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Review on Applications of Nanophotonics in Bioimaging and Biomedical Diagnosis

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Abstract: Optical sensors are increasingly used in healthcare biosensing and biomedical diagnostics due to their non-invasiveness and real-time monitoring capabilities. They can detect diseases, monitor vital signs, and analyze bodily fluids. Nanophotonics, involving physical processes like radiation-matter interaction and near-field optical microscopy, has revolutionized sensor technology by enabling high-resolution imaging and precise detection at the nanoscale. This opens up new possibilities in fields like biomedical research, environmental monitoring, and industrial quality control. In medicine, these nanostructures have led to advancements in imaging techniques like MRI and PET scans. In energy storage, photonic nanostructures have led to the development of compact and powerful batteries. As research continues, the possibilities for enhancing and optimizing photonics applications seem endless. This review looks into photonic nanostructures and their interactions, as well as nanoconfinement and applications. It emphasises the potential of optical sensors in disease prediction and testing.

Keywords: Optics; Nanoparticles; Bioimaging; Nanophotonics

I. INTRODUCTION

Biomedical imaging plays a crucial role in healthcare by providing non-invasive and detailed visualizations' of the human body. It enables healthcare professionals to accurately diagnose and monitor various medical conditions, leading to more effective treatment plans. Additionally, biomedical imaging aids in guiding surgical procedures and evaluating treatment outcomes, ultimately improving patient care and outcomes. Moreover, biomedical imaging also plays a significant role in research and development of new medical treatments and technologies. By allowing scientists and researchers to observe and study the internal structures and functions of the human body, it provides valuable insights into the mechanisms of diseases and the effects of experimental therapies. This knowledge can then be used to develop innovative diagnostic tools, drugs, and medical devices that can revolutionize healthcare practices. Without biomedical imaging, the progress in medical advancements would be severely hindered, as many breakthroughs rely on the ability to visualize and understand the intricacies of the human body.

Optics is the branch of physics that deals with the behavior and properties of light, including its interaction with matter (Field, 2011). Nanotechnology, on the other hand, involves manipulating and controlling matter at the nanoscale level, typically between 1 to 100 nanometers (Weiss et al., 2006). In the context of biomedical imaging, optics and nanotechnology are utilized to develop advanced imaging techniques and devices that can provide higher resolution and sensitivity for more accurate diagnoses and monitoring of diseases. These technologies have revolutionized the field of biomedical imaging, allowing for unprecedented visualization of cellular structures and processes. By combining the principles of optics and nanotechnology, scientists have been able to create imaging tools that can probe deeper into tissues, detect molecular changes, and even track the movement of individual cells in real-time (Zandonella, 2003; McNeil, 2005). This has opened up new possibilities for understanding disease mechanisms and developing targeted therapies.

Moreover, the integration of optics and nanotechnology has also led to the development of miniaturized imaging devices that can be used in point-of-care settings, bringing advanced imaging capabilities to remote and underserved areas. Overall, the synergy between optics and nanotechnology has propelled the field of biomedical imaging forward, revolutionizing our ability to visualize and study biological processes at a microscopic level (Sun et al., 2023). By harnessing the power of light and nanoscale materials, researchers and clinicians now have the tools to delve deep into the inner workings of living organisms, uncovering intricate details that were previously inaccessible. With continuous advancements in the field, the future holds promise for even more precise and personalized diagnostics, as well as targeted therapies tailored to individual patients.

The advancements of optics and nanotechnology in biomedical imaging lead to significant improvements in diagnostic accuracy and disease monitoring. By harnessing the power of optics and nanotechnology, researchers have been able to develop imaging techniques that can visualize cellular structures and molecular interactions with unprecedented detail. This has not only enhanced our understanding of diseases at the molecular level but also opened new avenues for targeted therapies and personalized medicine. Furthermore, the integration of optics and nanotechnology in biomedical imaging has revolutionized the field of drug delivery.

Nanoparticles can be engineered to carry therapeutic agents and precisely target cancer cells, minimizing side effects and increasing treatment effectiveness (Praetorius, & Mandal, 2007). Additionally, the use of optics in imaging has allowed for real-time monitoring of drug distribution within the body, enabling clinicians to optimize dosage and treatment regimens for individual patients. Overall, this review discusses the convergence of optics and nanotechnology in biomedical imaging and its tremendous potential in diagnosis and treatment.

