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# رویکردهای اتمی در درمان سرطان: پیشرفت‌ها، ساز و کارها و کاربردهای بالینی

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**چکیده**

**زمینه و هدف:** درمان‌های مبتنی بر اتم به‌عنوان یک طبقه نوظهور از روش‌های درمانی مطرح شده‌اند که از ویژگی‌های فیزیکی و شیمیایی منحصربه‌فرد اتم‌ها، به‌ویژه ایزوتوپ‌های رادیواکتیو و نانوذرات فلزی، برای هدف‌گیری دقیق و انتخابی تومورها بهره می‌برند. این رویکردها نسبت به درمان‌های مرسوم، مزایای قابل‌توجهی از جمله اختصاصیت بیشتر، حداقل تهاجم و قابلیت ادغام با ابزارهای تشخیصی را ارائه می‌دهند. این مرور با هدف ارائه یک دید جامع از راهبردهای درمانی مبتنی بر اتم در سرطان‌شناسی تدوین شده است و عناصر اتمی کلیدی، سازوکارهای اثرگذاری، کاربردهای بالینی و پیشرفت‌های فناورانه را برجسته می‌سازد. همچنین در این بحث به چالش‌های کنونی پرداخته شده و مسیرهای آینده در این حوزه در حال تکامل بررسی می‌گردد.

**روش بررسی:** این مقاله مروری، بر اساس دستورالعمل‌های PRISMA انجام شد. جستجوی جامعی در پایگاه‌های علمی معتبر شامل PubMed، ScienceDirect، Scopus و Web of Science طی بازه زمانی آوریل تا ژوئیه ۲۰۲۵ و با استفاده از کلیدواژه‌هایی مانند «درمان سرطان مبتنی بر اتم»، «رادیوداروها»، «نانوذرات»، «انتشاردهنده‌های پرتوهای آلفا»، «پروتون‌تراپی» و «ترانُستیک در انکولوژی» صورت گرفت. مقالات منتشرشده بین سال‌های ۲۰۰۰ تا ۲۰۲۵ که به زبان انگلیسی، متن کامل و داده‌های تجربی یا بالینی داشتند، وارد مطالعه شدند. در مجموع از میان ۲۱۵ مقاله شناسایی‌شده، پس از غربالگری و حذف موارد تکراری یا نامرتبط، ۱۹ مطالعه واجد شرایط برای تحلیل نهایی انتخاب گردید.

**یافته‌ها:** چندین درمان مبتنی بر اتم، مانند ید-۱۳۱ برای سرطان تیروئید، لوتسیوم-۱۷۷ برای تومورهای نوروآندوکرین و رادیوم-۲۲۳ برای سرطان پروستات متاستاتیک، نتایج درمانی قابل‌توجهی همراه با ایمنی مطلوب نشان داده‌اند. در همین راستا، بسترهای نوینی شامل نانوذرات طلا و اکسید آهن مسیرهای امیدبخشی را برای درمان فوتوترمال و رادیوسنسیتیزاسیون فراهم کرده‌اند. با این حال، موانعی همچون دسترسی محدود، دوزیمتری پیچیده و مقاومت‌های زیستی همچنان مانع از پذیرش گسترده این روش‌ها می‌شوند.

**نتیجه‌گیری:** درمان‌های مبتنی بر اتم یک پیشرفت تحول‌آفرین در انکولوژی نوین به شمار می‌روند و این پتانسیل را دارند که با افزایش دقت، کاهش سمیت سیستمیک و امکان پایش لحظه‌ای، شیوه‌های درمان سرطان را دگرگون سازند. تداوم پژوهش‌های میان‌رشته‌ای و توسعه زیرساخت‌ها برای انتقال این نوآوری‌ها به مراقبت‌های سرطان شخصی‌سازی‌شده و در دسترس همگانی، امری حیاتی است.

