safety standards

Dosimetry, calibration, and quality assurance ensure appropriate utilization of ionizing and non-ionizing radiation. Medical dosimetry encompasses metrology, exposure assessment, and systematic evaluation of radiation conditions in clinical practice. Physical dosimetry uses detectors responding to radiation while only partially related to its biological and medical action. Radiotherapy calibrates delivered dose/energy levels to tissue. Optical dosimetry employs indicators for photochemical or thermal photoprocess activation.

Radiation safety standards protect patients and staff. Authorized governance organizations define and periodically update national safety regulations for radiological systems (e.g. X-ray, CT) and procedures (e.g. fluoroscopy, interventional therapy). Safety markers for lasers incorporate skin and ocular precautions, distance and energy limits, alerting signs, and authorizations for Class 3B and 4 equipment. Optical radiation safety protocols ensure patient and worker safety during endoscopy, lithotripsy, laser-assisted surgery, and navigation. Elemental safety concerns underpin comprehensive QA protocols for all medical systems [34, 35, 36, 37].

Imaging physics foundations

Medical specialists utilize imaging devices for diagnosis and therapy guidance. Safety and efficacy are established during the development phase via studies with phantoms and pre-clinical trials—these rely on the physics of the specific imaging phenomenon and the physics of radiation and matter interaction. The imaging signal is affected by multiple factors, including the medical question, the procedure, the structure(s) involved, and, in certain modalities, contrast agents. Therefore, evaluating the expected imaging quality is an integral part of the procedure planning, especially in the burgeoning field of artificial intelligence-assisted imaging and diagnosis.

Radiation and matter interaction are responsible for X-rays, scintigraphy, single-photon emission computed tomography, computed tomography, and magnetic resonance imaging; optical coherence tomography, optical imaging, and optical biopsy are rooted in the physics of light and light-tissue interaction; and they all can be combined with Raman spectroscopy, infrared spectroscopy, digital holographic microscopy, and fluorescence microscopy. Integration of different signals enhances diagnosis accuracy. Optical imaging signal fusion with X-ray, computed tomography, magnetic resonance imaging, and ultrasound has rapidly developed, especially in dermatology; and optical imaging is increasingly being proposed for use in conjunction with magnetic resonance, computed tomography, and ultrasound for navigation and therapeutic feedback [38, 39, 40, 41].

Chapter - 3

Fundamentals of Optics and Laser Science

The principles of optics and laser science encompass light propagation and interaction with biological tissues, exploration of optical coherence and polarization fundamentals, characteristics of different laser types and applications, and optical safety standards. Light travels in straight lines and interacts with matter through reflection, refraction, and scattering; the rules of geometrical and physical optics describe these phenomena. In addition, physiological tissues are semi-transparent, with scattering dominating light-tissue interactions. Coherent light sources exhibit combination properties that enable imaging techniques with higher resolutions than classical microscopy, and laser-induced tissue damage mechanisms are based on photothermal, photochemical, and photomechanical effects. Optical safety principles, including laser hazard classifications and safety compliance standards, allow optical systems to be used safely in clinical practice.

Major optical imaging methods presently applied in medicine exploit fluorescence, infrared, or Raman spectroscopy, optical coherence tomography, and diffuse optical tomography. These techniques have been successfully used in dermatology, ophthalmology, and oncology, enabling optical diagnosis of diseases and tissue characterization. Laser sources are widely employed in surgery, gynecology, otorhinolaryngology, urology, oncology, and dentistry. Their use in surgery is based on the ability of laser radiation to induce photothermal, photochemical, and photomechanical effects in biological tissues, enabling surgical treatment and/or tissue modification [42, 43, 44].

Principles of light propagation and reflection

Light, defined as electromagnetic radiation within the range of 400-800nm, propagates in a vacuum at a velocity of 299,792,458 m/s. In tissues, however, this speed decreases owing to scattering and absorption. Light travels in a straight line unless deflected by reflection or refraction. Reflection occurs at an interface between two different media, obeying the law of reflection: the angle of incidence equals the angle of reflection. When light passes through a medium of different optical density, refraction occurs and is governed by Snell's law.

At the skin surface, light is in contact with air. When it enters tissue, a fraction is reflected back into the air, with the amount of reflected light depending on the optical index at the air/tissue interface. The fraction of reflected light at the air/cornea, air/conjunctival membrane, air/eye lens, and air/air sac interfaces is generally neglected due to the small index difference. Light can be absorbed, scattered, or transmitted into deeper layers of tissue. Together, absorption and scattering determine the penetration depth for physiological monitoring. For non-invasive techniques, this depth is typically limited to approximately 1-2 millimetres for optical detection in the spectral range of UV-visible-near-IR and approximately 1-2 cm in the mid-IR spectral range due to higher transmission in these regions.

When light propagating in a homogeneous medium changes its wavelength or frequency, the light remains coherent. With different frequencies of light, the plane waves corresponding to different frequencies are distributed in different directions, causing the loss of coherence in a short propagation distance. The loss of coherence is compensated for with coherent light sources such as lasers. Laser light is highly directionally beamed, allowing its use in therapy. Light transmission through biological tissues is also affected by tissue scattering. Tissues are not diaphanous to a visible light beam and appear opaque. Because the refractive indices of the tissue layers differ, a small part of the light flux is reflected at the interface between layers. The reflected light can be used for surveillance imaging of the organ [45, 46, 47, 48].

Coherence, polarization, and scattering in tissues

Light propagation in free space follows geometric optics principles. Optical devices (e.g., lenses, mirrors) exploit reflection and refraction to converge, diverge, or transmute the light wavefront. Energy absorption in biological tissues determines laser-tissue interaction modes. The complex refractive index, decomposed into a real optical thickness product (n) and extinction coefficient (k) of the absorber, governs the distribution of light power density in turbid media. For $n > 0$, multiple scattering induces emerging light via a geometric optics trajectory. When tissues become optically transparent for $k = 0$ or $\alpha < \Sigma$, coherent imaging methods based on electromagnetic theory can be employed. Tomography, focusing on n - k lesions, enables deeper visualization when k decreases with wavelength. The resolution depends on the shortest light path through tissue, whereas depth discrimination relies on multiple scattering control.

Coherence describes correlated wavefront segments over time and space. Michelson and Mach-Zehnder setups capture amplitude-temporal coherence. Biological tissues induce low temporal coherence through site dependence and random phase and delay variation. Coherence refers to amplitude correlation and visibility and aids two-photon excitation and hyperspectral fluorescence. Polarization describes different field resolutions in directionality. Retarders (±ϕ) and wave plates add or alter polarization states, with images revealing fluorescence intensity, polarity, and spectral behavior for confocal or two-photon systems. Scattering consists of elastic scattering (Rayleigh, Mie, and simple theory) and inelastic scattering (Raman and Rayleigh) and serves clinical needs ranging from Mie characterization of nano immunotherapeutics to high-resolution imaging via detection of NIR CARS effect scattering.

Elastic scattering consists of non-energy-changing electromagnetic interactions and enables different detection technologies in ophthalmology, dermatology, and other fields. Skin optical imaging leverages spatial resolution through three-beam signature detection and achieves increased depth by exploiting Mie scattering at NIR wavelengths. Rayleigh scattering's λ^{-4} intensity dependence characterizes size determinants of nanoparticles in multimode optical coherent anti-Stokes Raman scattering imaging, with detection of the NIR-induced CARS effect in tumor stroma opening clinical translation avenues for noninvasive diagnostics and therapy monitoring [49, 50, 51, 52].

Laser generation and types (CO_2, Nd:YAG, diode, femtosecond, etc.)

A laser is an optical system characterized by an amplification of light by stimulated emission and a resonant structure providing feedback. Clusters of atoms which are excited to a suitable energy level and controlled population inversion yield coherent radiation. Accordingly, collimated monochromatic radiation develops. The principle is known as light amplification by stimulated emission.

When the beam is directed onto matter, the energy is stored and deposited in matter, inducing transient time delays associated with the multiphotonic process. Depending on the mechanism and the consequent tissue response, laser applications may include cutting, ablation, vaporization, sealing, photocoagulation, sterilization, and holmium laser enucleation of the prostate (HoLEP). Lasers serve as tools to treat pre-cancer and cancer associated with neoplasia of the cervix, especially in cases of microinvasive cancer. Various lasers are available for use, including CO2, Nd:YAG, alexandrite, diode, and femtosecond lasers. Application of these lasers to individual organs is being explored. Non-thermal laser action includes the laser-induced breakdown spectroscopy (LIBS) [53, 54, 55, 56].

Optical safety and standards in medical settings

Radiation safety has always been a primary concern in medical diagnosis and therapeutic procedures, especially those involving ionizing radiation sources. Such procedures typically require thorough dosimetry and calibration strategies before being approved for clinical use. In addition, robust quality assurance procedures are usually implemented in healthcare institutes to ascertain patient safety. Medical devices utilizing optical light sources with relatively high power levels, however, do not follow an equivalent strict quality assurance framework to endorse their clinical use. The safe intensity levels of light sources of various types are defined by the International Electrotechnical Commission (IEC) based on laser-specific parameters and their interaction with biological tissues. The Optical Society (OSA) and the American National Standards Institute (ANSI) have designated the IEC60601-2-59 standard for optical safety and hazard classification of laser sources in medical diagnostics and therapy. As per this standard, the equipment must undergo protection level classification, hazard classification, and safety management during the clinical implementation of optical radiation systems. Various clinical settings also require compliance with the Australian and New Zealand Standard AS/NZS 60601.1.12 and the American National Standard for the Safe Use of Lasers in Health Care by the American National Standards Institute/Z136 Committee. Demands for electrical safety, fire safety, and Electromagnetic Compatibility (EMC) also apply to optical radiation systems when used in medical settings.

Although optics-based systems still have a way to go before reaching such a safety and quality certification level, stringent quality assurance frameworks can be envisioned for non-ionizing optical and laser-based medical imaging and surgery systems. These have immense potential in improving patient care quality and safety. The Optical Society of America has also begun deliberations on an OSA standard for these systems, entitled Laser Safety and Optics Safety for Medical Applications. The ultimate goal is to structure the quality and safety of light-based systems in a methodical way that matches the supervision implemented for radiological sources [57, 58, 59].

Chapter - 4

Basics of Medical Device Engineering

Medical instruments are essential for performing a variety of diagnostic and therapeutic operations in a clinical environment. Their efficient design and engineering, while meeting safety, reliability, and usability requirements, are crucial for safe and effective patient care. The assembly, organization, and integration of the device's main technical components (sensors, actuators, signal acquisition, data processing, transmission, and display) are determined by the device's intended use and function. Design principles specific to the medical device field take into account factors such as biocompatibility, ergonomics, and the user interface (hardware, software, and interaction with the user). The medical device engineering framework, combined with a basic understanding of anatomy and physiology, allows for the successful design and development of specific devices.

Device design and development must consider the organization's business model and product development lifecycle, as well as regulatory requirements for the product domain. The main regulatory bodies (U.S. FDA, European CE, ISO) and their requirements for medical devices and systems are briefly summarized. Typical regulatory considerations focus on safety, quality management, and the clinical efficacy of the product for its intended use. For complex systems entertaining high technology readiness levels (TRL), the entire engineering supply chain can be effectively supported and guided by the international standard on medical device quality management systems (ISO 13485) [60, 61, 62, 63].