II. OPTICS IN BIOMEDICAL IMAGING

Optics in biomedical imaging plays a crucial role in non-invasive diagnostics and treatment (fig 1). By harnessing the power of light, optical imaging techniques such as fluorescence and spectroscopy provide detailed information about tissue structure and function, aiding in early disease detection and accurate treatment planning (Mondal et al., 2014). Furthermore, the development of advanced optical imaging probes and contrast agents has revolutionized molecular imaging, allowing for precise targeting of specific biomarkers and facilitating personalized medicine approaches.

This non-invasive technique allows for the examination of cellular and molecular structures with high resolution, enabling researchers and clinicians to study diseases at a microscopic level. By utilizing various optical imaging techniques, such as optical coherence tomography and multiphoton microscopy (Ntziachristos, & Razansky, 2010), scientists can gain insights into cellular dynamics, tissue morphology, and even real-time physiological changes. This invaluable information aids in understanding disease progression, evaluating treatment efficacy, and developing new therapeutic strategies. Moreover, the non-invasive nature of these techniques minimizes patient discomfort and reduces the risk of complications, making them ideal for longitudinal studies and clinical applications (Gao, 2014). With further advancements in optical imaging technology, we can anticipate even more precise and detailed visualization of cellular and molecular processes, leading to improved diagnostics and personalized medicine approaches.

Optical imaging techniques offer cost-effectiveness, real-time imaging capability, and ease of implementation. They form images through photon absorption or scattering. Standard optical microscopes cast shadows, revealing transparency. Biomedical optical imaging approaches like fluorescence imaging and two-photon microscopy generate optical waves detected by optical sensors, resulting in bright pixel values.

Ellipsometry is a technique for studying thin-film dielectric properties by analysing the change in elliptical polarisation caused by transmission or reflection from the film surface (Damorsky et al., 2016). Because this technique is highly sensitive, it is best suited for small sample sizes. Ellipsometric biosensors have been studied for their ability to detect microorganisms, nucleic acids, proteins, and biomolecules. Nabok et al., (2019) for example, used total internal reflection ellipsometry (TYRE) in conjunction with LSPR to detect mycotoxins as low as 10 ppt. TYRE has also been used to detect human immunodeficiency virus, detect mycotoxin, and determine micromolar immunoglobulin levels. TYRE has also been investigated for bioimaging applications using AuNPs (Paiva et al., 2017). Ellipsometric techniques have recently been modified to study important biological processes such as protein adsorption, brain activity, and collagen susceptibility tensor imaging (Dow et al., 2016).

Raman scattering is a weak phenomenon that can be amplified by molecules close to the surface of nanostructured substrates. Surface-enhanced Raman scattering is an important mode of amplification (Das et al., 2017). Because the efficiency of the scattering signal depends on the geometrical properties of metallic nanoparticles, research in SERS-based diagnosis has focused on optimising nanostructured substrates (Pilot et al., 2019). SERS platforms, such as MNP-AuNP and MNP-AgNP assemblies, have been used for early-stage prostate cancer diagnosis. SERS-based genetic assays can perform bioimaging and cell differentiation and are four orders of magnitude more sensitive than PCR assays (Chaloupková et al., 2018). The infrared spectrum interacts with tissue, which is dominated by scattering, posing difficulties for optical imaging. Higher-energy portions of the electromagnetic spectrum are frequently absent in this interaction (Guhlke et al., 2016). Larger particles scatter light in all directions, whereas cell nuclei and mitochondria scatter light uniformly in all directions. In contrast, CT believes that a reading associated with a source-detector pair represents an absorption event along the straight line connecting the two. This assumption simplifies the process of reconstructing an unknown attenuation distribution function from its straight line integrals (Langelüddecke et al., 2015). Photon counts for any source-detector pair, on the other hand, are the result of numerous absorption and scattering events that occur across the medium. These functions from data determine the imaging problem, which can be complicated by anisotropic diffusivity. An anisotropic diffusivity is allowed in a more complete and realistic model, complicating the inversion problem even further.