**واژه‌گانِ کلیدی:** درمان مبتنی بر اتم، رادیوداروها، نانوذرات، ترانوستیک (ترکیب تشخیص و درمان)، درمان سرطان

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# Atomic approaches in cancer therapy: advances, mechanisms, and clinical applications

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## Abstract

**Background:** Atom-based cancer therapies have emerged as a promising class of treatment modalities that exploit the unique physical and chemical properties of various atoms, particularly radioactive isotopes and metallic nanoparticles, for precise and selective tumor targeting. These approaches offer significant advantages over conventional therapies in terms of specificity, minimal invasiveness, and potential for integration with diagnostic tools. This review aims to provide a comprehensive overview of atom-based therapeutic strategies in oncology, highlighting key atomic elements, mechanisms of action, clinical applications, and technological advancements. The discussion also addresses current challenges and explores future directions in this evolving field.

**Methods:** This review was conducted according to the PRISMA guidelines. A comprehensive search of PubMed, ScienceDirect, Scopus, and Web of Science was carried out between April and July 2025 using keywords such as "atom-based cancer therapy," "radiopharmaceuticals," "nanoparticles," "alpha emitters," "proton therapy," and "theranostics in oncology." Articles published between 2000 and 2025, written in English, with full-text availability and experimental or clinical data were included. From an initial 215 records, after screening and removal of duplicates and irrelevant studies, 19 eligible articles were finally selected for analysis.

**Results:** Several atom-based therapies, such as Iodine-131 for thyroid cancer, Lutetium-177 for neuroendocrine tumors, and Radium-223 for metastatic prostate cancer, have demonstrated strong therapeutic outcomes with favorable safety profiles. In parallel, novel platforms involving gold and iron oxide nanoparticles offer promising routes for photothermal therapy and radiosensitization. Nonetheless, barriers such as limited accessibility, complex dosimetry, and biological resistance continue to hinder widespread adoption.

**Conclusion:** Atom-based therapies represent a transformative advancement in modern oncology, with the potential to reshape cancer treatment through enhanced precision, reduced systemic toxicity, and real-time monitoring. Continued interdisciplinary research and infrastructure development are essential to translate these innovations into widely accessible and personalized cancer care.

**Key words:** Atom-based therapy, Radiopharmaceuticals, Nanoparticles, Theranostics, Cancer treatment

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## 1. Introduction

Cancer continues to be one of the most complex and life-threatening diseases of the 21st century. According to GLOBOCAN 2020 data, cancer was responsible for approximately 19.3 million new cases and 10 million deaths globally in that year alone [1]. The burden of cancer is expected to rise in the coming decades due to aging populations, environmental exposures, and lifestyle factors. Despite substantial advances in medical science, conventional treatment strategies such as surgery, chemotherapy, and external beam radiotherapy often exhibit serious limitations including non-specific targeting, systemic toxicity, and the emergence of resistant cancer cell populations [2, 3]. Atomic and nuclear-based techniques represent one of the most promising and innovative frontiers in cancer therapy. These approaches exploit the unique properties of various atoms, particularly their radioactive, magnetic, and photothermal characteristics, to selectively destroy cancerous tissues while minimizing harm to surrounding healthy cells [4]. The convergence of atomic physics, nuclear chemistry, biomedical engineering, and nanotechnology has opened new pathways for treating tumors at the molecular and cellular level, improving the therapeutic index of many treatment protocols [5, 6].

One of the earliest examples of atom-based cancer therapy is the use of radioactive iodine (Iodine-131) for the treatment of differentiated thyroid cancer. Since its introduction in the mid-20th century, this method has demonstrated high specificity and efficacy with minimal side effects [7]. More recently, a variety of radionuclides such as Lutetium-177, Yttrium-90, and Actinium-225 have been incorporated into targeted radiopharmaceuticals that selectively bind to tumor-specific receptors, enabling localized delivery of ionizing radiation. These radiopharmaceuticals have shown success in treating neuroendocrine tumors, prostate cancer, lymphomas, and certain metastatic malignancies [8, 9].

