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Nanotechnology in Medical Physics: Innovations and Applications

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Annotation: Nanotechnology is assertively presented as a transformative force in modern medicine, being considered revolutionary and innovative in terms of therapeutics, diagnostics, and imaging. The many commercial applications of nanotechnology to develop medical applications boasting nearly infinite prospective benefits can lead to pollution and risky exposures. This development emphasizes the other side of the coin inherent to revolutions and new technologies. Fundamental insights and existing boundaries that necessarily slow the speedy evolution of a research field are beyond initial enthusiasts of the revolution. Possible ethical, social, economic, and environmental challenges as barriers are discussed regarding the new revolution in nanobiotechnology, which still engenders a profusion of publications and public funding devoted to biomedical matters. The explicitly essay objectives are (i) to overview the key applications and implications of nanotechnology for medical purposes and (ii) to discuss extant and emerging disputes concerning this ongoing revolution in medicine and other bio-related activities, with a special emphasis on smart and multifunctional nanoparticles. Five years ago. This investigational work prompted an extended and vibrant debate that provided an open forum on the barriers to the flourishing and recommended investments in nanoscience and nanotechnology. Hampering the steadily incorporation of nanotechnologies has been a high priority for several countries ever since.

Keywords: Nanotechnology in Medical Physics, Innovative Applications of Nanomedicine, Nanoparticles and Diagnostics, Radiation Therapy and Nanomaterials, Medical Imaging and Nanotechnology.

1. Introduction to Nanotechnology and Medical Physics

The very small often exhibit unique and novel properties that cannot be displayed by their bulk counterparts. At dimensions on the order of a few nanometers, the different potential energy levels become tightly packed close together. These quantized energy levels manifest as a corresponding increase in energy bandgap relative to the material's bulk form. Many exciting developments have occurred across the scientific disciplines that characterise, produce, and apply the very small. This includes breakthrough technology in nanofabrication, which enables the ability to manufacture materials at the nanoscale – allowing unique and novel properties to be exploited. Researchers from around the world are working together to study the unique material properties in this very small scale. This research has blossomed into what we now know as nanotechnology - a promising scientific discipline with the ability to revolutionise medical diagnoses, treatments and technologies. [1][2][3][4]

In turn, a considerable amount of research money has flowed into this burgeoning field - resulting in innovative solutions and patented technologies for such applications. The convergence of medical physics and nanotechnology has fostered many innovative diagnostic and therapeutic techniques and equipment [5]. The application of the very small to medicine is termed "Nanomedicine", which exploits quantum mechanical and biological phenomena at the nanoscale by applying an array of emerging techniques and materials. Leading advances include gold nanoparticles uptaken in tumorous regions enhancing images for better visibility under various imaging procedures and the synthesis of nanosized materials for drug delivery. Broad collaborations between physicists, biologists, chemists, and medical doctors have shaped these pioneering approaches by conducting multidisciplinary experiments in understanding the findings. It is anticipated that, in the near future, more revolutionary nanotechnologies will be developed with the potential to profoundly affect the diagnosis and treatment of diseases. This emerging multidisciplinary field of Nanotechnology in Medical Physics services as a driving force to unite both medical and physical properties in treating fatal diseases, which encompass a varied assortment of novel and state-of-the-art studies and progress [6]. [7][2][8][9]

2. Fundamental Concepts in Nanotechnology

Nanotechnology is the science, engineering, and industry of tiny things; it is the ability to manipulate and control matter at the atomic or subatomic scale. A nanometer is a unit of measurement that is small, very small; a nanometer is a million times smaller than one millimeter. To give a perspective of how small that is, a sheet of newspaper is about 100,000 nm thick. Nanotechnology deals with materials and structures with a size range on the order of a nanometer. At the nanoscale, materials can exhibit unique physical, chemical, and biological properties, which can be tuned to obtain specific properties for different applications. For example, due to quantum effects, nanomaterials can exhibit different magnetic, optical, electrical, and mechanical properties compared to their bulk counterparts. Another key feature is the significant increase in the surface area to volume ratio of nanomaterials, which makes them ideal for absorption, reactions, or other interactions with other materials, surrounding environment, and biological systems. There are many different types of nanomaterials and ways to manipulate them, leading to an almost infinite variety of potential applications. Nanoparticles, such as quantum dots, metal nanoparticles, protein cages, and fullerenes, are often used for drug delivery or as imaging agents for both diagnostics and therapy. Nanowires and nanotubes are a class of materials that can be fabricated into a variety of nanoscale devices with applications in electronics, optoelectronics, sensors, and drug delivery to name a few. Other types of nanomaterial include superlattices, nanobelts, nanodots, nanofoams, and nanolayers. Common to all is a relatively high aspect ratio between the longest and shortest dimensions, leading to unique qualities attributed to this geometry. A wide variety of fabrication techniques are used to produce nanoscale structures, including top-down processes such as photolithography, etching, grinding, and coating, and bottom-up processes such as self-assembly, covalent synthesis, and atomic layer deposition. Often, combinations of these are employed to achieve the desired material properties and device characteristics [5]. It is the unique characteristics of nanoscale materials that increasingly excite scientists, engineers, and clinicians in a diverse range of fields, and which is expected to drive innovations with a massive impact on medicine and the wider world similar to that of biotechnology. [10][11][12][13][14]