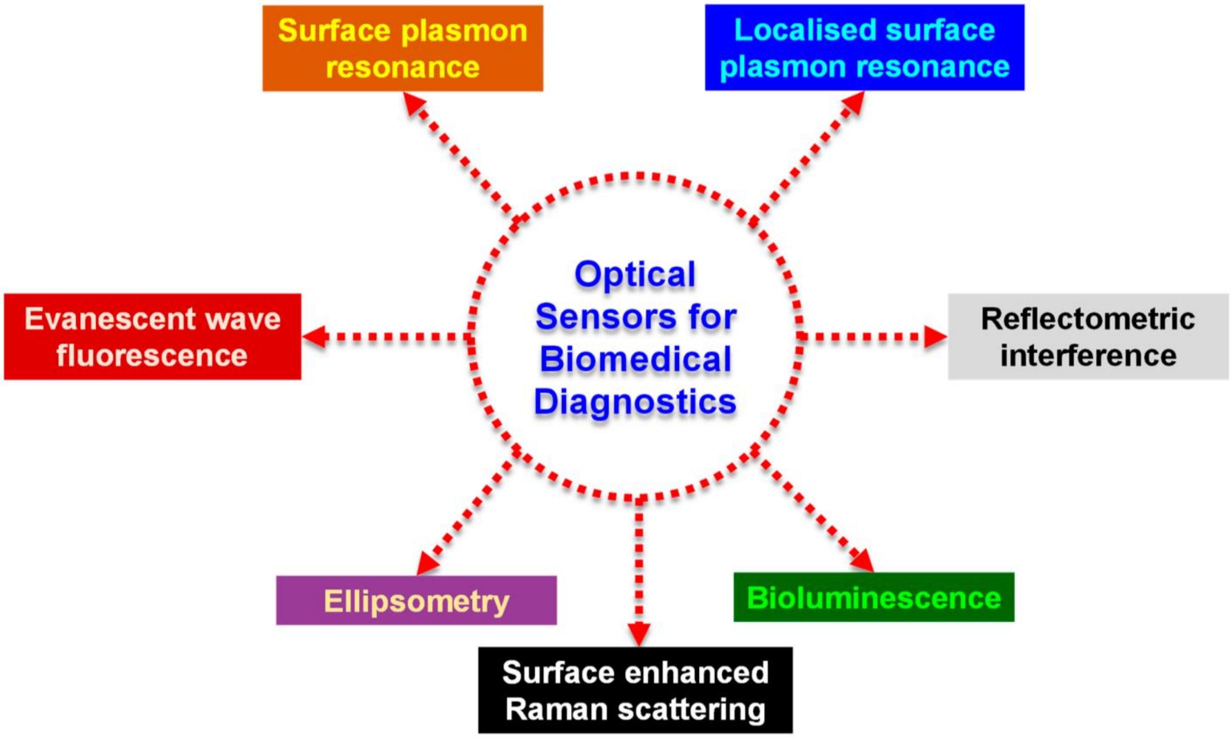

Fig 1: Optical sensors for biomedical applications (Source:

However, traditional optical imaging techniques have limitations in terms of penetration depth and imaging speed. Therefore, researchers are constantly exploring new advancements in the field to overcome these challenges and improve the accuracy and efficiency of disease diagnosis and monitoring. One promising approach is the development of non-invasive imaging techniques such as photoacoustic imaging and optical coherence tomography (Bertolotti et al., 2012). These techniques combine the advantages of optical imaging with other modalities, allowing for deeper tissue penetration and faster image acquisition. Additionally, the use of contrast agents and nanoparticles further enhances the sensitivity and specificity of these imaging methods, enabling more precise disease detection and monitoring.

Advancements in optics for improved resolution and depth perception in imaging have led to the development of novel techniques such as confocal microscopy and optical coherence tomography. These techniques provide higher resolution and deeper imaging capabilities, allowing for more precise evaluation of tissue structures and abnormalities. Additionally, researchers are also investigating the use of advanced imaging agents and contrast agents to enhance the visibility of specific cellular or molecular targets, enabling targeted treatments with higher efficacy.

Fluorescence in biomedical imaging:

Fluorescence microscopes are a common choice because of their propensity to offer rich details regarding photochemical reactions. Optical imaging is a widely used visualisation mode during research and laboratory diagnosis. Due to the development of new fluorescent dyes and nanomaterials, as well as the accessibility of a wide variety of probes, fluorescence microscopes are becoming more common (Yao et al., 2014). Additionally, they are used to image at the macroscopic level, providing more accurate data because the images are obtained while the subjects are still alive. The production of significant autofluorescence from the animal tissue and the requirement for a particular fluorescent probe that offers adequate contrast are obstacles to in vivo imaging, though (Del Rosal, & Benayas, 2018).

