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Gold Nanoparticles in Cancer Imaging and Treatment: A Narrative Review of Preclinical Progress and Translational Challenges

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Abstract

Background and Objective: Nanotechnology has emerged as a promising area in oncology for improving tumor imaging, treatment selectivity, and therapeutic response. Among the nanomaterials under investigation, gold nanoparticles (GNPs) have attracted substantial interest because of their tunable surface chemistry, high atomic number, and optical properties. This narrative review summarizes the current literature on GNP applications in cancer imaging, radiosensitization, and chemotherapy support, with particular emphasis on the translational gap between preclinical findings and clinical implementation. **Methods:** A narrative review of the literature was conducted using PubMed, Scopus, and Web of Science. English-language articles published through January 2026 were screened using combinations of the terms “gold nanoparticles”, “cancer imaging”, “computed tomography”, “magnetic resonance imaging”, “radiosensitization”, “radiotherapy”, “chemotherapy”, and “chemoradiotherapy”. Original studies and review articles addressing oncologic applications of GNPs were considered. Articles were excluded if they were non-English, not peer reviewed, not focused on cancer, or did not specifically evaluate gold nanoparticles. Evidence was synthesized across imaging, radiation-related applications, chemotherapy support, and translational limitations, with distinction made between *in vitro*, animal, and human data when available. **Key Content and Findings:** GNPs can enhance X-ray attenuation, serve as multifunctional imaging platforms, and increase radiation response through physical and biological mechanisms. They have also been investigated as drug-delivery and chemoradiotherapy-support platforms. However, much of the current evidence remains preclinical, and reported efficacy varies according to particle size, coating, tumor model, radiation energy, and delivery strategy. Clinical translation remains limited by concerns related to biodistribution, long-term safety, manufacturing reproducibility, and regulatory standardization. **Conclusions:** Gold nanoparticles remain a promising platform for oncologic imaging and therapy, but their clinical role has not yet been fully established. Future progress will depend on better standardization of nanoparticle design, more transparent study methodology, and stronger clinical evidence addressing safety, efficacy, and translational feasibility.

Keywords

Gold Nanoparticles, Cancer Imaging, Radiation Therapy, Chemoradiotherapy, Proton Therapy, Radiosensitization

1. Introduction

Nanotechnology is a branch of technology involving particles under 100 nanometers, commonly involving the manipulation of atoms and molecules [1]. In medicine, nanotechnology has proven to be useful in treatment at a cellular level, and its application covers a wide range of organ systems. Within the realms of cancer therapy and treatment, nanotechnology has been shown to effectively target cancer cells and provide enhanced treatment based on the nanoparticles and cancer cell's unique properties [2] [3]. Among the nanoparticles under investigation, gold nanoparticles (GNPs) have emerged as important candidates for cancer imaging and therapeutic applications because of their tunable surface chemistry, optical properties, and radiation-interaction characteristics.

2. Methods and Research Selection

This article was conducted as a narrative review of the literature on gold nanoparticles in oncologic imaging and treatment. Relevant studies were identified through searches of PubMed, Scopus, and Web of Science for English-language articles published through January 2026. The final literature search was completed on January 14th, 2026. Search terms included combinations of "gold nanoparticles", "cancer imaging", "computed tomography", "magnetic resonance imaging", "radiosensitization", "radiotherapy", "chemotherapy", and "chemoradiotherapy". Representative combinations of the above terms were used across databases, and articles were selected for relevance after title/abstract screening followed by full-text review.

Titles and abstracts were screened for relevance to the use of gold nanoparticles in cancer diagnosis or treatment. Full texts were then reviewed for eligibility. Articles were included if they addressed GNP applications in cancer imaging, radiation sensitization, chemotherapy delivery or support, or translational limitations relevant to oncology. Both original studies and review articles were considered in order to summarize mechanistic concepts, preclinical findings, and early translational developments. Articles were excluded if they were non-English, not peer reviewed, not focused on cancer, or did not specifically evaluate gold nanoparticles.

Because this was a narrative rather than systematic review, the goal was not to perform a formal meta-analysis, but to synthesize representative literature across major application domains. In the final narrative synthesis, evidence was organized by imaging, radiosensitization, chemotherapy-related applications, and translational limitations, with efforts made to distinguish *in vitro* findings, animal data, and human or clinical evidence where available.

3. Discussion

Gold nanoparticles are 1 to 100 nanometer-sized particles, which when suspended in water are known as colloidal gold. Based on their oxidation state, their color can range from red to a deep purple [3]. Gold nanoparticles have several properties that make them attractive candidates for cancer imaging and therapeutic research, including tunable surface chemistry, optical behavior, and radiation-interaction properties [1] (**Figure 1**). Bulk gold has historically demonstrated relative biocompatibility in some medical contexts; however, the safety of gold nanoparticle formulations depends on multiple factors, including particle size, shape, surface coating, dose, route of administration, biodistribution, and retention time [3]. Secondly, GNPs' unique physicochemical properties including surface plasmon resonance (SPR) and the ability to bind amine and thiol groups are conducive to modifications of the gold surface coat [4]. In terms of gold nanoparticles' usage in radiation therapy, gold nanoparticles are debatably thought to be better markers than previously used heavy particle markers because of their large

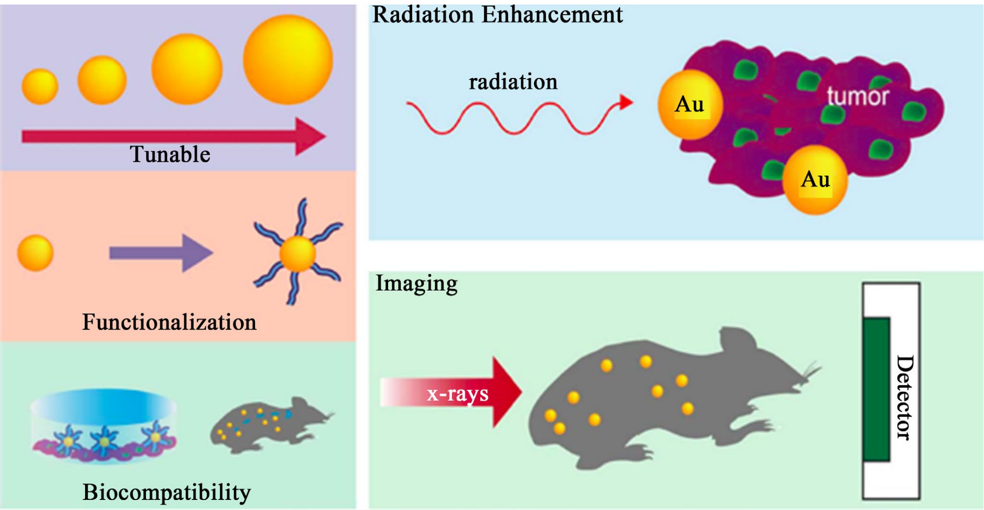

Figure 1. Gold nanoparticles are favorable to use in that they are tunable, easily modifiable, demonstrated biocompatibility in selected preclinical contexts, and enhance both diagnostic imaging and treatment. This image was taken from Dorsey *et al.*, "Gold nanoparticles in radiation research: potential applications for imaging and radiosensitization", Translational Cancer Research, 2013 [Vol 2, No 4].