In parallel, the application of nanotechnology has enabled the development of atomically engineered materials, such as gold nanoparticles (AuNPs), superparamagnetic iron oxide nanoparticles (SPIONs), and hafnium oxide particles, that can be activated through external stimuli like light, heat, or magnetic fields [10, 11]. These platforms allow for novel forms of therapy such as photothermal ablation, magnetic hyperthermia, and radiosensitization, which enhance tumor eradication while limiting collateral damage [12].

Moreover, particle therapy using protons or heavy ions (e.g., carbon ions) exploits the Bragg peak phenomenon, which delivers maximal energy deposition at a specific tissue depth. This allows for superior tumor targeting compared to conventional photon-based radiotherapy. Heavy ion therapy has shown particularly strong promise in treating deep-seated or radioresistant tumors, including sarcomas and head and neck cancers [13].

Despite the remarkable progress, atom-based therapies are still facing several scientific, logistical, and regulatory challenges. These include limited access to radionuclide production facilities, the need for specialized infrastructure, concerns about long-term radiation exposure, and the complexity of individualizing treatment plans based on tumor type and genetic profile [14]. Furthermore, long-term clinical data are still required to establish standardized protocols for many of these techniques.

In this context, the purpose of this review is to provide a comprehensive and up-to-date analysis of how various atoms and atomic-scale technologies are employed in the treatment of cancer. We will explore different therapeutic approaches, such as radiopharmaceutical therapy, particle therapy, and nanomaterial-mediated interventions, emphasizing the mechanisms of action, clinical applications, and technological innovations. Additionally, the review will discuss the current challenges and future directions in this dynamic and interdisciplinary field.

## 2. Materials and Methods

### 2.1. Search strategy

This review was conducted following the PRISMA guidelines. A comprehensive literature search was performed using major scientific databases including PubMed, ScienceDirect, Scopus, Web of Science. The search was conducted between April and July 2025, using the following keywords: "*atom-based cancer therapy*", "*radiopharmaceuticals*", "*nanoparticle cancer treatment*", "*alpha emitters*", "*proton therapy*", and "*theranostics in oncology*".

The search included articles published between 2000 and 2025, in English language only. Additional manual screening of reference lists from relevant reviews and original articles was also performed to ensure completeness.

### 2.2. Inclusion and exclusion criteria

Included studies met the following criteria:

- Focused on atom-based or atomic-level cancer therapies (radioisotopes, nanoparticles, particle beam therapy, etc.)

- Involved in vitro, in vivo, or clinical data
- Peer-reviewed and accessible in full text
- Published within the last 12 years

Excluded studies were:

- Not directly related to cancer treatment
- Focused on purely theoretical models without biological or clinical relevance
- Articles with incomplete data or unavailable full text
- Duplicates across databases

2.3. Screening and selection process

A total of 215 records were initially identified through database searches. After removing 23 duplicate records, 192 unique articles remained for screening.

In the first screening phase (title and abstract review), 102 records were excluded for not meeting the inclusion criteria, primarily due to being off-topic, non-oncological, or unrelated to atom-based methods.

The remaining 90 articles underwent full-text review. After detailed evaluation, 71 were excluded, including 39 that were not cancer-related and 32 that did not focus on atom-based therapies. Ultimately, 19 studies met all eligibility criteria and were included in this review (Figure 1).