A chemical entity that has been stimulated and retained its spin multiplicity exhibits fluorescence, a photophysical phenomenon, as a result of light scattering and absorption. It is a kind of luminescence that is classified as photoluminescence, a term that is an expansive term for any light-emitting photophysical phenomena involving the emission of radiation from an electrically or vibrationally excited species that are not in thermal equilibrium with their environment. An essential component of biological imaging is fluorescence.

When a molecule absorbs a photon, an electron moves to a higher electronic state, which results in the process known as fluorescence. Since it is not in thermal equilibrium with other molecules, this excited state is transient (Amorim et al., 2000). By generating a light photon known as fluorescence, the molecule subsequently releases its tension and returns to its ground state. Sir George Gabriel Stokes coined the term "fluorescence" for the first time in 1853. Stokes' law states that vibrational relaxation causes the fluorescence spectrum to always be at a wavelength that is longer than the excitation wavelength. The Stokes shift is the distance between the first excitation or absorption band and the emission band. Inserting an exogenous gene into a sample to make fluorescent protein or giving a fluorescent probe involves fluorescent-based optical imaging (Valeur, & Berberan-Santos, 2012).

When used in biological imaging, fluorescent probes offer a rich and effective means to visualise cellular function, the therapeutic effects of drugs, the effects of gene therapy, and the monitoring of biomolecular processes. They fall into two groups: direct imaging, which makes use of optical probes based on fluorophores, and indirect imaging, which makes use of transgenes or reporter genes to generate fluorescence-producing proteins. While indirect imaging studies protein activity and expression through genetic encoding, direct imaging uses immunolabelling to tag proteins.

III. NANOTECHNOLOGY IN BIOMEDICAL IMAGING

Nanotechnology refers to the manipulation and control of matter at the nanoscale, typically ranging from 1 to 100 nanometers (Guidance, 2011). In the field of biomedical imaging, nanotechnology has revolutionized the way we visualize and study diseases. By harnessing the unique properties of nanoparticles, such as their small size and large surface area-to-volume ratio, researchers have been able to develop highly efficient and versatile imaging probes. These nanoprobes can be engineered to target specific biomarkers on diseased tissues, allowing for early detection and accurate diagnosis.

Additionally, nanotechnology has enabled the development of advanced imaging techniques, such as nanoparticle-based contrast agents and nanosensors, which provide real-time monitoring of disease progression and response to treatment (Veiseh et al., 2015). Nanotechnology has revolutionized biomedical imaging by enabling the development of smaller and more sensitive imaging probes. These nanoprobes can be designed to specifically target certain biomarkers, providing highly specific and accurate imaging of diseased tissues. Furthermore, nanotechnology allows for the development of multifunctional imaging platforms that can simultaneously detect multiple targets, leading to a more comprehensive understanding of disease progression and response to treatment.

MRI, CT, US, SPECT, and PET are commonly used for detecting lesions, but their resolution remains macroscopic (Han et al., 2019). Fluorescence imaging technology, particularly near-infrared fluorescence (NIRF) imaging, provides the highest spatial resolution for disease diagnosis at the microscopic level. NIRF, on the other hand, has limitations such as deeper tissue penetration and less non-specific tissue autofluorescence. This reduces penetration depth and may result in low sensitivity for detecting abnormalities (Zhang et al., 2022). By loading more fluorescent dye molecules, preventing quenching of NIR fluorescence, and employing active and passive strategies to increase nanoparticle concentrations in lesions, nanoparticles can overcome these limitations. The extended time in circulation also allows for greater uptake in target lesions. Furthermore, nanoparticles can convert lower energy photons to higher energy photons, reducing the effects of blinking and photobleaching. Overall, nanoparticles have the potential to improve the resolution and sensitivity of lesion detection (Khemthongcharoen et al., 2014).

Additionally, nanotechnology has enabled the development of advanced imaging techniques, such as nanoparticle-based contrast agents and nanosensors, which provide real-time monitoring of disease progression and response to treatment. These advancements in biomedical imaging have greatly improved our understanding of diseases and have the potential to revolutionize personalized medicine.