number of electrons [3] [5]. These properties allow gold to absorb more of the photon energy, effectively increasing radiation dose enhancement to cancerous cells. Additionally, the relative size of GNPs allows for more precise marking of neoplastic cells by allowing them to enter through more porous vasculature of cancer cells and specifically target the tumor [6]. Based on these properties, gold nanoparticles are an attractive prospect currently being studied for possible applications in cancer diagnostics and treatment [7] (**Figure 2**).

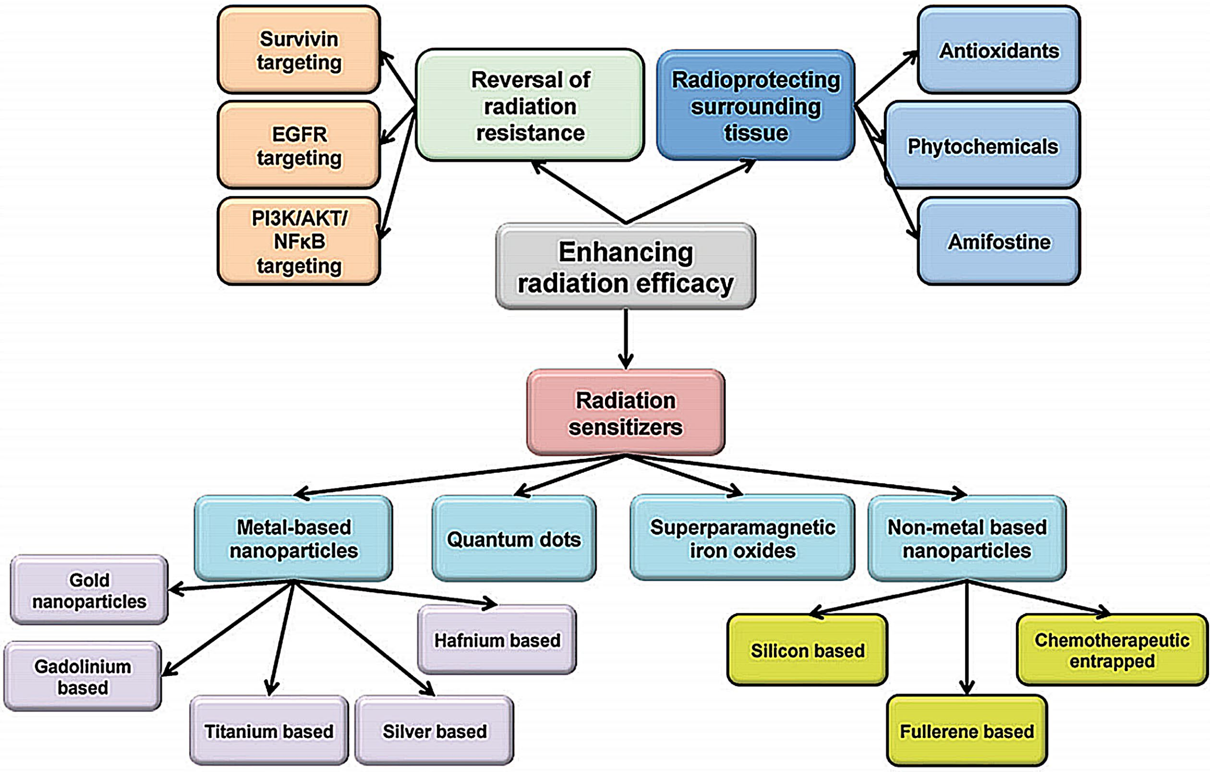

Figure 2. A summary of the various approaches for enhancing radiosensitization in cancer cells.

3.1. Nanotechnology for Cancer Imaging

In preclinical models, gold nanoparticles have been investigated as promising contrast agents across several imaging modalities, with reported improvements in tumor visualization and treatment planning [1]. Gold nanoparticles have been investigated as alternative contrast agents to traditional iodine-based contrast agents used in radiation therapy and computed tomography (CT)-based imaging modalities, which are associated with potential side effects and limitations despite their widespread use [3]-[5]. Traditional iodine-based contrast agents have been found to be limited in their usage due to its "fast clearance, short imaging times, requirement for high doses of radiation exposure from CT, and insufficient contrast resolution" [8]. Gold's higher atomic number (Au, 79) than iodine (I, 53) permits higher absorption and augmentation of ionization radiation and better X-ray attenuation for diagnostics and imaging [8]. At typical energy ranges used for clinical CT imaging, gold nanoparticles have a higher mass-energy X-ray absorption coefficient than traditional iodine, demonstrating 2.7 times greater attenuation per unit weight (**Figure 3**) [8]. Gold particles have also been demonstrated to serve as superior contrast agents in higher X-ray/photon energies (80 - 100 keV) [8]. With its ability to attenuate X-ray through its higher weight, gold prevents soft tissues from absorbing radiation, lowering patient radiation exposure levels. Simultaneously, gold's physical properties permit increasing image quality at lower radiation doses [9]. The decrease in imaging time, stability, and circulation time can be explained by the higher molecular weight of gold nanoparticles and the various ways they can be functionalized by conjugation to numerous biological surface molecules [2] [3]. Gold nanoparticles are intravenously injected into tumor tissue either by passive enhanced permeability and retention (EPR)-assisted accumulation or target delivery, and prior preclinical studies have reported significant CT contrast enhancement [10] [11].