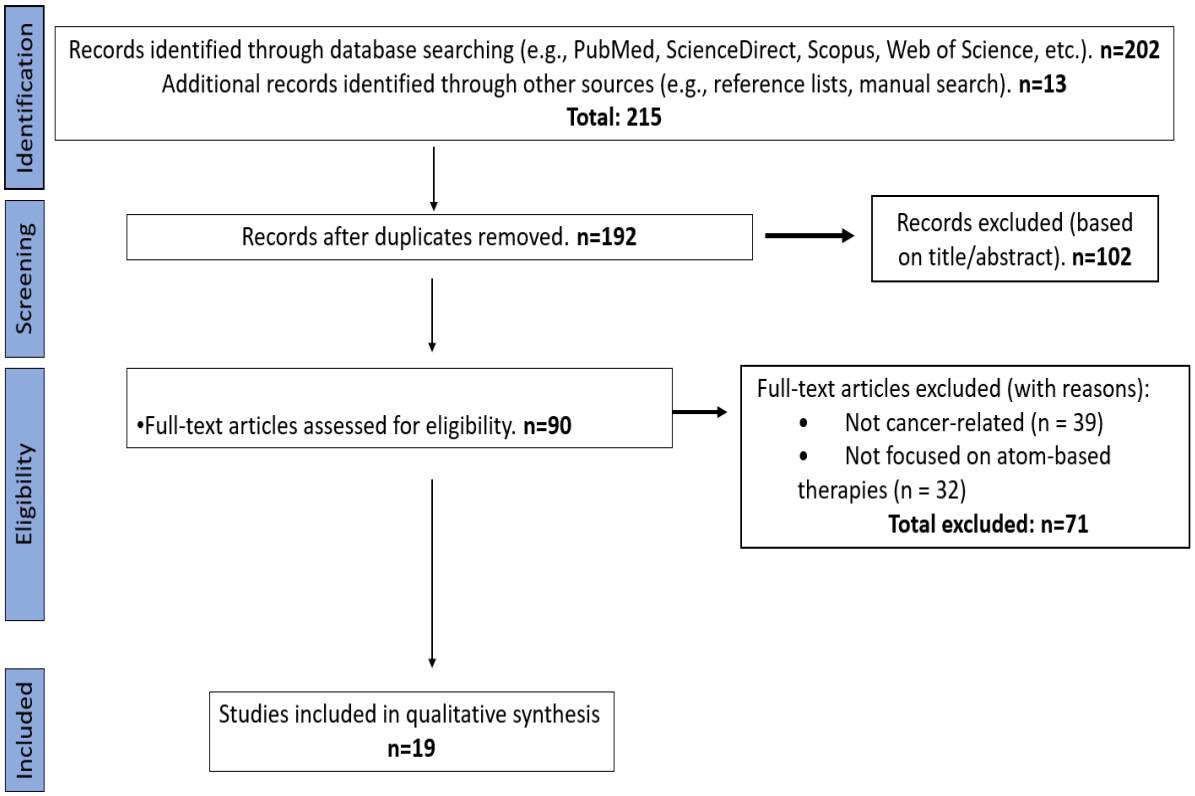


**Figure 1. PRISMA flow diagram of study selection**

**Table 1. Overview of the characteristics of the included studies**

| | Study (Author, Year) | Design | Intervention(s) | Outcome(s) |
|---|---|---|---|---|
| 1 | Sung et al., 2021 | Epidemiological report | N/A | Global cancer statistics |
| 2 | Miller et al., 2022 | Epidemiological report | N/A | Cancer treatment and survivorship statistics |
| 3 | Li et al., 2024 | Modeling/forecasting | N/A | Aging and cancer burden |
| 4 | Chakraborty et al., 2023 | Review | Radionuclides and radiolabelled peptides | Cancer therapeutics |
| 5 | Watabe et al., 2025 | Review | Emerging radionuclides | Theranostics and oncology PET |
| 6 | Samathoti et al., 2025 | Narrative Review | Nanomedicine & AI | Cancer health care applications |
| 7 | Sgouros et al., 2020 | Review | Radiopharmaceutical therapy | Clinical advances and challenges |
| 8 | Schubiger et al., 2004 | Review | Radiopharmaceuticals | From imaging to therapy |
| 9 | Brechbiel, 2007 | Review | Targeted α-therapy | Past, present, future |
| 10 | Gao et al., 2021 | Review | Gold nanoparticles | Cancer theranostics |
| 11 | Vangijzegem et al., 2023 | Review | SPIONs | Innovative cancer therapy applications |
| 12 | Dürr et al., 2013 | Review | Magnetic nanoparticles | Cancer therapy |
| 13 | Durante et al., 2017 | Review | Charged-particle therapy | Clinical uses & future perspectives |
| 14 | Jadvar, 2017 | Review | Targeted radionuclide therapy | Precision cancer treatment |
| 15 | Williamson et al., 2021 | Review | EBRT and brachytherapy | Cervical cancer treatment |
| 16 | Buczyńska et al., 2021 | Experimental/Clinical | Radioiodine treatment | Oxidative stress in thyroid cancer |
| 17 | Niu et al., 2024 | Review/Clinical | Lutetium-177 | Application in solid tumors |
| 18 | Alshehri, 2024 | Review | Radium-223 chloride | Bone-targeting in prostate cancer |
| 19 | Hu et al., 2024 | Experimental | Nanocascade reaction | Radiotherapy-sensitized immunotherapy |