Materials and Methods

3. Fundamental Concepts in Medical Physics

The fundamental principles of medical physics concerning with the interactions and applications of ionizing and non-ionizing radiation are outlined. Such interactions with matter form the core principle for the efficacy and safety of applications in the diagnosis and treatment of health for ionizing radiation and for imaging techniques and devices based on ionizing radiation in particular. In addition an overview of fundamental principles of safety considerations, properties of ionizing radiation, imaging techniques in daily clinical usage and recent technological developments, dose delivery via radiation therapy and properties and applications of non-ionizing radiation (NIR) that are widely used nowadays in medical applications are given. The measurements and calibrations of the radiation doses, on which safety in terms of the patients is heavily depending, are explained briefly in the following. [15][16][17]

Nutritional and physiological principles are explained in details for the better understanding of chemical bondings among atom, molecule, and substance. The discussion also focuses mostly on the radiation from the technological aspects of its observation, measurement, and production. The applications of the element of noble gas are also introduced as the comparison with those of the other elements. Especially in medical applications, noble gas elements are widely used for the purposes of the diagnostic imaging techniques based on MRI or Nuclear Medicine and the real-time imaging of the breathing motion during radiation therapy. Finally throughout this text, the roles of medical physicists in daily clinical practice and research in medical applications and those in close cooperation with industrial technologies are explained. There involve many emerging technologies and their beneficial or harmful influences on patient cares [18]. It indicates the uniqueness of the sensitive measurements and safety practices in order for their better understanding. Nevertheless, the effort will be that the conceptual explanation in the fundamental issues helps to create a broader picture of the medical applications as a whole. Hence, basics of the medical physicists are quite familiar, the fundamental principles in medical physics have not been given in detail. [19][20][21]

Results and Discussion

4. Intersection of Nanotechnology and Medical Physics

The evolution of healthcare is marked by advances in technology, research, and facility practice. New capabilities are used in diagnostics, adaptations are made in procedures, and improved outcomes are produced in patients. Throughout this development, the field of medical physics has consistently been at the center. Broadly, medical physics applies the concepts and methods of the physical sciences to medicine, with an increasing emphasis to develop and employ efficient technologies and methodology to aid the diagnosis and treatment of patients. Within this framework, numerous applications can be observed, from general quality assurance in imaging to more specialized techniques like mammography and nuclear cardiology. Most often, the term medical physics pertains to diagnostic imaging, treatments like radiation oncology or nuclear medicine, and research aspects. [22][23][24]

In parallel, nanotechnology concerns the understanding, manipulation, and control of matter at the scale of nanometers, with properties that arise due to its small size. This technology is currently experiencing remarkable advances and being integrated across industries. Significant investments in research and development continue to expand the boundaries of nanotechnology, stimulating further innovation. As a result, breakthroughs have been made in a plethora of fields, particularly in electronics, energy, and materials. While other applications in medicine are quickly gaining momentum, the intersection of nanotechnology and medical physics remains a relatively new area, with significant unexplored synergies and collaborative potential. [25][1]

By its very nature, much of the work in medical physics has always involved the nanoscale. The interactions of x-rays with individual atoms form the basic tenets of CT image reconstruction. Many radiation therapy protocols rely on altering cell DNA and therefore are concerned with the atomic level. Radiopharmaceuticals use nano-sized radioactive matter. What is new, however, is the use, understanding, and manipulation of nanoscale materials, themselves. This technology’s intersection with biological systems offers a number of unique exploitation potential. As an example, size-dependent bioclearance rates can span minutes to months. Meanwhile, the unique physical properties of nanomaterials can produce novel interactions with biological systems. A selection of mechanisms includes direct interactions, enhanced targetability, and producing cell damage through physical means. These features and more have tremendous transformative potential in medical diagnostics, therapeutics, and imaging, discussed in turn herein. With the potential to revolutionize many areas of patient care, interdisciplinary research and open communication between fields will help to discover and apply these new technologies to improve human health. However, due to these revolutionary technologies being at an early stage, the main technical barriers, multiple safety concerns, and regulatory environments encountered will be critically discussed. [26][27][28][29]

5. Nanoparticles in Medical Imaging

Introduction Nanoparticles have massive potential for a variety of applications in medical physics and medical imaging. It is easier to enhance the contrast in medical images using nanoparticles. For instance, if suspensions of nanoparticles are prepared at specific dilutions, these cause significant changes in contrast in X-ray or magnetic resonance imaging (MRI). In other imaging modalities like MRI, the resolution of the image can increase using well-arranged magnetic particles. Moreover, it opens the way to applying new imaging techniques like transluminal or transcutaneous. Medical imaging is a technique widely used in medical physics for diagnosis. The most common imaging techniques are magnetic resonance imaging (MRI), computed tomography (CT), Positron emission tomography (PET), radioX-ray, single-photon emission computed tomography (SPECT), mammography, and Ultrasound (US). This list is by no means exhaustive; some techniques are currently still on the bench, others taking off in research for some negative effects or poor images [30]. [31][32]