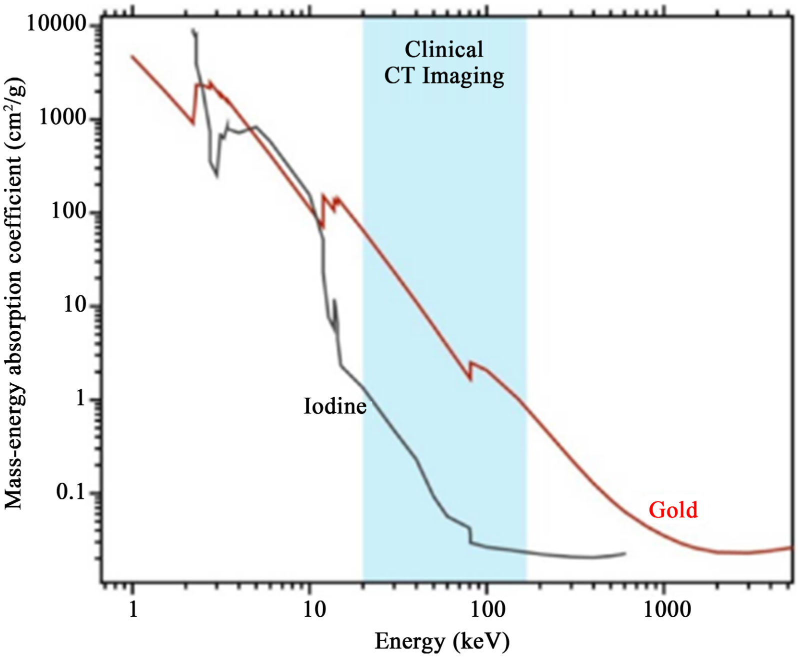

Figure 3. Mass-energy absorption coefficient of gold versus iodine. This figure demonstrates that gold's mass-energy absorption coefficient is greater in comparison to iodine, the traditional base for CT contrast agents, indicating gold's superior X-ray attenuation and contrast. This image was taken from Dorsey *et al.*, "Gold nanoparticles in radiation research: potential applications for imaging and radiosensitization", Translational Cancer Research, 2013 [Vol 2] [No 4].

Gold nanoparticles demonstrate adjustable optical properties due to their surface plasmon resonance, which lies in the visible range of the spectrum [1] [4] [5]. The localized surface plasmons (LSP) can be observed at the interface between gold and a dielectric when a photon interacts with the nanoparticle, which results in absorption (electron-hole excitations) [4]. Gold nanoparticles demonstrate enhanced light absorption at their plasmon resonance and highly efficiently convert this light into heat, which is constricted to the direct area of the nanoparticle. As a result, nanoparticles can be used in local applications targeting specific tumor tissues.

Gold contrast agents are seen as "molecular CT imaging platforms for tumors that are undetectable by structural and anatomical imaging modalities" [8]. According to Popvetzer *et al.*, the gold nanoparticles coated with tumor-selective antibodies bind to carcinoma cells, leading to the accumulation of attenuation coefficient [10]. The accumulation leads to five times greater CT attenuation compared to non-targeted cancer cells and normal cells. The technique is advantageous because of its ability to target antigens of cells that are metastasizing [8]. In murine studies, Reuveni *et al.* showed this ability when nude mice were injected with EGF-conjugated gold nanoparticles. The head and neck cancers of these mice showed contrast enhancement that were not detected under conventional CT [11]. Additionally, anti-CD4-target gold nanoparticles have been shown to enhance X-ray contrast of peripheral lymph nodes, which can help with radiation treatment planning for targeting tumors and normal organs [12].

In addition to enhancing CT imaging, gold nanoparticles have also been investigated as magnetic resonance imaging (MRI) contrast agents. Gold nanoparticles have also been investigated as MRI-related contrast platforms for two main reasons: 1) "improved sensitivity" relative to CT at low concentrations (the sensitivity of CT imaging of AuNPs tends to fall off at a concentration of about 0.5 mg/mL), and 2) the potential to provide complementary pathological or molecular information when combined with other imaging modalities [13]. Currently, gold nanoparticles are still being investigated in many different imaging methods. For example, researchers are currently exploring gold-iron oxide micellar formulation as a contrasting agent for CT and MRI imaging of tumors in mice. Choi *et al.* demonstrated gold-iron oxide micellar formulation through the use of hybrid FePt-Au nanoparticles in molecular MR imaging and other biological detection modalities and of dumbbell-shaped Au-Fe_3O_4 nanoparticles as MR imaging agents [14]. Collectively, these studies suggest that GNPs can improve contrast performance under selected experimental conditions; however, the evidence remains dominated by preclinical imaging models, and comparative human data remain sparse. Human clinical evidence remains limited.

3.2. Nanotechnology for Radiation Sensitizer

Radiation oncology consists of multiple technologies delivering cytotoxic ionizing radiation to malignant tumors. These technologies have taken advantage of various particle types, dose fractionation, and radiation doses in order to most effectively increase therapeutic benefits while minimizing harm to nearby normal organs [2]. The main adverse effect of radiotherapy is unnecessary radiation delivered to surrounding tissues, which may induce toxicities, organ failure, and consequent complications [1]. Thus, researchers and physicians have been working to discover better ways to provide radiation therapy with increased cytotoxicity to cancerous cells while limiting dosage to normal organs. Since the past two decades researchers have found some potential of gold nanoparticles to target cancerous cells as radiosensitizers [3]-[5].

Radiation sensitization is a process of enhancing the susceptibility of tumor tissues to injury by radiation. Gold nanoparticles' use as a radiosensitizer has received considerable interest from their ability to improve radiotherapeutic effects [6]. Gold nanoparticles are able to scatter and absorb high-energy photons, which leads to more accurate targeting of cellular components with tumor tissues to allow for more precise damage [15]. The goal is to maximize the tumor damage while limiting the amount of radiation doses to healthy tissue. Currently, usage of gold nanoparticles as a radiosensitizer is still being tested for effectiveness in cancer imaging and cancer treatment in mice and in human cells *in vitro* [3]. The theory behind how gold nanoparticles influence radiation is by locating the tumor cell and binding to it, improving local tumor imaging, hence better defining the target volume during the treatment planning process. Gold nanoparticles have a high atomic number (Z), resulting in more electrons and greater mass energy absorption of photons, which provides a much better contrast compared to soft tissue [3] [5] [6]. When combined with the idea that GNPs coalesce at the tumor site, imaging of cancer cells and their sites will improve. Additionally, gold nanoparticles have been shown to enhance radiation dosage to the cancer cells based on their properties in absorbing photons [2] [3]. In murine studies, Hainfield *et al.* found that upon intravenous injection of 1.9 nanometer diameter gold particles into mice with breast cancer (mammary carcinomas), there was an 86% one-year survival rate as compared to 20% in the control arm when both study arms were given high energy x-ray treatment [1]. This positive finding is attributed to higher tumor-to-normal-tissue ratio of gold nanoparticle concentration, which was 8:1 (**Figure 4**). Specifically, "radiation alone induced tumour growth delay; however,