Discussion on the use of nanoparticles in targeted imaging and drug delivery has gained significant attention in recent years. By attaching targeting ligands to the surface of nanoparticles, scientists can ensure that the nanoprobes selectively bind to specific cells or tissues, enhancing the accuracy and sensitivity of imaging techniques. Additionally, nanoparticles can also be loaded with therapeutic agents, allowing for targeted drug delivery directly to diseased areas while minimizing side effects on healthy tissues.

Advancements in nanotechnology for enhanced sensitivity and specificity in imaging have revolutionized the field of medical diagnostics. These nanoprobes can detect even the smallest abnormalities, providing early detection and precise monitoring of diseases such as cancer. Furthermore, the ability to precisely deliver therapeutic agents to diseased areas holds great potential for personalized medicine, as it allows for tailored treatments based on individual patient needs. Nanotechnology has also enabled the development of targeted drug delivery systems, which can deliver medications directly to affected cells or tissues, minimizing side effects and improving treatment outcomes. Additionally, nanoprobes can be used in combination with other imaging techniques, such as magnetic resonance imaging (MRI) or positron emission tomography (PET), to provide a more comprehensive and accurate diagnosis (Choi et al, 2008). Furthermore, nanotechnology has the potential to revolutionize cancer treatment by enhancing the effectiveness of chemotherapy. By encapsulating chemotherapy drugs within nanoparticles, these medications can specifically target cancer cells while sparing healthy cells, resulting in more efficient and less toxic treatments (Wang et al., 2008).

Moreover, nanotechnology can also play a crucial role in regenerative medicine, as it allows for the fabrication of artificial tissues or organs at the nanoscale, offering hope for patients awaiting organ transplants. Overall, the advancements in nanotechnology have paved the way for personalized medicine and improved patient outcomes in various medical fields.

IV. INTEGRATION OF OPTICS AND NANOTECHNOLOGY

Optical nanoparticles (NPs) are commonly used in low-tech items like sunscreen creams and optical coatings due to their tuned properties. Manipulation of these nanostructures is an intriguing future innovation. Despite high-tech industrial solutions like sensors, photonic crystals are still used in signal processing and optical circuitry. Currently, the most widely used optical nanomaterial applications are in low-tech products. Advanced solar cells based on NPs could lead to profitable businesses, but they are in the early stages of development. The atomic trap technology focuses on the use of tailored light to trap atoms in materials raised by evanescent fields in photonic waveguides (Bouscal et al., 2023). This technology is essential for ultra-cold atoms used in quantum devices. Evanescent fields, responsible for optical lattices and atomic trapping, can be used in optical fiber and waveguides. The dense lattice with nanoscale atomic trapping allows for atomic and photonic interactions. Waveguides can be integrated with other components for atomic properties, such as detections, manipulations, and single photon operations.

Integrated waveguides offer inherent properties that are not achievable through other atom-trapping methods. They allow for subwavelength-scale separation between adjacent traps and the design of curved structures, which is not possible with optical lattices or magnetic trapping. Atoms are trapped using evanescent, homogeneous light fields, eliminating fragmentation or reduced lifetime caused by technical noise from current sources.

A proposed platform for collective interaction between cold atoms and light utilizes a nano-waveguide composed of a silicon nitride core that utilizes evanescent field coupling with mirrors. Bi-chromatic evanescent field atom traps secure atoms at a minimal distance of 150 nm above the waveguide. Another system uses a silicon nitride ridge waveguide with a nano-antenna on top to trap atoms using an all-dielectric device (Karabchevsky et al., 2020).

Optical nanostructures have shown potential applications in optical communication, light-activated therapies, and optical diagnostics. One example of the integration of optics and nanotechnology in biomedical imaging is the development of nanoparticle-based contrast agents. These contrast agents, when combined with optical imaging techniques, can enhance the visualization of specific tissues or cellular structures, improving diagnostic accuracy. Additionally, the use of nanotechnology in combination with optics has also led to the development of advanced imaging modalities such as super-resolution microscopy, which allows for detailed imaging at the nanoscale level.