Contrast diagnostic agents The development and use of contrast agents are introduced in medicine to improve the corresponding images fundamentally. Those agents incorporate the nano-domain down to the nanoscale, and they are known as nanoparticles. Consequently, small contrast agent particles will be settled in no-flow vascularity within the human body, enhancing images of the no-flow blood portion and anywhere the contrast agent will settle like ischemic tissues. Besides that, those contrast agents have an immense potential to bring some new imaging methods from benches to the bedside, like transcutaneous or transluminal imaging. For examples, there are clinical case studies where oral administration of diluted nano TiO_2 particles or nano-iodine particles gave a significant contrast increase of CT; another example of diluted particles was found in nebulized gold nanoparticles enhancing X-ray images in rat lung; an excellent case study with multiple imaging methods on mice found contrast enhancement in PET/CT, X-ray, and MRI thanks to functionalized gold nanoparticles (6 different imaging methods used, but shear gold nanoparticles need regulatory approval). There are quite numerous papers where a useful synthesis of nanoparticles for imaging applications was reported like the enhancement of X-ray images of attenuation coefficients of 'biologically white tissues' BJ, the increase of MRI contrast in vital, both newly formed, and breathable tissues from magneto-fluorescent single-core and multi-core nanoparticles coated by SiO_2 and biocompatible polymers. There are excellent reviews emphasizing how much nanoparticles can be adapted to different imaging methods and improve images in positive ratios: magnetic nanoparticles – a review (possible functionalization, and an explanation of superparamagnetism, along with core-shell formation methods with the shell being suitable for functionalization), and a very comprehensive review that gives both contrast/ image enhancement principles for each kind of imaging method and a vast list of recent papers on each kind of imaging method. To conclude this part, it is worth mentioning several great reviews on the non-rare topic of contrast agents in medical imaging: for non-commercial and commercial synthesized various nanoparticles to be used as contrast agents, for an interesting look at the history of using nanoparticles in imaging and the barriers that the particles must fulfill to be effective as the contrast agents (powder size, good GMP, comfortable storage), while also giving a list of huge recent papers for an overview of contrast agent research (inert porous particles made by the solgel method can be used as injectable X-ray contrast agents decreasing the dose of used commercial media). [33][34][35][36][37]

6. Nanotechnology for Drug Delivery in Medicine

Nanotechnology involves the study of very small structures, typically between 1 and 100 nm in size. Nanoparticles can be manufactured and tend to have a variety of beneficial properties. These could include interesting magnetic, optical, structural, or catalytic properties which arise when particles are brought down to the nanoscale level. The saucepan effect is one example where the same amount of a drug can be given with a greatly reduced number of side effects. Today, nanotechnology is finding widespread application in markets for commercial goods, cosmetics, and clothing. There are large step-grandchildren in rug development which has shown that nanotechnology has lived up to the promise with drug release, lower liver toxicity, increased percentage of drug reaching the brain, and more effective delivery of therapeutic product. Medical nanoparticles, which refer to particles used in drugs, in a drug delivery system, in bonding material, or in a diagnostic that makes them unique, have found widespread applications in medicine. The main areas of focus are topical applications, oral applications, particles intended for carrying agents, imaging particles, or particles intended for vascularization procedures. [38][12][39][40]

Introducing Therapeutic Agents have been in use for a long time in the ways based on urinary and other biomarkers. Throughout the body, drugs are generally delivered through the systemic circulation and can reach any part of the body. That can cross the blood-brain barrier to target the central nervous system. Their small size allows nanoparticles to pass through the capillary wall as well, and so they are easily absorbed in the intestine and lungs. Once a vessel is affected and not present on the edge of a cancer site, particles located across the endothelial wall will quickly be absorbed by the highly leaky tumor vasculature, thus leading to an enhanced permeability and retention effect. Nanotechnology has also seen the introduction of many promising formulations for mediating systemic drug delivery purposes. For instance, a six-point-positive charge albumin nanoparticle of the size about 130 nm is approved in the UK and European Union for the delivery of paclitaxel gemcitabine and docetaxel-encapsulating [41]. As another clinical example, a pegalated doxorubicin containing a liposome is approved for treatment of sarcomas, metastatic breast cancer, and multiple myeloma. The preparation is successful in decreasing the rate of adriamycin stress, primary effect, G.I. Toxicity, and cardiomyopathy. Additionally, clinical trials are acts for testing it spilling at in combination with a variety of genetic interventions for tumors. Orally administered therapies can be produced through nanoparticles. To overcome the first-pass effect intranasal cocaine delivery can be nano formulated. Major side effects in chemotherapy could be reduced with the help of nanoparticles carrying drugs specifically to cancerous sites. Co-administration of nanoparticle milk the genes C in the same cell is a successful approach for reducing resistance of lung transfected cells toward paclitaxel. Optic anticancer drugs could also be developed for treating melanoma cells which are known for the resistance to the majority of potent drugs. Nasal nitric oxide nanoparticles which may give pain relief for migraine sufferers for up to 72 hours are developed. Using the nano-based controlled release compositions, agents can be provided so as to effectively treat or reduce the incidence of a variety of medical conditions. To achieve this, the forgoing composition can include therapeutically agents which can be released from nanoparticles. Broadly put, the invention involves methods and compositions for the delivery of an agent (i.e., drugs, probes, etc.) into an organism. In particular, there are exact methods of release of an agent to reach a target tissue while limiting the contact of the agent with non-targeted tissue within the organism. An agent can be, for example, a drug, a prodrug, or a probe. [42][43][44][45][46][47]

7. Nanotechnology in Cancer Treatment

Once considered a mysterious subject, the vital role of nanotechnology in medical physics has come to prominence due to its many advantages and innovations in novel drug designs and cancer treatments. Nanotechnology has the potential to develop new approaches to greatly improve cancer treatment modalities, such as targeted therapy; to minimize the side effects of conventional treatments; to develop photothermal therapy and drugs encapsulated in nanoparticles; to reduce the side effects of chemotherapeutics; and to enhance drug accumulation in tumor tissue. These nanotechnology applications have already shown their successes in preclinical studies and clinical trials. Nanotechnology will also play an important role in advancing innovative and smart medical techniques, including biochip sensors to detect cancer cells and production of multifunctional particles to realize multimodality imaging and therapy. Nevertheless, significant efforts are required to transform these innovative approaches from the laboratory to routine patient care. Many challenges remain to be overcome, particularly regarding the successful transport of nanomaterials to target sites in a therapeutic context. Furthermore, these advances need to account for the health of individuals [48]. There is no doubt that the medical and health community is currently experiencing an unprecedented technological revolution, driven by the joint development of an ever-increasing number of innovative monitoring, diagnostic, and therapeutic tools. Within this context, the role of nanotechnology is indeed gaining a distinctive aura, fostering the spreading of innovative solutions set to disrupt the public health landscape as currently unperceived. Although the transfer from the laboratory to actual clinical application is today still to be considered as a creeping process, the potential of many of the nano-bio-engineered solutions that have emerged so far is so outstanding to raise the expectations of a radical ramp-up in bio-nanomedicine integrated services. [49][50][51][52][53][54][55]