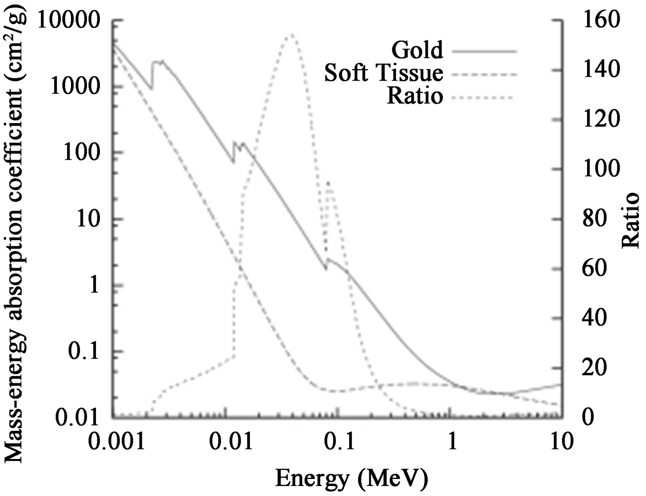

Figure 4. The graph depicts the photon mass energy absorption of gold compared to soft tissue. The ratio of mass energy absorption coefficients is shown as a function of photon energy. Image was taken from Butterworth *et al.*, "Radiosensitization by gold nanoparticles: effective at megavoltage energies and potential role of oxidative stress", Translational Cancer Research, 2013 [Vol 2] [No 4].

radiation and AuNPs actually led to a dramatic reduction in tumour growth when assessed 1 month after treatment" [15]. However, the mechanism for these results is still under investigation, as many factors such as gold nanoparticle shape, size, concentration and type of cell lines, and radiation energy and type may account for the uncertainty of gold nanoparticle effectiveness [6]. *In vitro* findings suggest similar positive effects in HeLa cells, although the results remain inconclusive [15] [16]. Thus, although currently research is in support of the development of gold nanoparticles as dosage enhancers for radiation treatment, more information must be determined before clinical phase trials can begin.

In theory, the potential of gold nanoparticles for radiation dose enhancement exists, but there are realistic limitations that still need to be examined. While benefits *in vitro* and *in vivo* (in mice) have been determined, there are realistic procedural issues, including the ability of intravenous injection of AuNPs to access deeper tissue, even concentration of gold particles within the desired target, and the longevity of the AuNPs in the bloodstream [4]. In addition, the ideal radiation dosage and AuNP concentration within a tumor have yet been realized, as current testing of these variables provide inconsistent results [4] [6]. Thus, in order for human effectiveness and efficacy trials to utilize this new approach to heavy-atom radiation therapy, more research must be done to make gold nanoparticles realizable in patient treatment.

Gold nanoparticles have been tested to see if they induce radiosensitization at megavoltage energy, despite previous research illustrating that radiosensitization occurs at kilovoltage energy [3] (**Figure 5**). As a result of modern testing, there has been more research that shows that radiosensitization has shown to occur at megavoltage energy, which is the typical energy used in current radiation therapy [1] [2] [3] [13]. For example, Jain *et al.* showed similar radiosensitization in breast cancer when comparing dose enhancement of megavoltage energy with dose enhancement of kilovoltage energy [16]. Recently, research has demonstrated gold nanoparticles enhance tumor-killing efficiency at megavoltage and illustrate similar efficiency for kilovoltage and megavoltage [4]. Dorsey *et al.* reported that gold nanoparticles can exhibit radiosensitization at megavoltage radiation energies [15]. Studies are being conducted to analyze how gold nanoparticles can affect radiosensitization at different ranges of energy [15] [16].

Another mechanism for gold nanoparticles in radiosensitization through enhancing "radiation damage by inducing cellular responses such as cell cycle acceleration, cytokinesis arrest, increased apoptosis, and reactive oxygen species (ROS)-induced DNA damage" [15] [16]. *In vitro* findings suggest that gold nanoparticles can enhance radiosensitization through multiple biological mechanisms; however, the extent to which these effects translate to clinical radiation therapy remains uncertain. Across cell lines and animal studies, there are various degrees of radiosensitization and tumor cell killing [15] [16]. In one example, Hainfield *et al.* demonstrated that injecting gold nanoparticles into mice caused accumulation, and mammary carcinoma killed through radiation [17]. In another example,