Exploration of how optics and nanotechnology can be combined for improved imaging techniques continues to be an active area of research. By harnessing the unique properties of nanoparticles, such as their ability to emit or scatter light, researchers are able to design novel imaging probes that can provide even greater sensitivity and specificity. These advancements hold great promise for the future of medical imaging, enabling earlier and more accurate diagnosis of diseases.

Discussion on the development of hybrid imaging modalities is also gaining momentum. By combining multiple imaging techniques, such as positron emission tomography (PET) and magnetic resonance imaging (MRI), researchers aim to overcome the limitations of individual modalities and provide a more comprehensive view of the human body. This integration of different imaging modalities has the potential to revolutionize diagnostics and treatment planning in various medical fields.

Understanding how drugs interact with cells is critical for personalised disease management. Nanophotonics employs optical techniques to map drug absorption, define cellular function, and predict future cytosolic interactions. This improves the utility of optical probe-based biosensing, bioimaging, and single-cell biofunction research (Huang et al., 2021). Light-guided and light-activated therapies have greatly improved molecular disease detection in nanomedicine. To guide nanoparticles to diseased tissues or cells for targeted drug administration in real-time drug efficiency monitoring, modern nanoparticle processing technologies necessitate sophisticated carrier groups, optical probes, and light-activated therapeutics (Fig 2).

Examples of successful integration of optics and nanotechnology:

In biomedical imaging include the development of nanoparticle-based contrast agents for enhanced imaging of tumors and the use of optical coherence tomography (OCT) combined with nanoparticles for improved visualization of blood vessels. These advancements have paved the way for more precise and targeted interventions, ultimately leading to better patient outcomes. As researchers continue to explore the possibilities of integrating optics and nanotechnology in biomedical imaging, we can expect further breakthroughs in disease detection and monitoring.

The antibacterial and anticancer activities of optical nanoparticles (NPs) synthesised with plant extracts were investigated (Malik et al., 2022). The nanoparticles inhibited active bacterial and cancer cell lines, demonstrating their biomedical potential. NPs disrupted the cell walls and membranes of active bacteria, resulting in bacterial death and reactive oxygen species. Similarly, NPs altered the DNA structure of cancer cell lines, causing apoptosis. The most recent research looks at advances in image sensing using nanostructured materials, as well as the integration of nanofabrication and technology development on both traditional and modern platforms. Photonic nanostructures, with proper manipulation and regulation of size and shape, have the potential to explore novel applications in innovative science and technology in the future.