8. Nanotechnology in Neuroimaging and Neurosurgery

The popularity and necessity of nanotechnology application in medical physics have been increasing in recent years because of innovations in the field of nanotechnology. Researchers are working on developing methodologies and tools that will allow the application of nanotechnology principles, methods, materials, and devices that are promising in medicine. The main advantages of those medical nanotechnology solutions are that they are set to be efficient and specific at the cellular and molecular level. An important area of nanotechnology application in medical physics is neuroimaging and neurosurgery. Nanomaterials, which are composed of particles smaller than 100 nm, have special physical, chemical, and biological characteristics. Nanomaterials have started to be used routinely in the field of biomedicine. These properties of biocompatible nanomaterials are the reason for the use and investigation of those materials in neuroimaging and neurosurgery. The use of biocompatible nanomaterials in neuroimaging increased the quality and sensitivity of images, which allows better diagnosis and treatment of neurological disorders. The latest advances and the application of nanomaterials in neuroimaging are discussed. Biocompatible nanoparticles have started to be used for transferring different drugs into the central nervous system. The functionalization of them allows transferring the desired therapeutic items into a cancerous region more effectively. The advances and application of biocompatible nanoparticles as a transporter of drugs for treatment purposes into the central nervous system are outlined. In addition, innovations using biocompatible nanoparticles in neurosurgical procedures are discussed, and the focus on the difficulties of blood-brain barrier penetration and biocompatibility is mentioned. Some of today’s common methods of this application are defined by putting light on certain experiments. These methods have led to great improvements in patient outcomes in complex neurological procedures such as brain tumor, epilepsy, Parkinson’s, Huntington, and such operations. However, the use of nanotechnology in this sensitive field brings ethical problems that are briefly considered. All of these issues are very relevant to the future integration of nanotechnology with the practice of neurophysiology. [56][57][58][59][60][61]

9. Nanotechnology in Therapeutic Applications

Nanomodification of medical appliances for prosthesis allows for obtaining a bone-like structure on the metal surface, modifying the smooth surface to a bioactive one, and increasing mechanical adhesion. This can stimulate the implant fusion of the human implant by forming a solid-phase structure on the bioactive metal basis that can serve as the growth places for new bone tissue. The formation of compounds of titanium and oxygen in human organism leads to the implant biointegration due to the implant surface similarity with the bone tissue. Bioactive implants have also been found to decrease the incidence of post-surgery inflammatory complications in the form of formation of sterile aseptic inflammation around the artificial joint. In this regard, the aim of this study is the development of bioactive spherical granules technology at the surface of the medical appliance by forming the titanium organic precursor around the polymer nanoparticle. The developed method allows for uniform spherical nanogranules to be formed on the surface of metal prosthesis by exposing the surface in the pulse plasma area of the discharge to titanium tetrachloride. [62][63][64][65]

10. Nanotechnology in Diagnostic Applications

By incorporating nanotechnology with diagnostic applications in medical physics, numerous advancements have been made to detect and monitor diseases early in various medical fields. With their high surface-to-volume ratios, nanomaterials can immensely enhance the sensitivity and specificity of diagnostic assays. In recent years, nanomaterials have been broadly utilized to enhance the performance of diagnostic assays. A wide range of applications, such as biosensors, imaging contrast agents, chromatography, and immunoassays, have been explored across the various medical fields. These developments have demonstrated the clinical need for early disease detection, as well as a substantial clinical impact. [66][67][68]

The use of nanomaterials has enabled the development of highly sensitive and sophisticated diagnostic assays compared to traditional bulky materials. A nanorod array-based device has been developed to detect interleukin-6, which is a biomarker of oral cancer, with a sensitivity nearly 1000 times greater than the traditional gold pad electrodes. The clinical trial using nano-architectured arrays for capturing vesicles demonstrated exciting results – vesicles carrying HER2 in patients with breast cancer were detected earlier, thereby opening an opportunity for a non-invasive point-of-care assessment. In another study, the use of nanodot-fluorescent Resonance Energy Transfer probes enabled investigation of the early pathophysiological changes caused by microvascular dysfunction in the acute stage of skin burn injuries. The obtained results may redefine near-future intelligent burn diagnostics and advanced solutions for treatment injury in the pre-clinical phase. Moreover, significant progress has been made in nanodiagnostics, a development that combines nanomaterials with diagnostic applications. These nascent technologies utilize tailorable nanomaterials to create promising new strategies for personalized medicine, instructive epidemiological studies, and point-of-care testing. Although there are still unresolved obstacles in achieving scalable and reproducible nanofabrication and nano-manufacturing for creating nanomedical devices, substantial improvements are foreseen. The use of nanomaterials in human subjects and marketed medical products is rapidly expanding, raising new regulatory issues. As the market for nanodiagnostics is projected to grow rapidly, a comprehensive understanding of the regulatory landscape is required. There is a broad agreement that nanodiagnostics will offer a significant new approach, offering more sensitive detection, improved therapeutic monitoring, and the possibility of a personalized medicine. In response to this, the Committee has called for an overhaul of regulatory pathways for the approval of medical devices. To deliver early diagnoses and differential cancer analyses conducive to better healthcare, the next-generation fluid biopsy approach shall merge powerful multiplexed quantum-dot barcoding and quantification. Highly discriminating challenges of 60 labels shall be validated using a custom-built scanning system and applied to a comprehensive patient cohort. [66][69][67][70]