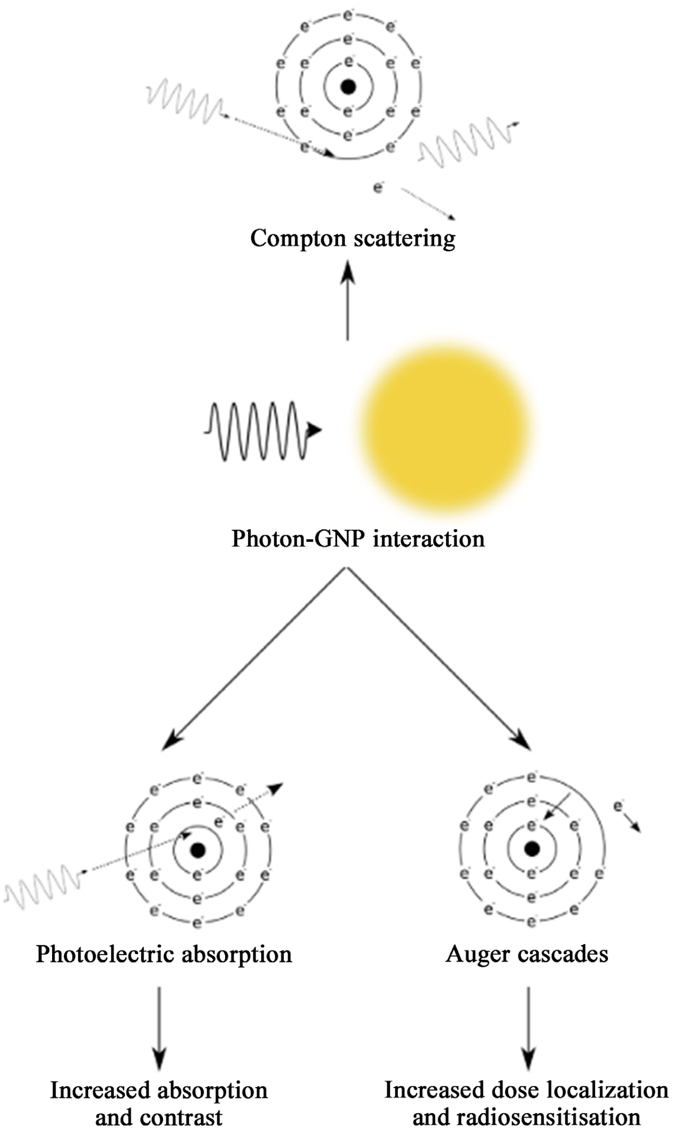

Figure 5. An image schematic of radiation interactions with gold nanoparticles relating to downstream applications in radiation research. Top, Compton scattering in which an incident photon is scattered by a weakly bound outer-shell electron. This process causes the photon to be deflected and lose energy, which is transferred to the electron which is ejected from the atom. Bottom: Photoelectric ionisation in which an incident photon is fully absorbed by an inner-shell electron, transferring energy to it and causing it to be ejected from the atom. Outer-shell electrons can fall into this vacancy, liberating further energy, often in the form of additional secondary Auger electrons. This image was taken from Butterworth *et al.*, "Radiosensitization by gold nanoparticles: effective at megavoltage energies and potential role of oxidative stress", Translational Cancer Research, 2013 [Vol 2] [No 4].

Chang *et al.* illustrated gold nanoparticles accumulation within melanoma cells, which then led to enhancing "the efficacy of ionizing radiation, inducing tumor cell apoptosis, retarding tumor growth, and resulting in significantly increased survival in tumor-bearing mice" [18]. There have been more results showing gold nanoparticles radio-enhancement for head and neck squamous cell carcinoma, prostate cancer, ovarian cancer, glioma cells, and brain tumors, leading to "enhanced DNA damage, tumor cell killing, and improved survival" [15] [18] [19]. The results from these studies suggest that gold nanoparticles cause higher efficacy in killing tumor cells, potentially leading to higher local control and survival rate. Importantly, reported radiosensitization is not uniform across studies and appears sensitive to nanoparticle design, intracellular localization, radiation energy, and tumor model, which limits straightforward clinical extrapolation. Human clinical evidence remains limited.

In preclinical studies, proton radiotherapy has been reported to show greater tumor-killing efficacy when tumors are loaded with gold nanoparticles. Polf *et al.* showed that loading gold nanoparticles into prostate cancer cells had an "increased ionization density and lower survival fraction when irradiated with proton beams compared to cells exposed to proton therapy alone" [20]. They discovered a significant increase of around 15% - 20% of proton therapy effectiveness when tumors are loaded with gold nanoparticles compared to proton therapy alone. They attribute this effect to "proton-Au scatter interactions and production of low energy delta-ray electrons, which result in lethal intracellular damage and lower cell survival for any given proton dose" [20]. In another recent study, Kim *et al.* demonstrated the irradiation of protons with injection of gold nanoparticles and discovered "significant dose enhancement with increased intracellular ROS generation *in vitro* as well as increased tumor regression and mouse survival *in vivo*, due to release of secondary electrons and particle-induced radiation" [15] [19] [21].

3.3. Nanotechnology in Chemotherapy

Chemotherapy treatment is used for many types of cancers. In many cases, chemotherapy is given with radiation, referred to as chemo-radiation therapy [22]. Chemo-radiation therapy has been shown to improve outcomes in selected cancer types and stages, although it may also increase toxicity compared with chemotherapy or radiation alone [22]. In preclinical models, gold nanoparticles are being examined for their potential to lower the levels of toxicity during chemoradiation therapy. Also, gold nanoparticles have been shown to improve the synergy between chemotherapy and radiotherapy, leading to more therapeutic efficacy [22] [23].

Studies have shown that the effects of gold nanoparticles on lowering toxicity for chemoradiation can be attributed to their molecular size. Because of their bigger size, gold nanoparticles have unique biodistribution when bound to chemo drugs [22]. Nanoparticles are unable to fit into the smaller vessels of normal vasculature and capillaries, and therefore travel into tumor vasculature [24] [25]. The lower drug concentration in normal vasculature results in reduced treatment toxicity [22]. Also, gold nanoparticles' larger size allows for it to be removed from circulation in two ways; through the mononuclear phagocytic system (MPS) and hepatic excretion [24]. The systematic clearance of nanoparticle-bound-chemo drugs will decrease the duration and area of exposure when compared to smaller molecules chemotherapeutics, which have multiple secretion routes in the body [22] [24]. Although nanoparticle-mediated delivery may reduce systemic exposure in some models, these benefits should be interpreted cautiously because biodistribution and tumor uptake remain highly context dependent. Human clinical evidence remains limited, and the magnitude of benefit in patients remains uncertain.

Gold nanoparticles have been shown to improve chemoradiotherapy through the enhanced permeability and retention (EPR) effect. Tumor angiogenesis causes rapid proliferation of endothelial cells that are poorly aligned, which leads to pores and leaky blood vessels [23] (**Figure 6**). Nanoparticles travel through these pores and blood vessels to reach the tumor. Unlike normal cells where the lymphatic system is able to clear out macromolecules, the irregular and rapid proliferation of tumor cells leads to defective lymphatic system. A defective lymphatic system allows for the nanoparticles to accumulate within the tumor by prevention of excretion of the nanoparticles [22] [26]. The buildup of nanoparticles then leads to the enhancement of "irregular tumor vasculature structure, high vascular density within the tumor, increased tumor vessel permeability, and defective lymphatic drainage", creating the EPR effect [25] [27]-[29]. Radiotherapy further enhances the target of tumors with the nanoparticles and drug concentrations accumulated at the tumor location because of the EPR effect (**Figure 7**). Studies have shown that accumulated nanoparticles can irradiate tumors better than non-irradiated tumors [30] [31]. In selected preclinical models, gold nanoparticles may improve therapeutic efficacy by allowing lower chemotherapy dosing and potentially reduced toxicity [30].