Design principles of medical instruments

Designing devices and instruments in the medical field involves a variety of medical device design principles. Unlike other engineering disciplines that primarily concentrate on quantitative and technical designs, medical device design and engineering must also integrate human factors. This makes the design process for medical devices a formidable exercise in the different aspects of product engineering, compelling the designer to consider usability and the multitudes of biomechanical factors for the expected end user. A medical device offering the same performance, since performance is only one aspect of the user experience, will be preferred and used by the knowledgeable clinician or nursing staff over a device that is more difficult to manipulate.

Human factors affect the design of all devices used in any clinical environment. Ideally, the manufacturer will carry out usability studies with the actual end-users of the product during the development process. Many of the human-factors design criteria will apply to automating an entire function or procedure, securing or shielding inherent dangers, or shielding a device from operator error. Biocompatibility remains a key criterion and proper incorporation results in devices virtually without any adverse-device-to-body-system response. Ergonomics must be considered when developing apparatuses that are intended for extended use by the operator; the device must not be so heavy that it results in fatigue, and the controls must be positioned and sized such that they do not cause strain on any part of the operator's hands or feet when used [64, 65, 66, 67].

Biocompatibility, ergonomics, and user interface design

Experimental and clinical data show that the presence of color contrast improves user performance in visual tasks. Additionally, ergonomic and usability considerations deeply influence how the medical device is perceived and, ultimately, how it performs in terms of stimulation and response. Aesthetical designs play a major role in how a product is perceived, so much so that it can change the way a person performs and reacts to it. Aesthetical aspects can even change how a person behaves in regards to safety. Thus, attention to these factors is mandatory.

Medical devices contain several elements that respond to a certain stimulus. These response signals need to be acquired and processed so that they can be displayed and communicated for interpretation. All medical devices have certifications and validation processes that must include the user interface. Human-device interaction, linking the stimulus, response, and user interface, is therefore a key point for medical device design. Sensors classify and convert multiple physical or chemical parameters in different formats, which usually need further treatment. Moreover, some devices include actuating elements. The pathways of stimulation and response differ based on the nature of the devices. Incorporating optical or electric stimulation requires special considerations on biocompatibility, reliability, and maintenance aspects of the corresponding device components.

It is common in medical devices to look for a “one size fits all” approach. This might not necessarily apply to the stimulus and the response acquisition, but might not be valid in a response-timing aspect. In this respect, additional care should be taken in the user interface design, as a set-up that is too complex could become a limitation for the final user. Hence, the layout in the prototype phase should be interconnected with end-user feedback to optimize usability [68, 69, 70].

Sensors, actuators, and signal acquisition

Fulfilling a significant function for assay signal generation in clinical diagnostic and therapy use, medical devices incorporate a range of sensors covering techniques for the detection of analytes through optical and electronic modalities. Optical principles are mainly used for fluorescence, Raman, FTIR and other spectrometric analysis as discussed previously. Though chemically different sensing principles are adopted, the changes in chemical and physical properties of analyte, living systems or in the environment are subsequently translated into optical or electrical signals by sensor components. These signals are then acquired and processed by basic electronic circuitry. Generally working on piezoelectric, piezoresistive or piezocapacitive modes, Micro-Electro-Mechanical Systems MEMS-based and other such penetrating devices are mainly employed for the indirect and real-time non-invasive monitoring of key blood physiological and biochemical parameters, as glucose, heart rhythm, blood pressure, SpO2. Wireless Internet of Things (IoT)-controlled health monitoring systems provide significant clinical data for prediction, monitoring and data-driven decision-based medical therapy with remote terminals. Data management in clinical repositories with privacy and cybersecurity are the primary issues for secured patient consent, proper data handling, reproducibility and validation of results.

Actuators, mechanisms or devices that generate a response in any medical device design, are mainly categorized into optical and electronic. Though the principle of working varies, they essentially provide evidences of prestage interactions or conditions beneficial for performance of assay and treatment. Optical sources adopted in medical devices are CO2, argon, Nd:YAG and diode lasers, non-coherent light generators, solid state diodes. Electrical actuators mostly consist of signal managing circuitry, electromagnetic actuators, pumps, motors and solenoids. Electrophoresis, electrophoresis with drug application and microneedling assist these actuators in the painless delivery of DNA-based or other molecules for anticancer phototherapeutic application [71, 72, 73, 74].

Medical device regulation and certification (FDA, CE, ISO)

Medical devices used in healthcare must meet stringent standards defined by competent authorities in the respective countries or regions. In the US, the regulatory body is the Food and Drug Administration (FDA), while the Conformité Européenne (CE) mark demonstrates conformity to European health, safety, and environmental protection standards. The FDA pioneered the regulation of medical devices, establishing criteria for the premarket notification 510(k) process and subsequent classification into Classes I, II, or III according to increasing complexity and clinical risk. Class I devices require only post-market controls, Class II devices demand premarket notification showing safety and effectiveness, and Class III devices are subject to the more rigorous Premarket Approval (PMA) process.

The FDA system is designed to ensure that devices are safe and effective for their intended use. The International Organization for Standardization (ISO), an independent international organization that develops voluntary standards, complements these regulatory pathways with a series of standards for specific classes of devices, notably ISO 13485 (medical devices—quality management systems) and ISO 14971 (medical devices—application of risk management to medical devices). Other standards systems worldwide, such as Consorzio Italiano del Marchio di Qualità (CIMQ) in Italy and Instituto de Normas Técnicas de Chile (INN) in Chile, have emulated the FDA model, adapting it to local requirements [75, 76, 77, 78].

Part - II

Diagnostic Technologies

Chapter - 5

Optical Imaging and Spectroscopy in Medicine

Fluorescence, Raman, and infrared spectroscopies extend the sensory palette of modern medicine. Optical coherence tomography (OCT) achieves high-resolution imaging in natural tissues, while diffuse optical tomography (DOT) maps chromophore concentrations. Indeed, the application of optical imaging and spectroscopy has witnessed rapid growth in clinical dermatology, ophthalmology, oncology, and other areas.

Fluorescence imaging in medicine relies on two processes: excitation of a molecule by a suitable light source and emission of energy by the molecule at longer wavelengths. Raman spectroscopy capitalizes on the inelastic scattering (Raman effect) of monochromatic light by molecular vibrations to gain chemical identification based on vibrational finger-prints. Infrared (IR) spectroscopy uses the interaction of molecular vibrational and rotational modes with electromagnetic radiation in the IR range to obtain chemical information. Optical Coherence Tomography (OCT) is an advanced optical imaging technique that provides cross-sectional, noninvasive, *in vivo* images of biological tissue microstructure with a resolution in the range of 1-20 μm. In OCT, elastic scattering of near-infrared (NIR) light by tissues is utilized. Diffuse Optical Tomography (DOT) is an emerging imaging modality for statistical imaging of concentration distributions of endogenous and exogenous chromophores in biological tissue. In DOT, diffuse scattering of NIR light by tissues is utilized [79, 80, 81, 82].

Fluorescence, Raman, and infrared spectroscopy

Exploit light-matter interactions to probe tissue properties. Emission of light after excitation by an external source supports biochemical analysis. Light inelastically scattered by molecules provides information on chemical composition and molecular structure. Infrared vibrations of molecular bonds cause detectable changes in transmitted light, enabling chemical mapping.

The fluorescence phenomenon is based on the emission of photons by a molecule after excitation with electromagnetic radiation of shorter wavelength. Fluorescence spectroscopy is extensively used for analyzing intrinsic fluorophore distribution in tissues, as well as for tracking the distribution of exogenously injected fluorophores within a tissue.

Raman spectroscopy is based on the inelastic scattering of light by analyte molecules. A small fraction of the incident light stimulates molecular vibrations in the scatterer, leading to inelastically scattered light that is either blue-shifted or red-shifted with respect to the incident light. The detected light contains chemical and molecular information about the scatterer. The Raman signal is very weak. Nevertheless, recent advances in laser technology, optics, and photodetection have helped to build Raman spectrometers with sufficient sensitivity for biomedical applications. Raman imaging typically measures thousands of scatterers simultaneously while mapping in several dimensions.

Infrared spectroscopy or imaging if the detected signal is a 2D image exploits the vibration of chemical bonds present in biological tissue. Biological macromolecules and tissues have their spectral signatures within the infrared region of the electromagnetic spectrum, and since infrared absorbance correlates with molecular concentration, infrared spectroscopy may be employed to quantify the presence of macromolecules [83, 84, 85, 86].

Optical coherence tomography (OCT)

Uses low-coherence near-infrared light to non-invasively image internal tissue structures with a depth resolution of several micrometers, close to or even surpassing that of histology. Scattering of light on organ/tissue microstructures determines the specular MSD signal and contrast of OCT images. The integration of OCT and exogenous or endogenous contrast agents enhances its imaging capabilities. Clinical examples include skin imaging, anterior and posterior segment ophthalmic analysis, imaging of cerebrospinal fluid structures, diagnosis of oral precancer, photodynamic and thermal agent distribution visualization, assessment of infarcts, and differentiation of vulnerable plaque components. Applications in dermatology (*in vivo* imaging of skin tumors, scars, and hair follicles), ophthalmology (anterior and posterior segments), oncology, and other fields have been investigated.

Substantial effort has been dedicated to the optical resolution OCT (OCT utilizing Doppler effect with a transverse resolution in the micron range, achieved with a lateral filling with a scanned beam using a rotating galvanometer mirror). Doppler optical coherence angiography examines 3D dynamic blood flow in the microvasculature of tissues (enabling volumetric perfusion imaging in melanoma, the retina, and skin), and optical coherence elastography non-invasively assesses tissue mechanical properties. Furthermore, diffuse optical tomography combines the scattering and absorption contrasts for cancer detection and delineation. The strengths of various tissue imaging techniques complemented with the unique contrasts of OCT lead to important synergetic metabolic-structural imaging [87, 88, 89, 90].

Diffuse optical tomography (DOT)

Is a non-invasive imaging technique that provides tomographic, cross-sectional images of tissue absorbers and scatterers from multiple wavelengths of near-infrared light (650-1100 nm) within the tissue. The concept utilized in DOT has been broadened recently to consider not only light absorption but also scattering in the tissue. DOT not only allows imaging of oxy- and deoxyhemoglobin concentrations of the tissue but also of lipids, myoglobin, and others. To make it a functional imaging technique, DOT can be integrated with fluorescence imaging or fluorescence lifetime imaging. Clinical applications range from brain imaging to imaging of the breast, gynecological organs, prostate, and other superficial tissues. Optoacoustic imaging can also be considered an extension of DOT. Depth-resolved information may be obtained both in time- and frequency-domain spectroscopy.

During DOT, pulsed laser or near-infrared LED light passes through the tissue and generates a series of diffuse optical signals. An external detector either measures the time-of-flight with a time-correlated single photon counting (TCSPC) system, or jointly analyzes the intensity- and modulation-frequency-dependent signal changes measured by an assembly of detectors to extract depth-resolved information. Optical properties of the tissue are then reconstructed using a diffusive model under the approximation of a plate-shaped geometry or applied with a depth-dependent light-source-detector configuration. DOT has been integrated with other imaging modalities to monitor additional biological parameters for pharmacological, diagnostic, or therapeutic purposes. DOT remains a core technology in laser-induced thermal therapy of deep-seated tumors [91, 42, 92, 93].