11. Regulatory and Ethical Considerations in Nanomedicine

Efforts to apply nanotechnology to medicine are a natural progression that aim to enhance medical technology. However, the convergence of nanotechnology with medicine raises both regulatory and ethical concern. On the regulatory side, it is a matter of considering which existing frameworks are in place for drug and medical product approval, and how these frameworks may require modification in terms of criteria and approaches when applied to products that are nanoscale [6]. Essential to this effort is the distinction between traditional medical products, which are mass-produced, and products that are developed on the nanoscale and are characteristically more variable, and may well be more difficult to predict. On the ethical side, it is essential to ask concerning nanomedicine which kinds of therapeutic applications safely and effectively will be developed, and what may be the untoward effects of the particles themselves, or the impact of nanomedicine on existing types of environmental hazards. Balancing innovation with compliance with necessary regulations is obviously difficult. At the same time, it is understood that the appropriate adaptations of regulation are case-specific and are therefore impossible to define in general terms, in advance. [71][72][73][74]

One approach to this difficulty may be the development of adaptive strategies, and of a broadly based dialog among stakeholders. This is the intention of a number of workshops and initiatives intended to bring together practicing scientists and regulators, social scientists, and stakeholders from industry, NGOs, and commentators on regulation. A further task is to educate research scientists or potential products of nanomedicine, and also to educate the general public, ensuring that responses or attitudes to nanotechnology in regard to medicine are appropriately based. This is seen as an important task for consideration by individual member states. However, it is also seen as a task to be taken up more broadly. Major concern is with the nature of the dialogue that at present exists amongst the different stakeholders, including scientists, industry, policymakers, and the wider public. Judged by existing outputs, this dialogue is at best rudimentary, and it is largely driven by scientists themselves. Broadly, such dialog is seen as necessary and as comprising several different kinds of discussions. The first is the specifically technical discussion. This includes the widely noted need for widely recognized and shared terminology. Arguably, it also includes an agreement on classification procedures, and on the most appropriate sites of research, among other things. [75][76][77][78][79]

12. Challenges and Future Directions in Nanotechnology in Medical Physics

As nanotechnology matures—receiving recognition even from governments—and adequate knowledge is available, more medical physics programs need to be tailored. This should cover the basic concepts and put more emphasis on the translational and interdisciplinary approach. Medical physics centers of excellence would be defined and, together with help from professional and funding organizations, education programs could be improved. In the future, patenting know-hows should be established as well [80]. For nanoscience to reach full maturity, a network of good practice could be developed to aid collaboration. [14]

Taking into consideration the perspectives given by experienced research groups from different branches of the nanomedicine "industry," a more realistic picture is drawn regarding the main challenges and future trends of nanotechnology in medical physics. Moreover, there are numerous details on nanoprocessing and biofunctionalization that affect well-established systems, but can also help the reader to explore the frontiers, thus furthering the necessary interdisciplinary approach. [2]

In conclusion, the potential and momentum of nanosciences are discussed and projected in a realistic rather than alarmingly exuberant view, which aims to define target research areas where original breakthroughs are more likely to occur. These recommendations are spread over 26 numbered points to make them more focused and are divided into four categories: general recommendations (education, patents, and recommended practices), processing it nanoparticles, applied to the medical and biological sciences, and further research topics. Thus, this perspective would best fit readers seeking the most profound industrial and research-related information, lacking a proper education or funding and considering themselves outsiders in the "nanofamily." However, even actors from the "nanofamily," used to this language and specialization, may seek service in this quasi-inventory of Good Practices because nanobiotechnology is a relatively young field [81], requiring organization and standardization efforts to push forward intense, efficient, and well-focused research. [82]

13. Conclusion and Summary of Key Findings

The interdisciplinary approach of Nanotechnology is enabling the birth of a new research challenge that is continuously bringing new advances in the scientific paradigm of Medical Physics. Those advances are sometimes so striking that they can rise an unconscious nostalgia about classical and well known therapeutic or diagnostic approaches. Images penetrated by enhanced contrast agents could provide improved oncological staging, and may identify the tumour size in the earliest stages of development. Multi-modal imaging methodologies may provide enhanced high resolution anatomical and functional imaging. These are features of great clinical interest in tumour assessment. Real time MRI imaging might enable more precise monitoring of the temperature field in tissues submitted to hyperthermic treatments, allowing the definition of more effective therapy strategies. The application of very small strategically placed

X-ray or magnetic field sources for therapies is of great interest to therapeutic radiation research.

A new approach to the treatment of malignant brain tumours and a solution for severe cases caused by the occurrence of multi-centric neurogenic carcinomatosis; the approach consists of a set of localized external X-ray sources and radioactive 125I seeds permanently implanted in several loci a few days after surgery. The need for improved treatment planning methodologies has risen the development of a number of research tools, being the in-house radiation transport Monte Carlo code the most innovative. Its main application is currently the dosimetric study of new therapeutic approaches based on the use of BNCT; two of these are being actively pursued for in-vivo assessment, and show promising results.