3.4. Current Limitations

Despite substantial interest in gold nanoparticles for oncologic imaging and therapy,

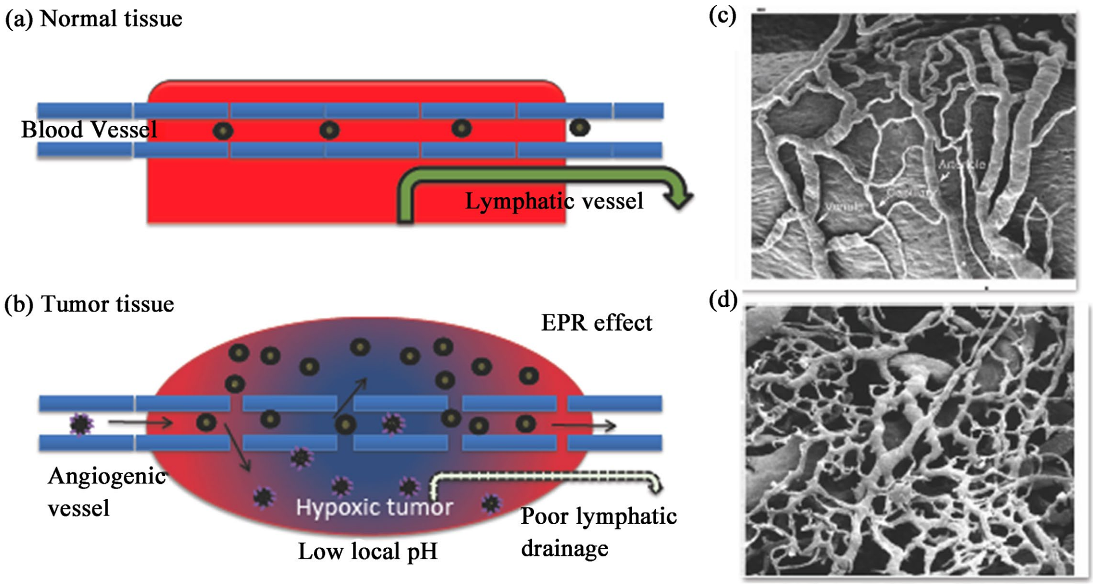

Figure 6. A diagram representing how differences in tumor vessel tissue can influence the localization of chemotherapy. This image is from Upreti *et al.* "Tumor microenvironment and nanotherapeutics", Translational Cancer Research, 2013 [Vol 2] [No 4].

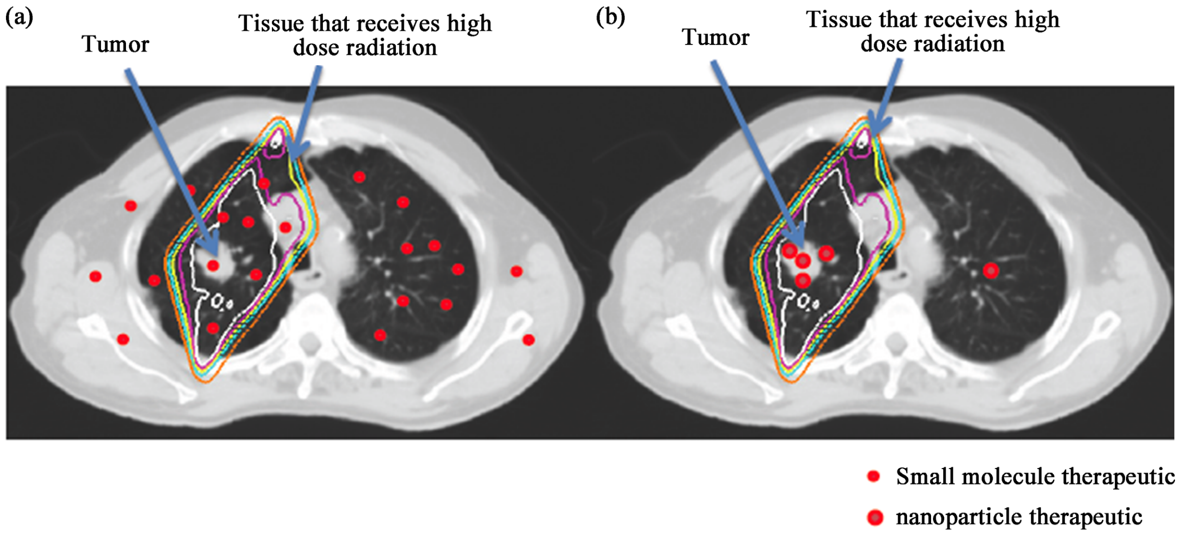

Figure 7. Diagram of lung cancer chemotherapy delivery comparing small molecule drugs (a) to nanoparticles (b). This image was taken from Eblan *et al.*, improving chemoradiotherapy with nanoparticle therapeutics, Translational Cancer Research, 2013 [Vol 2] [No 4].

clinical translation remains limited. Most published evidence remains preclinical, and comparisons across studies are complicated by major differences in particle size, shape, surface coating, tumor model, delivery route, and radiation energy [8] [15] [23]. As a result, findings from one platform cannot be assumed to generalize across all GNP formulations.

Safety also remains an important limitation. Although bulk gold has a history of medical use, nanoparticle formulations should not be broadly described as uniformly safe or non-toxic. Their biological effects depend on physicochemical properties such as size, coating, dose, route of administration, circulation time, organ accumulation, and clearance. Concerns remain regarding persistence in the reticuloendothelial system, delayed hepatic clearance, and possible renal or off-target tissue effects [32].

Another major translational challenge is tumor delivery [25] [29]. Many studies rely on the enhanced permeability and retention (EPR) effect to explain nanoparticle accumulation; however, EPR-based delivery is heterogeneous across tumor types and is not uniformly reliable in human tumors [25] [29]. This limits the predictability of intratumoral uptake and may reduce the consistency of therapeutic benefit in clinical settings [8] [25] [29] [33].

The current clinical evidence base is also narrow. Only a limited number of nanoparticle-based formulations have advanced to early-phase clinical evaluation, and these examples should be interpreted carefully. Gold-based platforms such as CYT-6091 and AuroShell particles illustrate translational efforts involving gold-containing systems, whereas NBTXR3 is a hafnium oxide nanoparticle and should be considered a non-gold comparator rather than a gold nanoparticle clinical example [23] [34].

Finally, large-scale clinical implementation will require improved manufacturing reproducibility, tighter control of nanoparticle size and surface functionalization, standardized characterization methods, and clearer regulatory pathways. Until these issues are addressed, gold nanoparticles should be viewed as promising but still investigational tools in cancer imaging and treatment [35]-[37].