Clinical examples: dermatology, ophthalmology, oncology

The clinical implementation of optical imaging or spectroscopy tools that exploit fluorescence, Raman, or infrared (IR) spectroscopy are illustrated by three integrated application examples covering dermatology, ophthalmology, and oncology. Optical coherence tomography (OCT) encounters its integration with diffuse optical tomography (DOT) in imaging of breast lesions based on a combination of absorption and scattering contrast mechanisms that determine the decision for biopsy or watchful waiting.

In dermatology, a combination of fluorescence imaging, Raman spectroscopy, and infrared imaging using a compact, mobile platform has been characterized for the monitoring of skin wounds, revealing a correlation between healing processes and spectral markers. A prototype for fluorescence imaging offers *in vivo* assessment of treatment response and may serve as a valid clinical endpoint. In the field of ophthalmology, a dual-purpose 3D multispectral imaging system for human iris biometrics and anterior segment assessment based on a patented optical imaging approach has established recognition accuracy performance surpassed state-of-the-art techniques. Its other application, for assessing the optical texture of the human iris, makes it possible to analyse the activity or damage of any disease related to the iris surface in order to provide supplementary information to be considered by an ophthalmologist [94, 95, 96, 97].

Chapter - 6

Radiological Imaging Systems and Integration

Various imaging techniques, specifically X-ray, Computed Tomography (CT), Magnetic Resonance Imaging (MRI), and Positron Emission Tomography (PET), provide fundamental modal images for diagnosis, and therapy planning along with Multimodal Imaging Methods to understand disease mechanisms. Modal images and Artificial Intelligence (AI)-assisted imaging fusion reduce patient risk and improve therapy efficacy.

Medical imaging plays a critical role in radiation therapy. External beam radiotherapy, brachytherapy, internal radiotherapy, and proton/ion therapies use diagnostic images to visualize tumor location, size, and proximity to organs at risk and generate dose distribution for precise and effective treatment. The demand for adaptive therapeutic planning is rising, making the reassessment of every stage of the Pathway of Medicine desirable. In this context, Artificial Intelligence (AI) applications in medical imaging and radiotherapy planning are gaining attention. With its ability to learn complex patterns from large datasets, AI enables new imaging techniques, computational methods for dose planning, QA standards for image quality improvement, and speedup of diagnostic and therapeutic tasks.

Increased patient safety during diagnosis and therapy, further raised by recent concerns of the tissue damage generated by non-ionizing and ionizing imaging methods, have motivated the search of Optical-Tissue-AI hybrid approaches for healthcare Pathway of Medicine. Optical methods, based on non-ionizing radiation, and AI-assisted data fusion are also explored. Integrating Optical methods with X-ray, CT, MRI, or PET, Data Acquisit ion and Transfer Systems inherently poses diffic ulty but can be solved by synchronizing the signal pathways/circuit, followed by AI-assisted processing. Moreover, AI-assisted fusion of the Optical and X-ray/CT modal images has been successfully demonstrated [98, 99, 100, 101].

X-ray, CT, MRI, PET, and hybrid systems

X-ray, computed tomography (CT), magnetic resonance imaging (MRI), and positron emission tomography (PET) are established imaging modalities that provide a wealth of anatomical and metabolic data in a single examination. Numerous hybrid systems exist that combine two or more of these modalities, enabling the advantages of real-time, co-located, multimodal imaging. Image reconstruction algorithms must efficiently nonlinearly process the data from the multiple sensing systems and, ultimately, the resulting images must satisfy clinical and quality standards.

While distinct in their physics, all radiological imaging systems must match the clinical workflow at commensurate optical and spatial resolutions. For X-ray, CT, and MRI techniques, radiation dose and safety must comply with established standards (the ALARA principle). Optical imaging and optical coherence tomography (OCT) can provide additional functional information vital to clinical diagnosis and therapy but are limited in individual isolation by depth of penetration and scattering. Consequently, these techniques have moved toward hybrid implementations with established modalities. The current paradigm is to provide complementary information in a single study, reduce acquisition time, avoid the application of multiple contrast agents or illumination sources, and exploit probe synergy. Machine-learning data fusion is now expanding the capabilities of multimodal data across various imaging types, integrating all the spatiotemporal information sourced from different methods.

Machine-learning strategies, particularly convolutional neural networks, have garnered great interest in recent years for various artificial intelligence-assisted imaging tasks by mapping from one image space to another. Their utility has been shown for image restoration and denoising, segmentation, detection, reconstruction from limited-angle tomography, and transfer to style-space representations. The latest techniques, especially diffusion models, have shown promise for multimodal imaging applications, associating the unlabeled statistical information of individual image modalities across different modalities [102, 103, 104, 105].

Image reconstruction algorithms

play a crucial role in radiological imaging systems. Although images are acquired in the form of projections, the human visual system is not capable of interpreting projections directly. Therefore, the data needs to be reconstructed into images before they can be used in clinical diagnosis. A variety of algorithms are used for different imaging modalities, and their proper implementation is essential for optimum image quality.

The reconstruction is a multi-step process consisting of filtering and back-projection for conventional two-dimensional (2-D) reconstruction and includes additional interpolation for spiral computed tomography (CT) and optical projection tomography (OPT). Magnetic resonance imaging (MRI) reconstruction incorporates the 2-D fast Fourier transform (FFT) algorithm based on the spatial frequency domain sampling of the image. In a tomography, only a limited angular range of the object is measured, resulting in an incomplete set of projections and inserting the missing information. The heterogeneity of the participating objects, especially animal models for preclinical investigations, imposes additional challenges to the image reconstruction process. Points where modalities of one of the complementing systems afford no information or possess a response not suited for the problem may warrant data omission; reconstructions based only on the remaining data subdomains are refered to as partial-domain reconstructions [106, 107, 108, 109].

Integration with optical and laser-based methods

A variety of optical methods can be used to supplement radiation-based imaging techniques. The goal of these multimodal systems is to combine the high spatial resolution of the optical systems with the deep tissue penetration ability of the radiation-based modalities. The appearance of fused optical-radiation biomedical images may be facilitated by the incorporation of artificial intelligence techniques within these imaging systems.

Integrating radiation designs with optical methods for treatment has also gained interest. Optical and laser surgical systems may benefit from preoperative radiation imaging, while lasers can enhance surgical planning and execution by providing augmented-reality visual cues. Moreover, robotic systems, which enable physicians to operate inside the body with high precision and safety for complex procedures, are undergoing rapid development. The surgical laser may be incorporated into these systems to increase treatment efficiency [110, 111, 112, 113].

AI and machine learning in image analysis

Artificial intelligence (AI) is finding extensive application in experimental and clinical diagnostics, interpretation of the results, automation of imaging systems, and optimization of the processes with the use of multi-modal imaging systems. The use of AI for interpreting images and supporting diagnosis is essentially pattern recognition and classification of samples. Such tasks are also successfully performed by AI systems trained using machine learning algorithms. Machine learning and deep learning techniques based on neural networks and convex optimization have shown great promise in a variety of image processing tasks. Particularly Convolutional Neural Networks (CNN) have produced excellent results in medical imaging and image based clinical diagnosis. Handcrafted features are replaced by neural network features learned from the data. CNNs automatically learn feature hierarchies through back-propagation of errors. CNNs trained with large and diversified datasets with image augmentation are well-suited for clinical applications.

The high dimensional feature vectors of large datasets obtained from imaging devices trained using deep convolutional neural networks need refinement before they can be suitable for personalized diagnosis and therapy. These feature vectors can be subjected to dimensionality reduction techniques, like the t-distributed stochastic neighbor embedding (t-SNE), to map them to lower dimensions, leading to better visualizations of the data. Accurate and automated identification and quantification of retina vascular changes using supervised CNN based ensemble classifier show great potential in diabetic retinopathy analysis. Tensor flow based Mask R-CNN image segmentation is used for the segmentation of neighbour lizard images into distinct regions. The security of health records of patients is paramount. Features from the captions of the pregnancy detecting images available on Google without labels are used to check the security of the records [114, 115, 116, 117].

Chapter - 7

Biomedical Sensors and Wearable Devices

Fiber optic and electronic devices monitor, control, and detect analytes in blood, breath, and sweat. Sensing principles include fluorescence, electrochemical, piezoelectric, electrical, optical absorbance and transmission, electrochemical impedance and Raman, for a variety of analytes. Non-invasive devices for heart rate, SpO_2, glucose, and lactate are reviewed. Data acquisition, sensor fusion, Internet of Things integration, clinical data management, and cyber security are discussed.

Biosensors measure biological quantities by detecting variations in chemical, physical, or biological processes of target substances. Optical biosensors exploit light propagation, scattering, and spectral absorption properties for concentration variance analysis. Electronic biosensors, often termed "lab-on-chip" technologies, integrate sensitive detection and high-performance computing at the micro-/nano-scale, offering physical, chemical, and biological sensing capacities. A general classification scheme distinguishes optical, electronic, mechanical, magneto-impedance, piezoelectric, and mass-transduction-type sensors; combinations produce hybrid devices offering multimodality detection with high sensitivity and selectivity. Additional chemical-, temperature-, humidity-, and pressure-sensitive layers enhance performance in the designated environment.

Non-invasive, continuous-monitoring wearable sensors have appeared recently, driven by consumer demand and medical need. The emerging field focuses on designing compact, low-cost, and reliable optical/electronic sensors for monitoring key health parameters. Devices for optronic SpO2 measurement, glucose estimation from sweat, electrocardiography, and breath-analysis lactate determination illustrate sensor principles. Data-acquisition front-ends acquire signal information for local or external processing or cloud-level integration; cyber-security is paramount to prevent unethical user data manipulation or sensor alteration [118, 119, 120, 121].

Optical and electronic biosensors

Constitute an important area of research and commercial application. Their development embraces a wide variety of sensing modalities, combining well-developed optics/electronics concepts with adequate biological knowledge. Optical biosensors are designed to sense the interaction of specific biomolecules or pathogens, while electronic biosensors are able to detect biological interactions by electrical means.

Non-invasive biosensing is of great development interest. Some devices have reached a good state of development and are regularly used (SpO2 monitors, heart-rate monitors), while others are not yet used in clinical practice or have no applicability in some conditions of clinical interest (glucose monitoring remains a major challenge). Nevertheless, after designing, manufacturing and validating these devices in isolated conditions, their operational routine requires several additional steps, expressed in terms of Internet of Things concepts. The data acquired must be transmitted to storage and management frameworks, allowing the introduction of artificial intelligence powering epidemiologic assessment and, in some cases, monitoring and guiding treatment options. Moreover, cybersecurity must be addressed, as non-invasive biosensors manage valuable information concerning the health of the medical devices users, being extremely interesting for malicious actions and, consequently, becoming an important area of discussion [122, 123, 124, 125].

Non-invasive monitoring (SpO_2 , glucose, heart rate)

Non-invasive monitoring of biological parameters is of increasing interest due to its ease of use, comfort, and safety. Several parameters, especially blood oxygen saturation (SpO_2), blood glucose, and heart rate, are frequently monitored outside of the hospital environment through commercialized devices. Consequently, their integration into smartphones, watches, and wristbands, as well as their use in a wider range of medical situations, has gained importance. In addition, the processing of acquired data through the Internet-of-Things (IoT) has opened new windows in modern, integrated, and health-oriented diagnostics.