References:

1. S. Malik, K. Muhammad, and Y. Waheed, "Emerging applications of nanotechnology in healthcare and medicine," Molecules, 2023. mdpi.com
2. A. Haleem, M. Javaid, R. P. Singh, S. Rab et al., "Applications of nanotechnology in medical field: a brief review," Global Health Journal, 2023. sciencedirect.com
3. S. S. Liyakat and K. K. S. Liyakat, "Nanotechnology in Healthcare Applications: A Study," *International Journal of …*, 2024. journalspub.com
4. K. Yadav, "Nanotechnology in diabetes management: Revolutionizing treatment and diagnostics," Journal of Molecular Liquids, 2024. [HTML]
5. K. K. Y. Wong and X. L. Liu, "Nanomedicine: a primer for surgeons," 2012. ncbi.nlm.nih.gov
6. M. Ebbesen and T. G. Jensen, "Nanomedicine: Techniques, Potentials, and Ethical Implications," 2006. ncbi.nlm.nih.gov
7. M. Rasool, A. Malik, S. Waquar, M. Arooj, and S. Zahid, "New challenges in the use of nanomedicine in cancer therapy," Taylor & Francis, 2022. tandfonline.com
8. F. Rommasi and N. Esfandiari, "Liposomal nanomedicine: applications for drug delivery in cancer therapy," Nanoscale Research Letters, 2021. springer.com
9. F. Vahedifard and K. Chakravarthy, "Nanomedicine for COVID-19: the role of nanotechnology in the treatment and diagnosis of COVID-19," Emergent materials, 2021. springer.com
10. C. Binns, "Introduction to nanoscience and nanotechnology," 2021. [HTML]
11. J. K. Patel, A. Patel, and D. Bhatia, "Introduction to nanomaterials and nanotechnology," in *Emerging technologies for nanoparticle*, Springer, 2021. [HTML]
12. Y. Khan, H. Sadia, S. Z. A. Shah, M. N. Khan, and A. A. Shah, "Classification, synthetic, and characterization approaches to nanoparticles, and their applications in various fields of nanotechnology: A review," Catalysts, 2022. mdpi.com
13. S. A. Ahire, A. A. Bachhav, T. B. Pawar, and B. S. Jagdale, "The Augmentation of nanotechnology era: A concise review on fundamental concepts of nanotechnology and applications in material science and technology," Results in ..., Elsevier, 2022. sciencedirect.com
14. S. Malik, K. Muhammad, and Y. Waheed, "Nanotechnology: A revolution in modern industry," Molecules, 2023. mdpi.com
15. AN Al-Thani, AG Jan, M Abbas, M Geetha, et al., "Nanoparticles in cancer theragnostic and drug delivery: A comprehensive review," Life Sciences, 2024. sciencedirect.com

16. H. Huang, Y. Zheng, M. Chang, J. Song, and L. Xia, "Ultrasound-based micro-/nanosystems for biomedical applications," Chemical, 2024. [HTML]
17. E. Sharifi, A. Bigham, S. Yousefiasl, and M. Trovato, "Mesoporous bioactive glasses in cancer diagnosis and therapy: stimuli-responsive, toxicity, immunogenicity, and clinical translation," Advanced, 2022. wiley.com
18. A. C. Hayes, "Applications of Nuclear Physics," 2017. [PDF]
19. H. Yin, Z. Chen, H. Zhao, H. Huang et al., "Noble gas and neuroprotection: From bench to bedside," Frontiers in Pharmacology, 2022. frontiersin.org
20. T. V. Basova, E. S. Vikulova, S. I. Dorovskikh, and A. Hassan, "The use of noble metal coatings and nanoparticles for the modification of medical implant materials," *Materials & Design*, 2021. sciencedirect.com
21. J. Yan, Y. Wang, X. Song, X. Yan, Y. Zhao, and L. Yu, "The advancement of gas-generating nanoplatforms in biomedical fields: current frontiers and future perspectives," Methods, 2022. [HTML]
22. T. Beyer, D. L. Bailey, U. J. Birk, I. Buvat, and C. Catana, "Medical Physics and imaging–A timely perspective," in Physics, 2021. frontiersin.org
23. W. D. Newhauser, D. A. Gress, M. D. Mills, "Medical physics workforce in the United States," Medical Physics, 2023. nih.gov
24. D. Sarrut, T. Baudier, D. Borys, A. Etxebeste, "The OpenGATE ecosystem for Monte Carlo simulation in medical physics," Physics in Medicine, 2022. nih.gov
25. A.S. Shah, B. Surnar, and N. Kolishetti, "Intersection of inorganic chemistry and nanotechnology for the creation of new cancer therapies," Accounts of Materials, 2022. acs.org
26. T. K. Shaw, P. Khamkat, A. Ghosh, and M. K. Ghosh, "Nanotargeted radiopharmaceuticals for cancer theranostics," in Theranostic Nanomedicines, Elsevier, 2021. [HTML]
27. X. Jiao, H. Hong, and W. Cai, "Nanoscale Radiotheranostics for Cancer Treatment: From Bench to Bedside," Wiley Interdisciplinary Reviews, 2024. wiley.com
28. P. Shende and S. Gandhi, "Current strategies of radiopharmaceuticals in theranostic applications," Journal of Drug Delivery Science and Technology, 2021. [HTML]
29. G. Poletto, L. Evangelista, F. Venturini, F. Gramegna, "Nanoparticles and radioisotopes: a long story in a nutshell," Pharmaceutics, 2022. mdpi.com
30. S. Siddique and J. C. L. Chow, "Application of Nanomaterials in Biomedical Imaging and Cancer Therapy," 2020. ncbi.nlm.nih.gov
31. M. Jeon, M. V. Halbert, and Z. R. Stephen, "Iron Oxide Nanoparticles as T1 Contrast Agents for Magnetic Resonance Imaging: Fundamentals, Challenges, Applications, and Prospectives," Advanced Materials, 2021. nih.gov
32. JCL Chow, "Magnetic nanoparticles as contrast agents in magnetic resonance imaging and radiosensitizers in radiotherapy," in … and Industrial Applications of Magnetic Nanoparticles, 2022, Elsevier. [HTML]
33. F. Sun, J. Zhou, X. Chen, and T. Yang, "No-reflow after recanalization in ischemic stroke: From pathomechanisms to therapeutic strategies," *of Cerebral Blood*, 2024. researchgate.net
34. T. Dalkara, L. Østergaard, and G. Heusch, "Pericytes in the brain and heart: functional roles and response to ischaemia and reperfusion," Cardiovascular, 2024. oup.com