## 3. Results

### 3.1. Types of atom-based therapies in cancer treatment

The integration of atomic and nuclear sciences into cancer therapy has led to the development of several innovative treatment modalities. These therapies rely on the unique physical and chemical properties of specific atoms, especially radioisotopes and metallic nanoparticles, to deliver therapeutic effects with high precision and selectivity. This section outlines the principal categories of atom-based cancer therapies, focusing on their mechanisms of action, clinical utility, and key atomic components [15].

#### 3.1.1. External beam radiation therapy (EBRT)

External beam radiation therapy is one of the most widely used atom-based modalities in oncology. In this method, high-energy photons (X-rays or gamma rays), generated from radioactive sources such as Cobalt-60 or linear accelerators, are directed toward the tumor from outside the body. These photons interact with cellular DNA, producing double-strand breaks that ultimately lead to cell death [3]. Modern EBRT techniques, such as intensity-modulated radiation therapy (IMRT) and stereotactic body radiation therapy (SBRT), have enhanced treatment precision while reducing radiation exposure to surrounding healthy tissues [15].

#### 3.1.2. Brachytherapy (internal radiotherapy)

Brachytherapy involves the placement of radioactive sources directly inside or near the tumor site. Radioisotopes like Iridium-192 and Cesium-137 are commonly used for this purpose. Because the radiation is emitted in close proximity to the tumor, brachytherapy provides a high localized dose with minimal impact on surrounding normal tissues. It is frequently used in the treatment of prostate, cervical, and breast cancers [15].

3.1.3. Targeted radiopharmaceutical therapy

Targeted radiopharmaceuticals are molecules that combine a therapeutic radionuclide with a targeting vector, such as a peptide, antibody, or ligand, that selectively binds to tumor-associated receptors. One prominent example is Lutetium-177-DOTATATE, used for treating neuroendocrine tumors, which delivers beta radiation directly to somatostatin receptor-positive cells. Similarly, Radium-223 dichloride, an alpha-emitter, is employed in treating bone metastases in castration-resistant prostate cancer. These therapies exemplify the power of atom-level targeting in achieving tumor-specific cytotoxicity while sparing normal tissue [14].

3.1.4. Proton and heavy ion therapy

Unlike conventional radiation that uses photons, particle therapy uses charged atomic particles such as protons or carbon ions. These particles exhibit a unique energy deposition profile known as the Bragg peak, where the bulk of energy is released at a precise depth within the tissue. This allows for maximal tumor cell killing with minimal exit dose, making it ideal for treating pediatric tumors and tumors located near critical organs [13].

3.1.5. Nanoparticle-mediated hyperthermia and radiosensitization

Metal-based nanoparticles, particularly those composed of gold (Au), iron oxide ($Fe_3O_4$), and hafnium oxide ($HfO_2$), have demonstrated significant potential in cancer therapy. When these nanoparticles accumulate within tumor tissue, they can be activated by external sources such as laser light (photothermal therapy), magnetic fields (magnetic hyperthermia), or ionizing radiation (radiosensitization). These processes generate localized heat or reactive species that enhance tumor cell death. Gold nanoparticles, for instance, can amplify the effects of radiotherapy by increasing the local radiation dose via secondary electron production [10, 11].