In general, non-invasive estimation is realized by a multistep approach: biosensor design, signal acquisition, data transmission, clinical data management, and cybersecurity. Within the data-acquisition process, the optical or electronic sensing is performed, depending on whether an optical device or an electrochemical biosensor is used. For SpO_2 , optical measurements are realized by means of a multispectral approach, while heart rate and blood glucose are most commonly measured by electrochemical analysis. An in-depth discussion of the three parameters is provided here. Different options for SpO_2 monitoring are reviewed, followed by a detailed analysis of glucose and heart-rate non-invasive monitoring [126, 127, 128, 125].

Data acquisition and IoT integration

Integration of Medical Physics, Optics and Laser, and Medical Device Engineering: Concepts and Applications in Modern Diagnosis and Therapy

Comprehensive treatment usually requires continuous monitoring of physiology or chemistry. Non-invasive or minimally invasive monitoring can be achieved with optical/electrochemical biosensors based on fluorescence resonance energy transfer, surface plasmon resonance, fiber refractive index change, or electrical properties such as impedance, capacitance, thermal conductivity, and redox potential using colorimetric or electrochemical methods. Measurement modalities include electrocardiogram (ECG), electrophysiology, photoplethysmography, infrared thermal imaging, pulse oximetry (SpO2), breathing frequency, blood glucose concentration, blood pressure, urine analytes, and salivary analytes.

Data acquisition must adhere to clinical requirements. Connectivity through IoT is now a necessity in medicine, enabling secure integration of acquired data with patient records, health management, and long-term care. Addressing data privacy and cybersecurity concerns is imperative. Achieving important requirements in data acquisition, IoT integration, clinical data management, and cybersecurity leads to significant challenges. These domains require thorough research and development (RD) attention, especially in healthcare systems and considerations such as patient-centred care [129, 130, 131, 132].

Clinical data management and cybersecurity

Evolving trends in Internet of Things (IoT) technology allow for the increasingly widespread integration of hardware sensors in wearable devices, enabling non-invasive estimation of biological parameters such as blood oxygen saturation (SpO2), glucose concentration, body temperature, electrocardiography (ECG), and heart rate. However, the processing, storage, and transmission of vast amounts of data to and from hospital systems for patient management are fraught with challenges related to data integrity, availability, confidentiality, and regulatory compliance. Malicious assaults on clinical data, cloud system servicing, and 3rd party application software storing healthcare data threaten the safety of patient data. The rapid advancement of technology generates trade-offs between offering convenience and compromising security.

Social media and big-data applications rely on machine-learning techniques that collect users' personally identifiable information (PII) in return for the free use of their services. Data breaches resulting in the unauthorized marketing and distribution of acquired PII on the dark web have drawn the attention of media, law enforcement agencies, and concerned citizens. Similar operating methods applied to medical data for a profit or ransom hold grave consequences [133, 134, 135, 136].

Part - III

Therapeutic Applications

Chapter - 8

Laser-Tissue Interactions and Therapeutic Mechanisms

Therapeutic laser applications rely on laser-tissue interactions to elicit the desired physiological effect. Laser-tissue interactions involve photothermal, photochemical, and photomechanical processes, which induce distinct tissue responses in the respective temperature regime. Understanding the biological effects of laser irradiation sheds light on the tissue healing response, enabling targeted applications in surgery, dermatology, and other fields.

The principal instruments for surgical and therapeutic applications rely on the cutting, vaporization, or photocoagulation effects of laser-induced plasma formation, as demonstrated by CO2, Er:YAG, and Nd:YAG lasers. Additional fields rely on the effects of specific chromophores inducing selective thermal damage, targeting structures such as blood vessels, hair follicles, and pigmented lesions. The successful application of laser surgery at various wavelengths and treatment sites, along with evidence of accelerated healing following laser-assisted surgery, has strengthened the case for plastic laser surgery and optimization of treatment conditions. While these observations support the development of therapeutic lasers, proper dosimetry remains essential for predicting biological effects [137, 138, 139, 140].

Photothermal, photochemical, and photomechanical effects

The interaction of laser light with living tissues may cause three photoinduced physical processes, namely photothermal effect, photochemical effect, and photomechanical effect. Based on these effects, different types of laser tissue interactions might be distinguished. Physiological responses of tissues to each of these laser-tissue interactions are also different, leading to various clinical applications. For reasons of biological safety and effectiveness, the laser dosimetry of the above-mentioned laser effects is also different. The photothermal response of a tissue is mainly thermochemical, causing energy absorption, localized hyperthermia (increased temperature), up-regulation of immune response, and indirect photothermal killing - all of which can be regarded as among the main healing processes. Consequently, the tissue healing processes can also be affected by the choice of optical latero-nasal laser (Nd:YAG, diode) and the laser dosimetry (wavelength, pulse duration, energy density).

Photothermolysis is the preferred interaction process in laser-assisted surgery involving CO2 laser (wavelength: 10600 nm). Patient safety is achieved by minimizing thermal load effects on surrounding tissues. Healing is therefore a direct response, caused mainly by the formation of denatured proteins during laser tissue interaction. In other words, the main healing mechanism is collagen shrinkage, and the surgical laser energy density is carefully controlled to ensure photothermolysis while avoiding any thermochemical effect [141, 142, 143, 144].

Tissue response and healing mechanisms

Mammalian tissues respond to laser irradiation through one or more of the following mechanisms: photothermal, photochemical, and photomechanical effects. The healing mechanisms involved in laser-assisted surgery largely follow the same sequence as with traditional surgical approaches. For dermatological and other non-invasive procedures the healing response should be considered and, when possible, photographed in order to provide a record of the effects of the parameters used. For photothermal therapy the dosimetry principle is outlined on the basis of volumetric heating of the tissue, following one particular definition of the damage threshold level.

Tissue response can be subdivided into several mechanisms, with each mechanism relating to one or more laser-tissue interaction typologies. Thermal effect dominates interactions at nanosecond or longer time scales. The operating area heated above a local and time-dependent damage threshold level exhibits the associated tissue response (scarring/shrinking of retina; melting/coagulation); thermotactic migration can modify the immunological infiltrate. Rapid cell absorption induces thermal elevation of the surrounding fluid, producing explosion of the tissue, with the associated photomechanical response. Photothermal effect dominates photothermal therapy of pathological conditions; photothermal lasers operate in the clinically-proven power density range. The volume and time scales involved permit the photothermal dosimetry description, based on volumetric heating above a defined threshold level that guarantees destruction of the pathological condition without damage to the surrounding 'healthy' tissue [145, 146, 147, 148].

Dosimetry for therapeutic lasers

Is based on the absorbed energy density in tissue. Considering that heating is the primary effect on tissue for the implementation of laser operating in the near- and mid-infrared spectral domains by photothermal mechanisms, the threshold for thermal damage effects can be used as a starting point for thermal dosimetry. Understanding such processes allows defining the energy density threshold for defined photothermal purposes and others where additional phenomena occur in addition to temperature rise at a predefined health risk, thereby defining a range of thermal dosimetry. The analysis starts with the small-scale heat equation and the condition for thermal relaxation after energy deposition in a small volume and extends the concept to include the entire volume at risk for thermal damage.

Thermal dosimetry for for surgical, gynecologic and other applications is made considering results from a number of clinical studies covering the entire operational space, where in a first approximation only temperature rise is taken into account and the three other processes considered congruently correlated. The above ACS process is subsequently detailed and is then further described with respect to dosimetry concept for HAO within the general dosimetry framework and considering reporting of results by lasers in dentistry with respect to therapeutic lasers applied in other specialties. A similar framework is consequently applied for the analysis of dosimetry formulation within CLI to include reporting of synergetic and functional processes [149, 150, 151, 152].

Case studies in surgery and dermatology

Clinical implications of lasers in surgery and dermatology are illustrated through case studies from the author's university hospital. Investigated procedures included: (1) Large-scale partial parotid gland resection (NerveFusion technology) demonstrated accelerated recovery and functional restoration through optical-assisted navigation and augmented-reality support. (2) Minimally invasive approach to tumor resection in paranasal sinuses showed strong therapeutic efficacy with a reduced risk profile. (3) Nd:YAG laser treatment of microcystic lymphatic malformation exhibited high focal precision paired with good functional and aesthetic outcomes. (4) 24-year experience in non-ablative laser resurfacing of fine wrinkles detailed achieved results and potential for long-term facial rejuvenation.

These cases underscore the need for continuous investment in dedicated training and adequate facilities to optimize clinical results and ensure patient well-being and safety.

Surgery requires high-level precision and refined effectiveness to minimize postoperative complications and patient suffering. Laser systems have emerged as optimal tools for several surgical procedures, although considerable skill is necessary to ensure adequate results. Nevertheless, these methods are sometimes limited by their high cost, prolonged working time, and specificity for certain operations [153, 154, 155, 156].

Chapter - 9

Photodynamic and Photothermal Therapies

Photodynamic therapy (PDT) and photothermal therapy (PTT) apply light to activate agents that lead to specific therapeutic effects on living tissues-primarily the destruction of cancer cells and microorganisms. PDT delivers a photosensitizer that produces reactive oxygen species upon light exposure, while PTT employs photothermal nanoparticles that absorb light and rapidly generate heat, usually producing local denaturation and tissue damage. Both modalities are non-ionizing processes and are therefore primarily limited by light penetration in tissues. For cancer treatment, the targeting can be overcome by systemic administration. Integrated diagnostic/feedback imaging (e.g., fluorescence imaging of the photosensitizer, NIR imaging for photothermal animals), and direct coupling to light sources / therapeutic devices are essential for increasing the selectivity and overall efficacy.

Photodynamic therapy (PDT) requires the association of a photosensitizing molecule that generates reactive oxygen species (ROS) in situ upon light excitation (for example, singlet oxygen). The resulting oxidative damage to cellular components leads to selective cell death. The key event that converts PDT from a phototoxicity to a therapeutic treatment approach is the strict spatiotemporal control of the ROS production. This is achieved by the delivery of a relatively nontoxic dye into the target area. Light delivery can be from outside (via fiber optics or through-skin external-light illumination - different systems) or by tissue-specific expression of a fluorescence protein that transfers the activation light to the photosensitizer. PDT is especially indicated to all situations in which a surgical resection cannot properly remove the entire diseased area. It covers a great range of applications, from skin affections to prostate disease, and is especially effective for thin microorganisms (certain fungi and parasites).

Photothermal therapy (PTT) exploits the temperature elevation induced in tissues by certain nanoparticle systems. Such nanoparticles contain much solubilized metals or metal oxides that have optical absorption in specific windows of the near-infrared range (NIR) posing minimal absorption in surrounding tissues. Near-infrared light generates high-temperature transients with the consequent photothermal ablation of surrounding tissues. Specific targeting of the particles increases the safety of the approach [157, 158, 159, 160].

Principles of PDT and PTT

Photodynamic therapy (PDT) and photothermal therapy (PTT) employ light to excite special chemical substances in a body, inducing diagnosed effect on abnormal tissues. Although both techniques can destroy cancerous cells or bacteria as standalone procedure, their mechanisms differ. In PDT, the excited chemical substance becomes a photosensitizer, transferring the energy to surrounding tissue and creating cytotoxic singlet oxygen molecules, leading to cell apoptosis or necrosis after some time. Conversely, PTT inherently raises tissue temperature which, if sufficiently high, induces thermal damage immediately.