5. Summary and Conclusions

Gold nanoparticles represent a versatile and promising platform for enhancing cancer imaging, radiation therapy, and chemotherapy [8] [13] [19] [37]. Their unique properties enable improved tumor targeting, increased treatment efficacy, and potentially reduced toxicity. However, translation to routine clinical practice requires overcoming challenges related to safety, reproducibility, and regulatory approval [17] [19]. Ongoing research and well-designed clinical trials will be critical to realizing the full potential of GNPs in oncology [3].

Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

References

[1] Hainfeld, J.F., Slatkin, D.N. and Smilowitz, H.M. (2004) The Use of Gold Nanoparticles to Enhance Radiotherapy in Mice. *Physics in Medicine and Biology*, **49**, N309-N315. https://doi.org/10.1088/0031-9155/49/18/n03

[2] Gavas, S., Quazi, S. and Karpiński, T.M. (2021) Nanoparticles for Cancer Therapy: Current Progress and Challenges. *Nanoscale Research Letters*, **16**, Article No. 173. https://doi.org/10.1186/s11671-021-03628-6

[3] Hainfeld, J.F., Dilmanian, F.A., Slatkin, D.N. and Smilowitz, H.M. (2008) Radiotherapy Enhancement with Gold Nanoparticles. *Journal of Pharmacy and Pharmacology*, **60**, 977-985. https://doi.org/10.1211/jpp.60.8.0005

[4] Sun, L., Liu, H., Ye, Y., Lei, Y., Islam, R., Tan, S., *et al.* (2023) Smart Nanoparticles for Cancer Therapy. *Signal Transduction and Targeted Therapy*, **8**, Article No. 418. https://doi.org/10.1038/s41392-023-01642-x

[5] Hossain, M. and Su, M. (2012) Nanoparticle Location and Material-Dependent Dose Enhancement in X-Ray Radiation Therapy. *The Journal of Physical Chemistry C*, **116**, 23047-23052. https://doi.org/10.1021/jp306543q

[6] Jain, S., Hirst, D.G. and O'Sullivan, J.M. (2012) Gold Nanoparticles as Novel Agents for Cancer Therapy. *The British Journal of Radiology*, **85**, 101-113. https://doi.org/10.1259/bjr/59448833

[7] McMahon, S.J., Hyland, W.B., Muir, M.F., Coulter, J.A., Jain, S., Butterworth, K.T., *et al.* (2011) Biological Consequences of Nanoscale Energy Deposition near Irradiated Heavy Atom Nanoparticles. *Scientific Reports*, **1**, Article No. 18. https://doi.org/10.1038/srep00018

[8] Niżnik, Ł., Noga, M., Kobylarz, D., Frydrych, A., Krośniak, A., Kapka-Skrzypczak, L., *et al.* (2024) Gold Nanoparticles (AuNPs)—Toxicity, Safety and Green Synthesis: A Critical Review. *International Journal of Molecular Sciences*, **25**, Article 4057. https://doi.org/10.3390/ijms25074057

[9] Mesbahi, A. (2010) A Review on Gold Nanoparticles Radiosensitization Effect in Radiation Therapy of Cancer. *Reports of Practical Oncology & Radiotherapy*, **15**, 176-180. https://doi.org/10.1016/j.rpor.2010.09.001

[10] Popovtzer, R., Agrawal, A., Kotov, N.A., Popovtzer, A., Balter, J., Carey, T.E., *et al.* (2008) Targeted Gold Nanoparticles Enable Molecular CT Imaging of Cancer. *Nano Letters*, **8**, 4593-4596. https://doi.org/10.1021/nl8029114

[11] Reuveni, T., Motiei, M., Romman, Z., *et al.* (2011) Targeted Gold Nanoparticles Enable Molecular CT Imaging of Cancer: An *in Vivo* Study. *International Journal of Nanomedicine*, **6**, 2859-2864. https://doi.org/10.2147/ijn.s25446

[12] Eck, W., Nicholson, A.I., Zentgraf, H., Semmler, W. and Bartling, S. (2010) Anti-CD4-Targeted Gold Nanoparticles Induce Specific Contrast Enhancement of Peripheral Lymph Nodes in X-Ray Computed Tomography of Live Mice. *Nano Letters*, **10**, 2318-2322. https://doi.org/10.1021/nl101019s

[13] Georgeous, J., AlSawaftah, N., Abuwatfa, W.H. and Husseini, G.A. (2024) Review of Gold Nanoparticles: Synthesis, Properties, Shapes, Cellular Uptake, Targeting, Release Mechanisms and Applications in Drug Delivery and Therapy. *Pharmaceutics*, **16**, Article 1332. https://doi.org/10.3390/pharmaceutics16101332

[14] Choi, J., Jun, Y., Yeon, S., Kim, H.C., Shin, J. and Cheon, J. (2006) Biocompatible Heterostructured Nanoparticles for Multimodal Biological Detection. *Journal of the American Chemical Society*, **128**, 15982-15983. https://doi.org/10.1021/ja066547g

[15] Dorsey, J.F., Sun, L., Joh, D.Y., *et al.* (2013) Gold Nanoparticles in Radiation Research: Potential Applications for Imaging and Radiosensitization. *Translational Cancer Research*, **2**, 280-291.

[16] Jain, S., Coulter, J.A., Hounsell, A.R., Butterworth, K.T., McMahon, S.J., Hyland, W.B., *et al.* (2011) Cell-Specific Radiosensitization by Gold Nanoparticles at Megavoltage Radiation Energies. *International Journal of Radiation Oncology*Biology*Physics*, **79**, 531-539. https://doi.org/10.1016/j.ijrobp.2010.08.044

[17] Hainfeld, J.F., O'Connor, M.J., Dilmanian, F.A., Slatkin, D.N., Adams, D.J. and Smilowitz, H.M. (2011) Micro-CT Enables Microlocalisation and Quantification of Her2-Targeted Gold Nanoparticles within Tumour Regions. *The British Journal of Radiology*, **84**, 526-533. https://doi.org/10.1259/bjr/42612922

[18] Chang, M., Shiau, A., Chen, Y., Chang, C., Chen, H.H. and Wu, C. (2008) Increased Apoptotic Potential and Dose-Enhancing Effect of Gold Nanoparticles in Combination with Single-Dose Clinical Electron Beams on Tumor-Bearing Mice. *Cancer Science*, **99**, 1479-1484. https://doi.org/10.1111/j.1349-7006.2008.00827.x