35. W. He, Q. Mei, J. Li, Y. Zhai, Y. Chen, R. Wang, and E. Lu, "Preferential targeting cerebral ischemic lesions with cancer cell-inspired nanovehicle for ischemic stroke treatment," Nano Letters, 2021. [HTML]

36. K. Luo, Y. Wang, E. Lu, W. Nie, and X. Yan, "Ischemic Microenvironment-Targeted Bioinspired Lipoprotein Sequentially Penetrates Cerebral Ischemic Lesions to Rescue Ischemic Stroke," Applied Materials, 2024. [HTML]

37. J. Gao, Y. Song, Q. Wang, J. Chen, Q. Li, and H. Tan, "Precisely co-delivery of protein and ROS scavenger with platesomes for enhanced endothelial barrier preservation against myocardial ischemia reperfusion injury," Chemical Engineering, 2022. [HTML]

38. S. Khan and M. K. Hossain, "Classification and properties of nanoparticles," Nanoparticle-based polymer composites, 2022. [HTML]

39. S. Raha and M. Ahmaruzzaman, "ZnO nanostructured materials and their potential applications: progress, challenges and perspectives," Nanoscale Advances, 2022. rsc.org

40. R. Abbasi, G. Shineh, M. Mobaraki, and S. Doughty, "Structural parameters of nanoparticles affecting their toxicity for biomedical applications: a review," *Journal of Nanoparticle*, 2023. springer.com

41. K. Sonamuthu, "Applications of Nanotechnology in Drug Delivery Systems," 2019. [PDF]

42. T. Sahu, Y. K. Ratre, S. Chauhan, L. Bhaskar, "Nanotechnology based drug delivery system: Current strategies and emerging therapeutic potential for medical science," Journal of Drug Delivery, Elsevier, 2021. [HTML]

43. S. Sim and N. K. Wong, "Nanotechnology and its use in imaging and drug delivery," Biomedical reports, 2021. spandidos-publications.com

44. O. Afzal, A. S. A. Altamimi, M. S. Nadeem, and S. I. Alzarea, "Nanoparticles in drug delivery: From history to therapeutic applications," Nanomaterials, 2022. mdpi.com

45. H. Park, A. Otte, and K. Park, "Evolution of drug delivery systems: From 1950 to 2020 and beyond," Journal of Controlled Release, 2022. nih.gov

46. ZM. Mazayen, A.M. Ghoneim, and R.S. Elbatanony, "Pharmaceutical nanotechnology: from the bench to the market," Future Journal of ..., 2022. springer.com

47. J. F. Hsu, S. M. Chu, C. C. Liao, C. J. Wang, Y. S. Wang, and M. Y. Lai, "Nanotechnology and nanocarrier-based drug delivery as the potential therapeutic strategy for glioblastoma multiforme: An update," *Cancers*, 2021. mdpi.com

48. C. M. Siamof, S. Goel, and W. Cai, "Moving Beyond the Pillars of Cancer Treatment: Perspectives From Nanotechnology," 2020. ncbi.nlm.nih.gov

49. M. Dessale, G. Mengistu, and H. M. Mengist, "Nanotechnology: a promising approach for cancer diagnosis, therapeutics and theragnosis," International Journal of ..., 2022. nih.gov

50. J. A. Kemp and Y. J. Kwon, "Cancer nanotechnology: current status and perspectives," Nano convergence, 2021. springer.com

51. S. Mosleh-Shirazi, M. Abbasi, and M. R. Moaddeli, "Nanotechnology advances in the detection and treatment of cancer: an overview," 2022. nih.gov

52. A. Nasir, A. Khan, J. Li, and M. Naeem, "Nanotechnology, a tool for diagnostics and treatment of cancer," Current Topics in ..., 2021. researchgate.net

53. S. Kumari, P. K. Choudhary, and R. Shukla, "Recent advances in nanotechnology based combination drug therapy for skin cancer," Journal of …, 2022, Taylor & Francis. [HTML]