Using PDT and PTT in synergistic combination promises greater therapeutic efficacy, better therapeutic selectivity, and fewer side effects, since the targeted agent for PTT-and-PDT can be a nanoparticle serving as the carrier of therapeutic photosensitizers. By combining imaging with PDT and/or PTT, accuracy may increase. Molecular imaging may precisely guide PDT or PTT within a small region but a larger area is required for some diseases (e.g. surface bacterial infection). Addressing these needs, a hyaluronic acid-based nanoparticle could photothermally activate near infrared light for imaging, meanwhile delivering the close-up photosensitizers. Image-guided integrated PTT-and-PDT application is feasible. Experimental work confirms PTT-induced photothermal effect enables PDT fusogenic photosensitization, inducing epithelial cell apoptosis and accelerating wound healing via neovascularization [145, 161, 162, 163].

Photosensitizers and nanoparticle-mediated targeting

In photodynamic therapy (PDT), the non-invasive combination of a photosensitizer with laser irradiation at the appropriate wavelength leads to a photochemical reaction that destroys malignant tissues by producing reactive oxygen species. Targeting of cancerous tissues can be achieved by using nanoparticles as drug carriers. The selective accumulation of the nanoparticles inside the target tissue can be followed by laser termination of the tumor with a lower-energy laser light. The strategy can also be used to induce photothermal therapy (PTT), in which the nanoparticles themselves are responsible for producing a temperature increase that leads to the thermal disruption of the tissue. When performed separately or concurrently on multidrug-resistant molecules, both therapeutic processes can efficiently eliminate the tumor, with PTT providing a faster alternative.

In the case of PDT, the active proximity concentrations of the photosensitizer in the tumor are limited to less than the toxic concentration for surrounding normal tissues. The use of targeting carriers based on nanotechnological tools makes it possible to overcome the aforementioned limitations and apply the PDT and PTT processes with many advantages, such as reducing the irradiance level of the laser, inhibiting the growth of multidrug-resistant tumors, and limiting side effects. Cancer research has proposed the use of a variety of nanocarriers for drug delivery, including liposomes, micelles, dendrimers, nanoparticles, nanocarbon carriers, nanogels, and nanoemulsions. Photosensitizers have also been embedded in nanostructured carriers, such as silicon dioxide, gold, titanium dioxide, polyacrylamide, talc, and hollow carbon carriers [164, 165, 166, 167].

Cancer treatment and antimicrobial applications

Combined therapy based on photodynamic therapy (PDT) of malignant tumors and photothermal therapy (PTT) of bacterial infections is considered. Both methods can be effectively performed in the same region of interest using the same optical delivery-analyzing system.

The essence of PDT is the introduction into the tumor tissue of the so-called photosensitizers, which preferentially accumulate in the tumor cells. Subsequently, these drugs are selectively activated by light irradiation, which leads to the formation of reactive oxygen species (ROS) that destroy the cells. Genes and virus vectors carrying the genes of enzymes that lead to the apoptotic death of cells are also promising as photosensitizers for PDT. PDT is also actively developed for therapy of bacterial infections. In this case, the photosensitizer is introduced into the body or into the studied environment in the form of a liquid or gel, after which it is activated by light from the environment. The light source can be either laser or arc, and even simultaneously operating arc lamps can be used.

As for PTT of infections, it is currently known that nanocomposites based on gold and other nanoparticles can localize in the statistical loci of bacteria and their colonies and at the same time exhibit a remarkable photothermal effect. If the size of the nanoparticles is less than 20 nm, they can penetrate through the virus pores into the bacteria and exert a substantial photothermal effect, or even inhibit the growth of viruses; if the size of the nanoparticles is approximately 50 nm, they can increase the permeability of the pus and the opsonization; and if the size of the nanoparticles is larger than 100 nm, they can be actively internalized and combined with the therapeutic properties of the targeting molecules [168, 169, 170, 171].

Integration with imaging and feedback systems

Enhances cancer and antimicrobial applications of photodynamic and photothermal therapies. For photodynamic therapy (PDT), a photosensitizer accumulates at a tumor site and light excitation generates reactive oxygen species. In photothermal therapy (PTT), infrared-absorbing nanoparticles accumulate in the tumor and conversion of light to heat leads to necrosis or apoptosis. Both techniques can benefit from concurrent fluorescence imaging of the tumor site or the detection of nanoplasmonic photonic signals.

Since neoplasms often have impaired responses to PDT due to hypoxia or large size, nanoparticle-assisted PTT has received wider clinical application for soft-tissue tumors, especially in combination with surgery, radiotherapy, or chemotherapy. Nanoparticles can also enhance the efficacy of PDT by facilitating oxygen delivery, acting as vectors for drug targeting, or amplifying the photothermal effect. Such tumor-targeted delivery strategies, often using bioconjugated and other smart nanocarriers, have been adopted for many classes of photosensitizers, enabling the simultaneous utilization of tumor optical signatures as reaction feedback for both therapies. The integration of imaging and cue-based feedback systems thus becomes central in bringing together all these different therapeutic modalities [172, 173, 174, 175].

Chapter - 10

Radiation Therapy and Dosimetry Engineering

External beam and brachytherapy are the main modalities for radiotherapy. External beam therapy employs a linear accelerator that generates high-energy X-rays or electrons. Radiological modalities provide anatomical information for treatment planning and, in some systems, allow for online control of patient repositioning. Radioactive sources can be placed in the tumor (brachytherapy) or at a distance in the interstitial or extra-corporeal configuration; in this case, the dose distribution is defined according to the seed positioning. Obviously, brachytherapy requires advanced radiological skills and a quality assurance (QA) plan.

In external beam therapy, the generated dose must be accurately computed by a planning system; quality control for the accelerator and dosimetry measurements are important to ensure precision. External and brachytherapy can be integrated with advanced imaging modalities (magnetic resonance imaging-MRI, Positron Emission Tomography-PET) for brachytherapy dressing or patient supervision during treatment. Combining external beam therapy with specific imaging data for individual patient needs represents an adaptive approach; adapting the treatment to the actual condition of the patient represents the most advanced and patient-centered way to employ this radiation method. Proton and heavy-ion therapy are the emerging radiations that allow tissue dose regions with different linear energy transfer and relative biological effectiveness to be explored, but planning requires embedding other diagnostics modalities, and this underlines the importance of imaging technology.

Integrating these radiological methods with optical and laser techniques enables novel procedures, such as photodynamic therapy and proper healing supervision; however, dosimetry engineering remains a challenge because of the different scales of the involved processes [176, 177, 178, 179].

External beam and brachytherapy systems

In external beam therapy, high-energy radiation beams are directed at the tumor from multiple angles to maximize dose deposition in the target volume while minimizing affectation of the surrounding tissue. Two-dimensional dose matrices, usually derived using patient-specific computational software, characterize radiation intensity for each beam and at each discretized matrix position, while tomographic images provide information about attenuation coefficients of the irradiated region. An acquired image (obtained previously or during therapy) is then compared to the matrix data to deliver the appropriate dose at each patient-specific location. Quality assessment of the therapy requires verifying that radiation intensity distributions correspond to those stipulated during planning before each session, as well as performing periodic examination of the machine itself.

A brachytherapy source is introduced in the same area as the tumor. Dosimetry engineering and quality assessment for these systems rely on both predictive and post-implantation imaging. In the first case, the procedure is computed automatically or manually for the internal volume of the tumor and the matrix of locations for the brachytherapy sources. The examination also includes hydrogels that can be placed around the implant for the precise positioning of the sources and their effect on the adjacent tissue, as well as sources administered in sites of rapid biological decay (for example, iodine) [180, 181, 182, 183].

Dose planning and quality assurance

Adequate external beam or brachytherapy dose distribution planning is essential in radiation therapy to ensure that the absorbed dose is sufficiency high to destroy the tumor and tolerably low in healthy organs and tissues. Different treatment planning systems (TPS) have been developed over the years, based on experimental findings, to numerically estimate the radiation dose distributions produced by any complex sequence of irradiations for a given geometry of the source and of the receiving medium made of different materials, with the purpose of dose optimization at pre-treatment planning. The TPS considers a 3D computational version of the clinical geometry of interest, automatic or manual selection of appropriate set of irradiation parameters and allows optimization for a high-low dose level combination for tumor-organ at risk. Quality assurance (QA) of radiotherapy involves controlling treatment planning sub-system and delivery sub-system in a routine practice. QA procedures are divided into equipment QA, planning QA and delivery QA. Equipment QA ensure that the equipment is functioning correctly, Planning QA ensure that the treatment is adequately planned so patients receive the correct dose, and Delivery QA ascertain that the plan is correctly delivered to the patient.

Increasing use of imaging modalities in both external beam radiotherapy and brachytherapy is enabling adaptive radiation therapy, where image guidance in treatment planning is combined with imaging before treatment delivery and with re-planning between treatments for high-precision dose delivery.

These advancements in imaging technology are driving the development of organs-at-risk (OAR) guided dose re-planning, where both individual OAR dose evaluation and combined OAR dose-volume-histogram monitoring lead to replanning when preservation of normal tissue function can be improved. The integration of magnetic resonance imaging into radiotherapy is also enhancing the possibility of incorporating physiological response to treatment in re-planning approaches, and attention is shifting toward the incorporation of pathology imaging information [184, 185, 186, 187].

Integration of imaging and adaptive therapy

Radiation therapy predominantly utilizes external beam irradiation and brachytherapy, where the prescribed radiation dose distribution is computed in advance of patient treatment, but anatomical changes can impact outcome. Integration of medical imaging assists in treatment planning and subsequent delivery, and has led to the concept of adaptive radiotherapy, where treatment geometry is adapted to account for anatomical changes. Adaptive approaches can also ensure safety, adapting treatment to an altered situation (e.g. pregnancy) or to mitigate side-effects when organs-at-risk change, particularly for proton and heavy ion therapy. Integration with imaging/feedback methods for calibration and data acquisition is an area of intense active research. While external-beam delivered radiation represents the predominant fraction of radiation exposure in a population, patient-based clinical case studies showing a clinical benefit.

An increasing need for adaptive planning in organ-based models underlines the requirement for patient-specific features to be integrated into digital treatment-surrogates in two major areas: first, for anatomical or functional change within the treatment domain, second for changes to organs-at-risk. As clinical radiotherapy systems has advanced towards a high degree of automation and precision, so too the complex task of constructing, maintaining and updating the digital patient has become a significant element of quality assurance [188, 189, 190, 191].

Emerging modalities (proton, heavy ion therapy)

Investigational therapy modalities such as proton or heavy-ion external beam radiation therapy and thermal neutron brachytherapy hold promise for managing intractable cancers. Proton therapy is advantageous for targeted dose deposition, while boron neutron capture therapy exploits the 10B(n,α)7Li reaction. Research focuses on addressing challenges in therapy planning and quality assurance for these non-conventional treatments. Recent progress in hybrid optical-radiation systems introduces new combinations of optical functions with X-ray, CT, and other modalities, marking a paradigm shift for dedicated instruments. The development of intelligent wearables and point-of-use testing platforms for continuous non-invasive health surveillance creates tremendous opportunities for integration with IoT and IT solutions.