[19] Penninckx, S., Heuskin, A., Michiels, C. and Lucas, S. (2020) Gold Nanoparticles as a Potent Radiosensitizer: A Transdisciplinary Approach from Physics to Patient. *Cancers*, **12**, Article 2021. https://doi.org/10.3390/cancers12082021

[20] Polf, J.C., Bronk, L.F., Driessen, W.H.P., Arap, W., Pasqualini, R. and Gillin, M. (2011) Enhanced Relative Biological Effectiveness of Proton Radiotherapy in Tumor Cells with Internalized Gold Nanoparticles. *Applied Physics Letters*, **98**, Article 193702. https://doi.org/10.1063/1.3589914

[21] Kim, J., Seo, S., Kim, H., Kim, K., Chung, M., Kim, K., *et al.* (2012) Enhanced Proton Treatment in Mouse Tumors through Proton Irradiated Nanoradiator Effects on Metallic Nanoparticles. *Physics in Medicine and Biology*, **57**, 8309-8323. https://doi.org/10.1088/0031-9155/57/24/8309

[22] Eblan, M.J. and Wang, A.Z. (2013) Improving Chemoradiotherapy with Nanoparticle Therapeutics. *Translational Cancer Research*, **2**, 320-329.

[23] Hheidari, A., Mohammadi, J., Ghodousi, M., Mahmoodi, M., Ebrahimi, S., Pishbin, E., *et al.* (2024) Metal-Based Nanoparticle in Cancer Treatment: Lessons Learned and Challenges. *Frontiers in Bioengineering and Biotechnology*, **12**, Article ID: 1436297. https://doi.org/10.3389/fbioe.2024.1436297

[24] Hobbs, S.K., Monsky, W.L., Yuan, F., Roberts, W.G., Griffith, L., Torchilin, V.P., *et al.* (1998) Regulation of Transport Pathways in Tumor Vessels: Role of Tumor Type and Microenvironment. *Proceedings of the National Academy of Sciences*, **95**, 4607-4612. https://doi.org/10.1073/pnas.95.8.4607

[25] Jain, R.K. and Stylianopoulos, T. (2010) Delivering Nanomedicine to Solid Tumors. *Nature Reviews Clinical Oncology*, **7**, 653-664. https://doi.org/10.1038/nrclinonc.2010.139

[26] Kwatra, D., Venugopal, A. and Anant, S. (2013) Nanoparticles in Radiation Therapy: A Summary of Various Approaches to Enhance Radiosensitization in Cancer. *Translational Cancer Research*, **2**, 330-342.

[27] Noguchi, Y., Wu, J., Duncan, R., Strohalm, J., Ulbrich, K., Akaike, T., *et al.* (1998) Early Phase Tumor Accumulation of Macromolecules: A Great Difference in Clearance Rate between Tumor and Normal Tissues. *Japanese Journal of Cancer Research*, **89**, 307-314. https://doi.org/10.1111/j.1349-7006.1998.tb00563.x

[28] Maeda, H., Wu, J., Sawa, T., Matsumura, Y. and Hori, K. (2000) Tumor Vascular Permeability and the EPR Effect in Macromolecular Therapeutics: A Review. *Journal of Controlled Release*, **65**, 271-284. https://doi.org/10.1016/s0168-3659(99)00248-5

[29] Chauhan, V.P., Stylianopoulos, T., Boucher, Y. and Jain, R.K. (2011) Delivery of Molecular and Nanoscale Medicine to Tumors: Transport Barriers and Strategies. *Annual Review of Chemical and Biomolecular Engineering*, **2**, 281-298. https://doi.org/10.1146/annurev-chembioeng-061010-114300

[30] Lammers, T., Subr, V., Peschke, P., Kühnlein, R., Hennink, W.E., Ulbrich, K., *et al.* (2008) Image-Guided and Passively Tumour-Targeted Polymeric Nanomedicines for Radiochemotherapy. *British Journal of Cancer*, **99**, 900-910. https://doi.org/10.1038/sj.bjc.6604561

[31] Lammers, T., Peschke, P., Kühnlein, R., Subr, V., Ulbrich, K., Debus, J., *et al.* (2007) Effect of Radiotherapy and Hyperthermia on the Tumor Accumulation of HPMA Copolymer-Based Drug Delivery Systems. *Journal of Controlled Release*, **117**, 333-341. https://doi.org/10.1016/j.jconrel.2006.10.032

[32] Longmire, M., Choyke, P.L. and Kobayashi, H. (2008) Clearance Properties of Nano-Sized Particles and Molecules as Imaging Agents: Considerations and Caveats. *Nanomedicine*, **3**, 703-717. https://doi.org/10.2217/17435889.3.5.703

[33] O'Brien, M.E.R., Wigler, N., Inbar, M., Rosso, R., Grischke, E., Santoro, A., *et al.* (2004) Reduced Cardiotoxicity and Comparable Efficacy in a Phase Iiitrial of Pegylated Liposomal Doxorubicin HCL(CAELYX™/Doxil®) versus Conventional Doxorubicin Forfirst-Line Treatment of Metastatic Breast Cancer. *Annals of Oncology*, **15**, 440-449. https://doi.org/10.1093/annonc/mdh097

[34] Chatterjee, D.K., Wolfe, T., Lee, J., *et al.* (2013) Convergence of Nanotechnology with Radiation Therapy-Insights and Implications for Clinical Translation. *Translational Cancer Research*, **2**, 256-268.

[35] Butterworth, K.T., McMahon, S.J., Taggart, L.E. and Prise, K.M. (2013) Radiosensitization by Gold Nanoparticles: Effective at Megavoltage Energies and Potential Role of Oxidative Stress. *Translational Cancer Research*, **2**, 269-279.

[36] Urban, C., Urban, A.S., Charron, H. and Joshi, A. (2013) Externally Modulated Theranostic Nanoparticles. *Translational Cancer Research*, **2**, 292-308.

[37] Sharma, D.K. (2025) Recent Advancements in Nanoparticles for Cancer Treatment. *Medical Oncology*, **42**, Article No. 72. https://doi.org/10.1007/s12032-025-02609-4

Abbreviations List

GNP	Gold Nanoparticle
SPR	Surface Plasmon Resonance
CT	Computed Tomography
MRI	Magnetic Resonance Imaging
EPR	Enhanced Permeability and Retention
LSP	Localized Surface Plasmons
ROS	Reactive Oxygen Species
MPS	Mononuclear Phagocytic System
Z	Atomic Number
PDT	Photodynamic Therapy
AuNP	Gold Nanoparticle