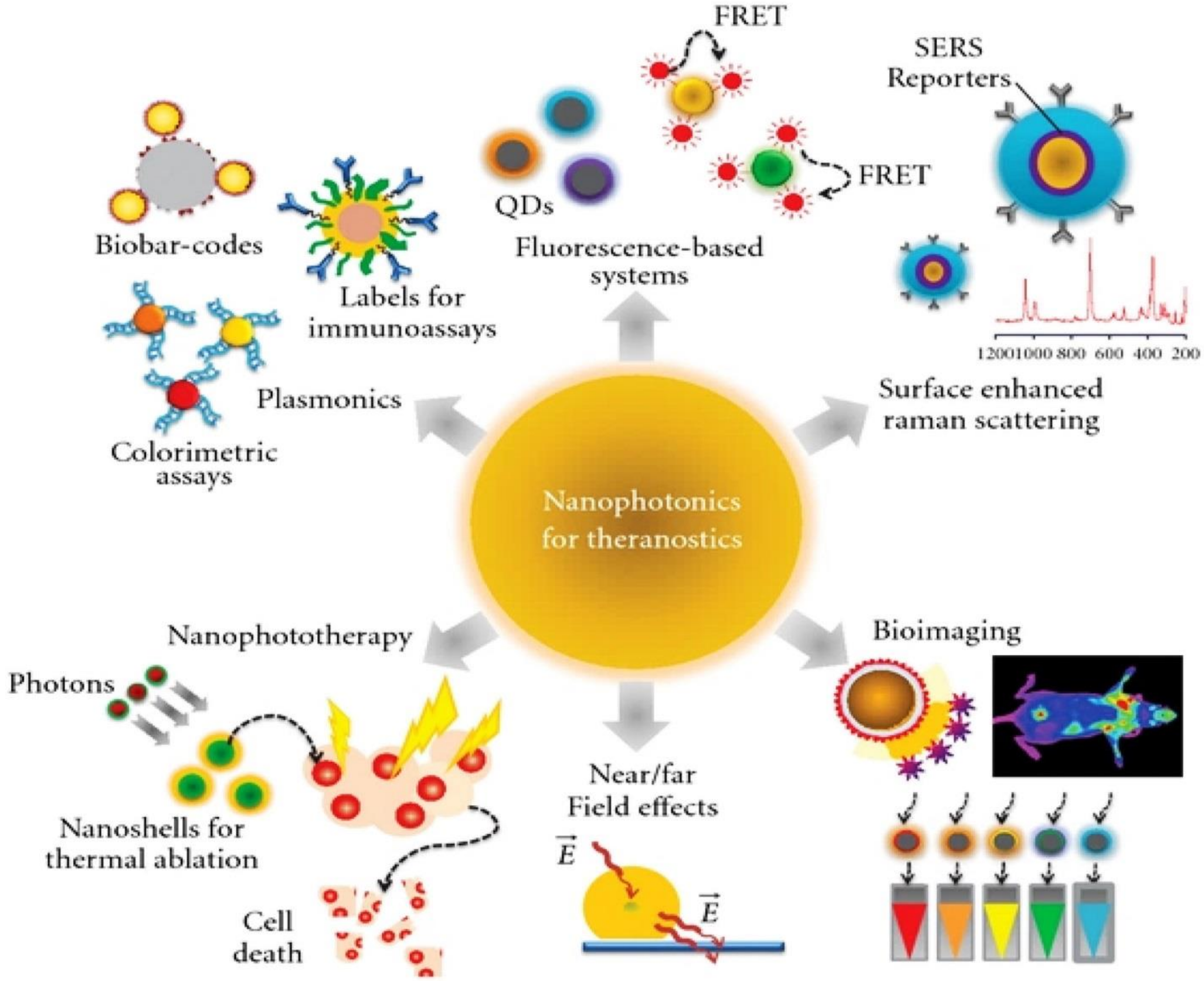

Fig 2: Applications of nano-optics in biomedicine (Source: Conde et al., 2012)

V. BENEFITS AND FUTURE IMPLICATIONS

One major benefit of integrating optics and nanotechnology in biomedical imaging is the ability to detect diseases at an earlier stage, when they are more treatable. This can potentially save lives and reduce the need for invasive procedures. Additionally, the use of nanoparticles in conjunction with optical coherence tomography can provide real-time monitoring of treatment effectiveness, allowing for personalized and adaptive therapies. As technology continues to advance, we can anticipate even more precise and non-invasive imaging techniques that will revolutionize the field of medicine.

Overview of the benefits of advancements in optics and nanotechnology in biomedical imaging

Advancements in optics and nanotechnology have significantly improved biomedical imaging by offering numerous benefits. Firstly, these advancements have enabled the development of high-resolution imaging techniques, allowing for the detection of diseases at their earliest stages. This early detection can greatly increase the chances of successful treatment and improve patient outcomes.

Moreover, these technologies have also facilitated the development of minimally invasive procedures, reducing patient discomfort and recovery time. Additionally, the use of nanoparticles in conjunction with optical coherence tomography provides real-time monitoring of treatment effectiveness

VI.CONCLUSION

The imaging techniques and their benefits are crucial in the medical field. By understanding the advancements and capabilities of these technologies, healthcare professionals can make informed decisions about patient care and treatment plans. Because of scientific curiosity and societal demand for energy-efficient, compact technologies, nanophotonics has a bright future. Market-driven innovations will create economic opportunities, but their relative youth will have a significant impact on the development of new technologies. Additionally, ongoing research and development in this area are continuously improving the accuracy and efficiency of these imaging techniques, further enhancing their impact on disease detection and treatment. The use of imaging techniques in the medical field has revolutionized the way diseases are detected and treated. From X-rays and CT scans to MRI and PET scans, these technologies allow healthcare professionals to visualize and analyze internal structures and functions of the body. This not only aids in accurate diagnosis but also helps in determining the most effective treatment options for patients. Furthermore, the non-invasive nature of these imaging techniques minimizes patient discomfort and reduces the risks associated with invasive procedures. Overall, the advancements in imaging technologies have greatly contributed to the improvement of patient outcomes and the overall quality of healthcare.

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