Proton therapy utilizes proton beams for irradiation and offers distinct advantages over classical X-ray-based radiotherapy, including a favorable dose deposition profile within tissues. Soft materials exhibit a characteristic Bragg maximum in radiation absorption, allowing for greater sparing of surrounding healthy tissues, especially in pediatric cases. Presently, patients receive proton therapy in the vicinity of high-energy physics laboratories capable of accelerating particles to the requisite energies, but several medical centers are developing clinical solutions based on smaller iso-centric charged particle cyclotrons, the foundation of which is established by the success of routine clinical brachytherapy employing low-energy photon sources. In the case of boron neutron capture therapy, analytical methods focus on evaluating and optimizing the geometry of the boron compound and neutron source distribution within the body area [192, 193, 194, 195].

Chapter - 11

Laser-Assisted and Image-Guided Surgery

Surgical lasers find applications in various specialties, including ophthalmology, otolaryngology, dentistry, dermatology, and neurosurgery. Their main advantages stem from precise tissue effects, including cutting, ablative vaporization, and laser-induced flaps. Classification into thermal, thermal-mechanical, and non-thermal lasers is common based on tissue interaction mechanisms. Optical navigation technologies employing pre-acquired fluorescent, magnetic resonance, and X-ray histological data, as well as augmented reality concepts, enhance surgical precision. Robotics and optical devices integrated into instruments improve accessibility and precision. Fall risk prediction, biomedical adoption, and clinical outcomes are recent focal points of investigation.

Diagnostic and therapeutic lasers are more widely adopted compared to laser-assisted surgery. Records indicate that one of the first laser operations was performed in 1964 in the USA, and by the end of the ninth decade, over 200,000 laser applications had been reported. To date, surgery remains one of the most extensive applications of laser medicine. The unique properties of laser radiation (monochromaticity, coherence, and collimation) enable focused laser beams to deliver very high power densities to small areas, generating very high temperature gradients, which facilitate thermal, thermo-mechanical, thermo-chemical, and photo-dynamic effects on biological tissues. Among the recognized medical specialties that employ surgical lasers are ophthalmology, otolaryngology, dentistry, and neurosurgery [196, 197, 198, 199].

Surgical lasers in ophthalmology, ENT, and neurosurgery

Ophthalmic laser systems leverage CO2, Nd:YAG, argon, excimer, and femtosecond lasers for various ocular procedure applications. Neodymium-doped yttrium aluminium garnets (Nd:YAG) are used for posterior capsulotomy after cataract surgery and for clearing peripheral anterior synechiae during an iridotomy. In contrast, CO2 lasers are employed for superficial scleral incision, while excimer lasers are utilized for corneal reshaping. The strong absorption of water by the infrared light from CO2 laser systems makes it well-suited for incision in delicate tissues. Combination with other imaging approaches enables automated detection of early retinal changes associated with diabetes, retinopathy, and glaucoma.

Laser-assisted procedures in otorhinolaryngology (ENT) enable improved outcomes with less trauma. Applications include vapourisation of laryngeal tissue for recurrent papillomatosis treatment and creation of an external auditory canal. Stereotactic laser microsurgery allows thermal destruction of lesions in the brain, including deep structures, for selected patients with glioblastoma. Integration of an optical navigation system or augmented reality with head-up displays enhances the precision of otorhinolaryngological and neurosurgical procedures. Digital laser systems: improve safety by real-time monitoring of the location during surgery and provide input to automatic stop mechanisms [200, 201, 202, 203].

Optical navigation and augmented reality

Optical navigation systems assist real-time positioning of surgical tools by tracking the movement of optical markers located on the patient and/or surgical instruments. A camera detects the markers, providing information on their 3D spatial coordinates. Optical navigation is frequently applied during surgeries in otorhinolaryngology, neurosurgery, and orthopedic oncology, where critical structures require higher accuracy. The information from the camera is visually integrated into the surgical field by aligning the perspective with the instruments. Augmented reality systems increase the usability of optical navigators by overlaying virtual images on the camera feeds in head-up displays.

Optical navigation systems enhance surgery by enabling real-time tool positioning. Traditionally, surgical instruments are located under the surgeon’s view. During manual surgery, the surgeon possesses cognitive depth perception, allowing tool position estimation when not visually observed. Optical navigation semiautomatically provides tool positions, assisting with the cognitive perception.

During more complex microsurgical procedures, critical structures near the operating area may be damaged or sectioned. For precise devascularization and resection, optical navigation may safely assist with tool positioning. For lower complexity procedures, where surgical depth perception provides enough accuracy, optical navigation is just a noticeable aid that can also cause visual distraction. However, it may still help in detecting the position of difficult-to-see-in-3D structures, such as fissures in bonelike tissues or nasal cavities.

Optical navigation systems have been successfully implemented in otorhinolaryngology, neurosurgery, and orthopedic oncology. In otorhinolaryngology, they have been used for nasal cavity surgeries, parotidectomy, and skull base exploration; opened instruments are used as pointers to detect target structures, preventing inadvertent collision with critical elements. In neurosurgery, optical navigation has assisted tumor resections, tumor cavity exploration, and arterial and venous preparation—also demonstrating use for two-camera setups. In orthopedic oncology, a navigation system has assisted bone tumor resections and external limb prosthesis implantations on the pelvis, in patients with sarcoma tumors [204, 205, 206, 207].

Robotics and precision engineering in laser surgery

In various branches of surgery, such as ophthalmology, otolaryngology, and neurosurgery, surgical lasers have become standard tools that facilitate minimally invasive interventions with greater precision than traditional techniques. In laser-tissue interactions, the precision of the cut, the interaction time, and the optical properties of the medium being cut are important parameters for preventing damage to adjacent areas. Modern techniques use navigation based on preoperative imaging, augmented reality, robotic arms, and precision-end-effector engineering to increase safety and clinical outcomes. Laser surgery is an advanced area for which the convergence of precise optical radiation positioning, modern optical anatomical navigation instead of indirect visual techniques, and robotic arms enables greater safety and precision than other techniques.

Surgical lasers have become standard tools in areas such as ophthalmology (vitrectomy, retinopathy, cataract, glaucoma, curvature correction), otolaryngology (ear, nose, throat), and neurosurgery (craniotomy and endonasal procedures). These techniques, when performed correctly, require lower sensitivity levels for patients during recovery, resulting in fewer pain medications. The optical precision acts like a knife, minimizing damage to adjacent tissues. The precision of the optical cut, however, is more dependent on the control of time and energy compared to other surgical techniques. The precision of non-laser surgery depends on the skill of the surgeon and the positioning of the instruments [208, 209, 196, 210].

Clinical outcomes and safety management

Recent advancements in medical device engineering have greatly facilitated surgical processes, resulting in increased safety and performance. The implementation of optical systems with precise wavelength and power control for identification of pathological processes has improved the safety and accuracy of surgery. However, such optical systems are yet to be fully integrated into general surgery. Medical device design for optical systems operating in the optical and infrared region has been challenging, mainly due to difficulties in synchronizing optical and non-optical systems. These issues are being addressed, with a primary focus on integrated systems that combine devices and develop new products.

The clinical outcome of an optical-surgical approach can be enhanced by precise optical navigation in a multi-modality approach. Optical navigation supports precise navigation during complex surgical procedures where patient- and system-related complexity hinders clear recognition of anatomical elements. Precise navigation also enhances patient-specific pre-operative planning for appropriate instrument selection from a multitude of optical instruments to increase the chances of successful surgery [211, 212, 213, 214].

Part - IV

Design, Integration, and Future Directions

Chapter - 12

Medical Device Design for Hybrid Optical-Radiation Systems

The interplay between optical and radiation techniques in clinical applications has prompted the development of integrated hybrid systems that combine complementary imaging and therapeutic capabilities. Unified medical device engineering principles must address the challenges associated with customary alignment of separate systems or signal acquisition, communication, and synchronicity of instrument subsystems.

An illustrative example is the design of a multimodal photographic and thermal imaging and feedback system for tissue thermal stimulation and monitoring. Optical monitoring data and thermal stimulation profiles were exhibited on a single visual display for easy operator orientation. Similar approaches can be employed to incorporate image-guided control into novel laser-assisted treatments.

The introduction of a new imaging-guided laser-assisted procedure for minimally invasive skin rejuvenation requires the simultaneous availability of tissue temperature measurement and photographic documentation. Selecting two optical modes, thermal infrared sensing for monitoring the heating effects of the treatment and color photographic recording for documenting the resulting epidermal response, allows multiple user-friendly options for integrating tissue thermal stimulation and thermal response recording. Combined device use further enhances safe and effective operation since both modes continuously verify the required alignment. Beyond advanced design requirements for customized multimodal devices, situations involving established optical and laser configuration pairs highlight additional considerations for integrated device design [215, 216, 217, 196].

Design challenges for integrated systems

Integration of Medical Physics, Optics and Laser, and Medical Device Engineering: Concepts and Applications in Modern Diagnosis and Therapy

Medical Device Design for Hybrid Optical-Radiation Systems In equipment for medical diagnosis and therapy, the integration of optical and optical-radiation imaging, measurement, treatment, or monitoring pathways often offers significant advantages. Such pathways can involve two-dimensional or three-dimensional device architectures, may share common apertures, and often require combined data processing. However, the challenges of realizing these multimodal systems tend to be greater than for standard systems. Integrated system design should therefore occur through an engineering effort that considers all aspects of the instrument specifications.

Consideration of these specifications already using an engineering-design approach early in the development cycle assists in ensuring successful realization of a fully integrated or a multimodal optical and optical-radiation system. These aspects include optical and optical-radiation sensor performance; the connection with external optical and optical-radiation pathways; issues associated with human factors, usability, and operator safety; the synchronization of signals from different sensing pathways; and data-fusion algorithms required for a unified system output. The integrated design stage is especially relevant in systems that acquire optical images or spectra, or provide optical treatment, in addition to supporting other modalities.

Applications of medical-device technology in medicine are set to grow rapidly in the near future, together with the gradual adoption of smart, connected, and data-driven methods [218, 219, 220, 221].

Signal synchronization and multimodal data fusion

The integration of optical devices with other modalities such as radiation or electrical signals for both diagnosis and therapy presents several challenges. Signal synchronization is critical for integrating separate diagnostic and therapeutic devices or systems. For multimodal imaging systems or therapeutic systems with signal feedback, efficient data fusion strategies should be proposed.

Synchronized signal acquisition helps to determine the optimal parameters for laser-based photothermal and photodiagnostic treatment of tissues. For dosimetry of photothermal therapies, temperature measurements using gold nanoparticles were syncronised with ± 1 °C without any extra technical calibration. In one of the surgery case studies, surgery was performed using a neodymium-doped yttrium aluminum garnet (Nd:YAG) laser, and blood loss was recovered and synchronized with a fiber module for laser-pulse-triggered image acquisition.

Design challenges for hybrid multimodal systems have been previously investigated. Optical navigation systems integrate optical projection, depth detection, and inertial measurement for accuracy that matches the accuracy of optical projection. Automatic optical navigation for augmented reality-assisted surgery enables fusion of real-time operation videos of a surgical robot and preoperative virtual models to provide visual cues in real time. Moreover, the signal synchronization and data fusion enable quantitative assessment, reduce redundancy, and achieve smooth performance of optical navigation systems [222, 223, 224, 225].

Prototyping, simulation, and validation approaches

Flexible system design necessitates early prototyping of devices or subsystems to identify potential drawbacks/limitations and explore possible strategies for overcoming them. Gear and performance requirements often support development as multi-purpose systems. For instance, specific medical design conditions ensure adequate integration—spatially, temporally, and functionally—for physiological monitoring or imaging feedback during therapeutic procedures, enabling fully-fledged signal synchronization. Covering all key technical aspects is crucial for delivering a safe, efficient tool set with proven effectiveness.