54. W. Yin, F. Pan, J. Zhu, J. Xu, and D. Gonzalez-Rivas, "Nanotechnology and nanomedicine: a promising avenue for lung cancer diagnosis and therapy," Engineering, Elsevier, 2021. sciencedirect.com
55. N. Yadav, T. Dahiya, and A. K. Chhillar, "Nanotechnology in cancer diagnostics and therapeutics: a review," Current, 2022. [HTML]
56. S. Singh, S. Kumar, G. Kumar, and S. Mukherjee, "Neuro-compatible Biomaterials: Pioneering Solutions for Brain and Nerve Disorders," Biomaterials and …, 2025. [HTML]
57. R. Thangam, R. Paulmurugan, and H. Kang, "Functionalized nanomaterials as tailored theranostic agents in brain imaging," Nanomaterials, 2021. mdpi.com
58. B. Conklin, B. M. Conley, Y. Hou, and M. Chen, "Advanced theragnostics for the central nervous system (CNS) and neurological disorders using functional inorganic nanomaterials," Advanced Drug Delivery, 2023. sciencedirect.com
59. W. Du, L. Zhou, Q. Zhang, X. Liu et al., "Inorganic nanomaterial for biomedical imaging of brain diseases," Molecules, 2021. mdpi.com
60. MKA Al-Muhanna, AA Alghamdi, and B Alrfaei, "Surface-engineered quantum dot nanocomposites for neurodegenerative disorder remediation and avenue for neuroimaging," Nanotechnology, 2024. degruyter.com
61. N. Li, X. Song, P. Luo, J. Su, and Z. Yao, "Innovative Applications of Advanced Nanomaterials in Cerebrovascular Imaging," Frontiers in Bioengineering. frontiersin.org
62. J. Li, P. Zhou, S. Attarilar, and H. Shi, "Innovative surface modification procedures to achieve micro/nano-graded Ti-based biomedical alloys and implants," Coatings, 2021. mdpi.com
63. M. Chen, C. Luo, Y. Yuan, H. Zhou, and Z. Li, "Modification of PEEK for implants: Strategies to improve mechanical, antibacterial, and osteogenic properties," Reviews on Advanced, 2024. degruyter.com
64. F. Abaszadeh, M. H. Ashoub, and G. Khajouie, "Nanotechnology development in surgical applications: recent trends and developments," *Journal of Medical*, 2023. springer.com
65. E. Campodoni, M. Montanari, C. Artusi, G. Bassi, "Calcium-Based Biomineralization: A Smart Approach for the Design of Novel Multifunctional Hybrid Materials," Journal of Composites, 2021. mdpi.com
66. E. C. Welch, J. M. Powell, T. B. Clevinger, "Advances in biosensors and diagnostic technologies using nanostructures and nanomaterials," Advanced Functional, 2021. [HTML]
67. Q. Zhao, D. Lu, G. Zhang, D. Zhang et al., "Recent improvements in enzyme-linked immunosorbent assays based on nanomaterials," Talanta, 2021. [HTML]
68. E. Heydari-Bafrooei and A. A. Ensafi, "Nanomaterials-based biosensing strategies for biomarkers diagnosis, a review," Biosensors and Bioelectronics: X, 2023. sciencedirect.com
69. U.D. Markandan, V. Chaudhary, and A. Numan, "Emergence of infectious diseases and role of advanced nanomaterials in point-of-care diagnostics: a review," Biotechnology and ..., 2024. [HTML]
70. M. Srivastava, N. Srivastava and P. K. Mishra, "Prospects of nanomaterials-enabled biosensors for COVID-19 detection," Science of The Total Environment, 2021. nih.gov
71. L. Hassan and A. Fathi, "The Convergence of Nanotechnology and Biotechnology: Small-Scale Solutions for Big Challenges in Medicine, Energy, and Environment," Journal of Academic Sciences, 2024. mzjournal.com

72. D. Helbing and M. Ienca, "Why converging technologies need converging international regulation," Ethics and Information Technology, 2024. springer.com
73. C. Amutha, A. Gopan, I. Pushbalatatha, and M. Ragavi, "Nanotechnology and Governance: Regulatory Framework for Responsible Innovation," Nanotechnology in ..., Springer, 2024. [HTML]
74. N. Mehta, S. Shetty, B. G. Prajapati, and S. Shetty, "Regulatory and ethical concerns in the use of nanomaterials," Disease and Advanced Drug, 2024. [HTML]
75. D. Anurogo and N. A. Hidayat, "THE ART OF TELEVASCULOBIOMEDICINE 5.0," 2023. [HTML]
76. R. Gutierrez Jr, "Guiding the Next Technological Revolution: Principles for Responsible AI and Nanotech Progress," Artificial Intelligence in the Age of Nanotechnology, 2024. [HTML]
77. C. Apel, K. Kümmerer, A. Sudheshwar, and B. Nowack, "Safe-and-sustainable-by-design: State of the art approaches and lessons learned from value chain perspectives," *Current Opinion in*, 2024. sciencedirect.com
78. I. Malsch and E. Willighagen, "Ethical Impact Assessment of Sharing Nanosafety Data," Open Research Europe, 2024. europa.eu
79. RGL da Silva, A. Blasimme, and E. Vayena, "How Do Molecular Systems Engineering Scientists Frame the Ethics of Their Research?" AJOB Empirical, 2024. tandfonline.com
80. T. I. Ramos, C. A. Villacis-Aguirre, K. V. López-Aguilar, L. Santiago Padilla et al., "The Hitchhiker’s Guide to Human Therapeutic Nanoparticle Development," 2022. ncbi.nlm.nih.gov
81. H. A. L. A. M. O. D. A. KENZAOUI BLANKA, B. O. X. HELEN, V. A. N. ELK MEREL, G. A. I. T. A. N. SANDRA et al., "Anticipation of regulatory needs for nanotechnology-enabled health products," 2019. [PDF]
82. C. Domingues, A. Santos, and C. Alvarez-Lorenzo, "Where is nano today and where is it headed? A review of nanomedicine and the dilemma of nanotoxicology," ACS Publications, 2022. [HTML]
83. M. Alberto M. Ferreira and J. António Filipe, "Nanotechnology Applications The future arrived suddenly," 2022. [PDF]