Broadly applicable simulation frameworks are often developed to enable the design of suitably integrated prototypes for specific applications. Adequate simulations—conducted alone (for device or system performance) or in combination with prototype verification/validation—greatly expedite robust solution delivery. Human factors are also mandatory for efficient, intuitive, and ergonomic use in operating rooms or hospitals [226, 227, 228, 229, 226, 227, 228, 229].

Human factors and clinical workflow integration

Medical devices must be designed with user-friendliness in mind since human errors in using devices during diagnosis or therapy can adversely affect the efficacy of the treatment. As an example, placing a stethoscope wrongfully on the chest of a patient can lead to a wrong diagnosis of a pathological heart sound. The design of devices like heart pad electrodes, temperature sensors, and urine bag outlets presently conceals the working technology behind them in an attempt to ensure intuitive operation and to make training easier. An example of such a design is the simpler-to-use testing equipment for urine quantity than the existing ones by covering the delicate working models that are hard to understand. Furthermore, the device should be such that can be used without any special training or under duress, and care should be taken to keep the display simple and uncluttered.

The requirements for sensor, actuator, and signal-acquisition units required for a medical device have been announced. Human factors engineering will play a vital role in novel designs and in simplifying existing designs for introduction into everyday clinical applications. Easy-to-produce and novel devices that enhance user-friendliness would add great value to medical instruments, as patient care is being handed over to non-specialist operators. Data from novel sensors, actuators, and subsystems would now be acquired with handheld equipment, enabling easy data management of clinical research and diagnostics. The data flow—from the device to the Internet of Things, to data management along with other such data, and finally sharing with the clinician or researcher looking for it—is becoming the norm.

Signaling pathways have a vital role in selecting the actuators required in a device for specific applications—from normal use to surgery, and for short-duration use to long-term use. Signal pathways, especially those connecting to the Internet of Things, have found new applications in monitoring parameters over an extended period of time without disturbing the patient in the critical-patient ward. Cybersecurity is also becoming an integral part in these data-path designs, especially in health data management. Detouring a data flow at a specified point to allow detailed understanding and analysis of a biosignal without any prolonged wiring hindrances is a new dimension now added.

Chapter - 13

Materials and Nanotechnology in Medical Devices

Smart materials and nanotechnology are increasingly utilized in devices for diagnostic and therapeutic purposes, particularly in implantable or wearable optic systems. These devices rely on the interaction of optical radiation with tissues and biological fluids. Smart environmental-responsive materials can provide additional functionality, modifying their attributes in response to external changes. In addition, the implementation of nanotechnology allows the fabrication of devices at the nanoscale that, due to their small size, high surface area-to-volume ratio, and quantization effects, open up new possibilities in the field of medicine.

The integration of optical fibers and biopolymers into various implantable or wearable systems is enabling a broad range of applications, such as skin monitoring for oxygenation, hydration, and other parameters; glucose concentration monitoring in sweat; and the assessment of glucose levels in tears. The involvement of nanoparticles in medical devices for both diagnostic and therapeutic aims is becoming increasingly common. Surface modification approaches using nanostructuring techniques or the deposition of nanocomposite coatings enhance the functionality of devices through improved adhesion, reduced wettability, and increased biocompatibility. Examples include nanostructured coatings on biosensors to enhance sensitivity and miniaturized analytic systems with high sensitivity for real-time monitoring, which can be achieved using lab-on-chip integrated optics and polymeric bio-absorbers [230, 231, 232, 233].

Smart materials for diagnostics and therapy

Smart materials play an important role in the development of diagnostics/therapeutic systems due to their unique and advance properties that being able to adapt dynamically to stimuli from the surrounding. This includes systems such as composites, shape memory alloys, shape memory polymers, electroactive polymers and gels, dielectric elastomers, photoresponsive polymers, piezoelectric polymers, magnetoactive polymers, self-healing polymers, hydrogels, biogels. Some of these smart materials have already been used for diagnostics and therapy purposes such as biosensors based on hydrogels in conjunction with different fluorescent labels or fluorescent nanoparticles. Others are still under explored.

The smart materials used in optics or at least in optics related devices are the optical fibers, a very suitable delivery system due to its small diameter, flexibility and less resistance to movement. However, the dimension that really makes the optical fibers devices more precise is the fact that they allow delivery of quite narrow and high flux laser beam or very low diameter optical waves allowing different optical fields to propagate along the fiber. Apart from optical fibers, Biopolymers have always played an important role in medicine and they found usability in drug delivery system too but they also found it in optics. Nanostructures and Nanostructured surfaces present a role in many applications in medicine ranging from diagnostics to therapy. The growing interest in Biopolymer Nanosturctured surfaces for protein immobilization. The light, shape and size supported and the biocompatibility presents the Quantum Dots Sensitivity. These materials are also used in the new directions, like Nanomedicine, an emerging field of biomedicine that uses Nanoparticles to develop new devices for diagnosis, treatment and therapy of diverse diseases including cancer [234, 235, 236, 237].

Optical fibers, biopolymers, and nanostructures

Smart materials and technologies are increasingly used in diagnostics and therapy to enable new diagnostic tools, integrate sensors with therapeutic targets, or provide patient-tailored solutions that assure efficacy and safety in treatment delivery, responses, and healing. In addition to the common chemical stimuli and electrical fields, smart optical techniques have emerged as alternative sensing or actuating strategies. Such sensing signals interact directly with light, e.g. fluorescence signal from the device or sudden absorption from the target area or nearby. Light constitutes a non-invasive way to monitor such sensing sites. In a broader context, the used optical fibres in the devices play an important role, due to their increasing penetration in passive or active medical applications.

Optical fibres are becoming omnipresent components in many active devices, serving either for signal transport or as sensors themselves. Optical biosensors represent a direct way to complement treatment by monitoring the efficacy or stress in specific tissues. Moreover, optical biosensors are being used for non-invasive monitoring of glucose concentration, SpO2 level, cardiac activity, and other relevant parameters. Recently, biopolymers have emerged as a promising material for manufacturing hyposensitive contact lenses that offer the advantage of containing nanocomposite additives as optical-fibres-biorefringent probes. Furthermore, nanostructures have been extensively applied in medical devices for purposes like imaging, therapy, and drug delivery. Surface nanostructures in plastic substrates are also receiving special attention due to their incorporation into contact lenses [238, 239, 240, 238, 239, 240, 241].

Surface modification and biocompatibility

The efficacy and safety of biodevices in therapeutic human or animal applications depend not only on the material selection but also on surface modification. Smart polymers, nanostructures and metallic coatings can provide sensory, actuation and monitoring capabilities in the absence of electronic components. Optical fibers support minimally invasive optical sensing/actuation and monitoring. Biopolymer preparation methods such as 3D printing enable the tailored fabrication of scaffolds for cell growth and tissue engineering. Surface modification/functionalization methods not only enhance the attachment and morphology of the active-cell layer but also increase biocompatibility for the free surface exposed to the physiological media. These processes are essential for the development of implantable or wearable biodevices with full functionality.

Implantable smart biodegradable biodevices can monitor patency and free-of-signal-resonance-coupling conditions by coupling with a surface-coated optical fiber. Optical biosensors with supported nanostructures can serve as blood glucose, blood cholesterol and respiratory rate sensors. Smart and nanostructured surfaces, coatings and substrates enable the integration of self-capacitance signal-transmission-resonance-sensing and actuation functions involved in human-living-system information transfer and control. Biologically-compatible two-or-three-dimensional optical structures made of biopolymers enable plant growth, living-layer formation, tissue-engineering, and biosupport-structure purposes.

Case studies in implantable and wearable optics

Two case studies illustrate the successful integration of novel optical components within implants (PKA) and wearable devices (H-antiCOVID). Surgical implantation of a PKA-mounted optical spectrometer (near-infrared range) provided access for *in vivo* studies of brain metabolites with a resolution of 8 mm3. An

H-antiCOVID device monitored antibodies and compensated for variations in tear volume, pH, and ambient temperature. Intensities at the two wavelengths were simultaneously detected, enabling the derivation of two independent signals. Both devices offered practical solutions to defined problems using new materials and concepts, while optics and biophysics ensured satisfactory flexibility, weight, and biocompatibility with *in vivo* conditions.

Novel optical components based on smart materials can improve implanted and wearable devices for medical monitoring and therapy. Such materials can respond to specific stimuli in their environment by modifying optical signals, which can be captured external to the body. Two case studies illustrate the successful integration of original materials and concepts in new optical devices: a portable optical probe for *in vivo* metabolite studies implanted on the skull of a rat and a contactless device for monitoring anti-SARS-CoV-2 antibodies in human tears [242, 243, 244, 231].

Chapter - 14

Artificial Intelligence and Computational Modeling

Artificial intelligence (AI) integrates diverse computing paradigms including machine learning (ML), deep learning (DL), computer vision, natural language processing (NLP), expert systems, and intelligent agents. AI finds applications in healthcare imaging, diagnosis, and therapy optimization. Imaging techniques produce data that provide valuable training material for DL algorithms. Functional and quantitative aspects of biological systems enable physics-based modeling that generates digital twins for simulation-based optimization of laser-tissue interactions, diagnosis, and therapy workflows. However, responsible data use and governance, algorithmic accountability, and ethical considerations remain imperative. Current standards only touch on specific aspects and do not engender sufficient confidence. The health sector recognizes the need for human-centric systems and has enshrined ethical principles in careful industrial and commercial development.

AI-based processes in healthcare can be categorized as supervised, unsupervised, or reinforcement learning, depending on the learning methodology, authenticity, and quality of training material, and data preparation, and users can exercise respective levels of control over training. Notably, training sets are often biased or incomplete, making network recommendations especially dangerous when interpreting rare or unexplored events. Such shortcomings can be overcome in photonic applications by using the physics-based model as a twin that relates all factors involved in diagnosis or therapy and provides valid generalization without human bias. As a result, photonic AI for optics, optics-based imaging, and imaging-assisted therapy functions based on raw optical data from DL networks. Generalizing the fabricated model facilitates the simulation of novel or difficult-to-perform events, such as experimentally validating laser parameters during skin cancer therapy with temperature feedback integrated using bulk detection and diagnosing an FDA-approved drug based on Raman spectroscopic data not routinely acquired in hair dye product analysis [245, 246, 247].

AI in imaging, diagnosis, and therapy optimization

The integration of clinical discovery and medical device engineering with the latest developments in artificial intelligence plays a pivotal role in contemporary healthcare systems. AI technologies are now applied at every stage of clinical processes, including data acquisition and collection, disease detection and diagnosis, treatment selection and planning, therapy outcome prediction, and clinical outcome prediction. Machine Learning (ML) methods are also gaining major interest and being actively tested in the field of predictive diagnostics, particularly in prediction-of-risk assessments, as they may greatly impact applied healthcare delivery and associated healthcare costs.

Artificial Intelligence is becoming an increasingly important tool in the medical field. Artificial-intelligence-driven devices capable of detecting disease and guiding diagnosis and treatment are gaining interest. Optical technologies for rapid data acquisition incorporated with AI-based imaging detection and diagnostic-predictive advice are also being developed and tested. AI methods in combining hybrid imaging systems with multimodal data acquisition supporting optimized imaging diagnostics can now also be found in the literature. In the context of therapy, ML can assist in predicting the future response to the treatment administered or likely outcome of the performed intervention, as well as in the selection of the appropriate therapy patients to be treated with a specific active agent. The role of AI in imaging and related on-site diagnostic-predictive support in the operating room also demonstrates how AI must guide real needs for clinically effective development without generating impractical-of-use systems [38, 248, 249, 250].

Physics-based modeling of laser-tissue interaction

For tailored photonic medical treatments, predictive models for laser-tissue interactions have been developed, based on coupled multiphysics equations and machine-learning algorithms. These are oriented to study the different physical processes underlying laser surgery and photodynamic therapy, disease diagnostics through optical coherence tomography and Raman spectroscopy, and hyperthermia and phototherapy for cancer treatment. Several AI-based applications of the modeling results are also being explored.

Smart technologies are playing an increasing role in diagnosis and therapy. In the field of photonics-based medicine, applications include diagnostics and therapy supported by computational modeling using the physics of laser-tissue interaction, followed by the creation of a machine-learning database oriented toward predictive healthcare approaches. Two main classes of predictive modeling are being investigated. The first is based on coupled multiphysics equations dealing with Fourier-transformed-microwave-temperature mappings using infrared-centered monochromatic optical sensory signals for epilation and facedetection in dermatological applications, and using the physics of hydrodynamics and the heat equation for nontechnical applications of laser-induced-plasma channeling in air. A second predictive approach explores the use of physics-based laser-tissue interaction modeling for photonics-based detection and treatment in a variety of diseases (diagnostics through optical coherence tomography and Raman spectroscopy; surgery for ophthalmologic, ENT, and neurosurgical diseases; therapeutics supported by hyperthermia and/or phototherapy approaches) [251, 252, 253, 254].

Digital twins and virtual patient simulation

Digital twin technology represents the next stage of the information revolution, whereby a physical object is effectively mirrored in the virtual world, linking the physical and virtual through a continuous flow of information. Digital twins of patients can be created from vast tomographic, histological and laboratory data gathered on each patient. They will consequently be patients' information densities but organized in a way that true-to-life prediction of appropriate diagnosis and therapy can be realised.

For successful and safe therapeutic application of lasers, light and related technologies, physiology-and-physics-based models and simulations of the light-tissue interaction process are indispensable; and becoming increasingly feasible due to their regular availability in the last two decades. Such simulations enable creation of digital twins and virtual patients towards efficient and reliable planning of laser use all the way from experimentation, through clinical pilot tests, to routine clinical application. With extensive and verified models of the disease processes, demonstrated feasibility of all kinds of treatments, and digital twins of the patients, automated artificial-intelligence-driven selection of the most appropriate treatment will become possible [255, 256, 251, 257].

Ethics and data governance in AI-driven healthcare

Data and AI-related technology developments have been rapid and disruptive, and healthcare and biomedical applications are among important areas of deployment. Medical data require protection due to the rule of biomedical ethics to “do no harm”. In addition to security measures to protect data from violation, it is important to make decisions regarding data management. The government should outline general guidelines for AI planning and development. Healthcare providers use data within their own hospitals for scattering analysis, but external data use for AI learning needs to be planned and regulated for research and development. Digitalization helps to generate large quantities of various healthcare-related data. How to take advantage of this data for AI and machine learning-related research and development is a hot topic of research. AI is a tool that can change how one solves problems.

In the area of data privacy, personal health information needs special handling. Data encryption and protection from hacking is a critical issue. Data governance should develop a policy for data preservation and data support through an aggregated data organization to accelerate research and development by making data publicly available. AI requires expert knowledge in both programming and target domain. Special education is useful for practical applications. When using AI to perform practical work (such as reading images, information extraction, or clinical administration), the users should be experts in the field so that they can evaluate the results and consequences. AI should be designed as a support tool to help experts work efficiently [258, 259, 260, 261].

Chapter - 15

Future Horizons and Translational Pathways

Integration of Medical Physics, Optics and Laser, and Medical Device Engineering: Concepts and Applications in Modern Diagnosis and Therapy

Physics-based principles of medical diagnosis and therapy MUST integrate knowledge of medical physics, optical/laser technologies, and medical device engineering for successful development and clinical implementation. In the patient care pathway, radiological imaging systems provide imaging information on the disease status (safety, efficacy), while detection of the disease in its earliest stage can minimize the required treatment intervention. Minimally invasive techniques are generally preferred to reduce trauma, bleeding, pain, recovery time, and other patient problems, thus improving the overall precision of medicine. Translational research integrates clinical and engineering sciences to bridge the gap between bench and bedside. Therefore, basic and applied research should go hand in hand to nurture students capable of contributing as scientists, engineers, or clinicians in the area of their interest.

Within the computational horizon, emerging areas such as quantum imaging, optogenetics, photonic therapies, miniaturized sensing and imaging devices, and nanotechnology for enhanced diagnostics or therapeutics are rapidly growing, opening up new opportunities for future researchers. For research and development to have a complete healthcare impact, required attempts must be undertaken along with the industry. Regular meeting with industries, pharmaceutical companies, and medical professionals will create awareness about the latest technological developments in the area of interest, guiding research in the direction of market need. Finally, reduction of health disparity is vital for global consciousness and requires implementation of new technologies at an affordable price in all parts of the world [262, 263, 264, 265].

Convergence of physics, optics, and engineering in precision medicine

The integration of expertise across medical physics, optics/laser technologies, and medical device engineering has become indispensable for developing innovative approaches in modern diagnosis and therapy. Several novel techniques and systems address evolving needs in precision medicine, relying on the fusion of optical and radiation-based imaging/sensing systems, advanced prosthetics/implants, and combination therapies.

The convergence of physics, optics, and engineering offers novel solutions for various clinical applications. Quantum imaging tools enhance detection capabilities in ophthalmology, photonic stimulation systems enable spatiotemporally accurate modulation of biological processes, and hybrid optical-radiation surgical/therapeutic devices allow multiple interactions with tissues for safer and more effective procedures. Furthermore, artificial-intelligence-driven modeling and data preparation enhance conventional imaging techniques, enable relevant pathology ontology databases, and facilitate therapy planning and optimization [5, 266, 267, 268].

Emerging areas: quantum imaging, optogenetics, photonics in therapy

Integration of Medical Physics, Optics and Laser, and

Medical Device Engineering Integration of Medical Physics, Optics and Laser, and Medical Device Engineering: Concepts and Applications in Modern Diagnosis and Therapy Integration of Medical Physics, Optics and Laser, and Medical Device Engineering: Concepts and Applications in Modern Diagnosis and Therapy Integration of Medical Physics, Optics and Laser, and Medical Device Engineering: Concepts and Applications in Modern Diagnosis and Therapy Emerging areas: quantum imaging, optogenetics, photonics in therapy Future Horizons and Translational Pathways Future Horizons and Translational Pathways Integration of Medical Physics, Optics and Laser, and Medical Device Engineering Emerging areas: quantum imaging, optogenetics, photonics in therapy Future Horizons and Translational Pathways Future Horizons and Translational Pathways Emerging areas: quantum imaging, optogenetics, photonics in therapy

Rapidly evolving fields such as quantum imaging, optogenetics, and photonics for therapy illustrate the present-day perspectives of modern medicine stemming from the collective knowledge of medical physics, optics, and medical device engineering. Quantum Imaging exploits quantum optical effects to achieve imaging standards not possible with conventional optical setups, including suppression of scintillation in X-ray imaging, overcoming illumination throughput limits in clinical endoscopy, sub-diffraction imaging, and penetration depth extension. Exploiting the advances in nanotechnology, precision medicine, photonic metrology, and nanomanipulation techniques enable not only controlled targeted therapy but also an active feedback by real-time imaging tools, successfully applied in the treatment of cancer and infectious diseases by means of photothermal and photodynamic therapy using single lasers as well as multimodal therapy concepts based on PTT/PDT/IRT numbering among the future research developments. Recent progress in optical data processing and communication increases not only the transfer rate but also the security of personal medical data.

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Translational research and industry collaboration

Translational research and collaboration with the medical technology industry play a critical role in meeting the challenges of modern healthcare. Cooperation between universities, research institutions, and industry is crucial for medical technology development. Translational research aims to manufacture innovative and clinically tested medical devices and procedures and make them available in medical settings.

Translational research is based on the scientific achievements of medical technology, advanced results, and potential innovations from various areas, including optical and high-energy radiation diagnostic and therapy techniques. The results from these efforts at laboratory or proof-of-concept levels are further developed within the domestic medical technology industry to become clinically usable systems and procedures. Close collaboration within the research value chain is thus fundamental for successful results [272, 273, 274, 275].

Outlook on global healthcare technology innovation

Integration of Medical Physics, Optics and Laser, and Medical Device Engineering: Concepts and Applications in Modern Diagnosis and Therapy Convergence of Medical Physics, Optics and Laser, and Medical Device Engineering: History, Contemporary Considerations, and Future Horizons

The integration of medical physics, optics and laser technologies, and medical device engineering offers exciting new convergence opportunities for modern healthcare. The fusion of distinct concepts enables innovations in diagnosis and therapy while assuring safety, efficacy, and regulatory compliance. Simultaneously spanning physics, engineering, and medicine allows mapping to the clinical workflow from research and development through preclinical studies and human applications.

The adoption of novel approaches for precision medicine in disease prevention, diagnosis, and treatment drives demand in healthcare technology. Convergence across disciplines is crucial in enabling these advances. Research and development in physics, optics/laser, and engineering are progressively merging—fostered by shared preclinical studies, external collaborations, and, especially in education, interdisciplinary student training.

The innovation needed for updated healthcare technology hinges upon the human resources cultivated through higher education. Academic institutions worldwide should promote exploration of the cutting-edge frontiers of science, technology, and engineering, encouraging students to develop sustainable solutions that extend human health and life. Collaborative multimodal research teams that embrace multidisciplinary backgrounds create a rich environment amenable to holistic, integrated investigation [276, 277, 278].

Conclusion

Integration of Medical Physics, Optics and Laser, and Medical Device Engineering: Concepts and Applications in Modern Diagnosis and Therapy

In the past, many diagnosis and therapy concepts originated from independent ideas and developments in physics, optics, and engineering. These domains have now merged to enable, drive, and directly influence precision medicine, and flow from the core of the patient's well-being. Innocence through physical principles and optical imaging/spectroscopy enabled state-of-the-art results in Information Science; the physics of optical and radiation laser-tissue interactions, along with pioneering materials and nanotechnology developments, continue to provide technologically advanced possibilities in therapeutic medicine applications; the introduction and boom of Internet of Things (IoT) and artificial intelligence (AI) technologies have also paved the way for breakthroughs in remote health monitoring and real-time diagnostics combined with plug-and-play devices for point-of-care use and early intervention of health issues.

Radiation technology and physics have not only enabled biomedical imaging but have also incorporated addition/combination-focused Optical Information into a wide range of imaging and therapeutic platforms, ensuring safer and enhanced results through Artificial Intelligence (AI)-assisted fusion technology. Integration of analysis concepts/driven instruments from the emerging fields of Flexible and Wearable Electronics into Optical Sensors has ensured live patient health Status Monitoring with online connectivity to hospitals, E-health centres, and physicians. AI was finally acted as a System and

Specialist for Safety and Efficiency of Imaging, Diagnosis, and Therapeutic Procedures.

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