**3.2. Key atomic elements used in cancer therapy**

Various atomic elements have found therapeutic applications in oncology due to their radioactive decay properties, selective tissue accumulation, or physicochemical characteristics. These elements serve as the core of diverse therapeutic strategies ranging from radiopharmaceuticals to nanoparticle-mediated therapies. In this section, we highlight the most clinically relevant atoms and describe their specific roles in cancer treatment [16].

3.2.1. Iodine-131 ($^{131}I$)

Iodine-131 is a beta- and gamma-emitting radionuclide widely used in the treatment of differentiated thyroid carcinoma. It selectively accumulates in thyroid tissue due to the organ's natural affinity for iodine, allowing for targeted ablation of cancerous thyroid cells while sparing other tissues. Its use has significantly improved recurrence rates and long-term survival in thyroid cancer patients [16].

3.2.2. Lutetium-177 ($^{177}Lu$)

Lutetium-177 is a beta-emitting radionuclide with ideal physical and chemical properties for targeted radionuclide therapy. When conjugated to ligands such as DOTATATE, it enables precise treatment of somatostatin receptor-positive neuroendocrine tumors. Its short tissue penetration range and gamma co-emission also make it suitable for combined therapy and imaging (theranostics) [17].

3.2.3. Radium-223 ($^{223}Ra$)

Radium-223 is an alpha-emitting radionuclide used in the treatment of metastatic prostate cancer with bone involvement. Its high linear energy transfer (LET) and short path length result in potent, localized cytotoxic effects on bone metastases while minimizing damage to surrounding bone marrow [18].

3.2.4. Gold (Au)

Gold atoms, primarily in the form of gold nanoparticles (AuNPs), are extensively researched for their use in photothermal therapy and radiosensitization. Due to their high atomic number (Z), gold particles enhance radiation dose deposition through photoelectric effects, leading to increased DNA damage in tumor cells. Furthermore, gold nanoparticles can be functionalized for active tumor targeting and real-time imaging [10].

3.2.5. Iron (Fe)

Iron oxide nanoparticles (e.g., $Fe_3O_4$) are employed in magnetic hyperthermia therapy. When subjected to alternating magnetic fields, these particles generate heat that selectively kills tumor cells. They also have potential as MRI contrast agents, offering a dual role in diagnosis and therapy [11] (Table 2).

**Table 2. Atomic elements with therapeutic applications in oncology**

| Atomic Element | Therapy Type | Mechanism | Clinical Use | Advantages |
|---|---|---|---|---|
| Iodine-131 | Radiopharmaceutical | DNA damage via β-emission | Thyroid cancer | Targeted, widely used |
| Lutetium-177 | Theranostic radiotherapy | Receptor-targeted β-emission | Neuroendocrine tumors | High specificity |
| Radium-223 | Radiopharmaceutical | Localized DNA damage via α-emission | Bone metastases in prostate cancer | High LET, minimal marrow toxicity |
| Gold (Au) | Nanoparticle-assisted therapy | Photothermal & radiosensitization | Solid tumors (experimental) | Biocompatibility, dual use |
| Iron (Fe) | Magnetic hyperthermia | Heat generation in AMF (alternating magnetic field) | Solid tumors (experimental) | Dual role (therapy & MRI), selective heating |

### 3.3. Mechanisms of action of atom-based cancer therapies

Atom-based cancer therapies exert their therapeutic effects through several well-defined physical, chemical, and biological mechanisms. These mechanisms vary depending on the nature of the atom used, whether radioactive or non-radioactive, and the method of delivery. A detailed understanding of these mechanisms is essential for optimizing treatment efficacy and minimizing off-target toxicity [7,13].

#### 3.3.1. DNA damage by ionizing radiation

One of the most direct mechanisms involves the emission of ionizing radiation from radioactive atoms such as Iodine-131, Lutetium-177, and Radium-223. These isotopes release beta or alpha particles that interact with cellular components, especially DNA. The result is the induction of single-strand and double-strand breaks, chromosomal aberrations, and ultimately apoptotic or mitotic cell death. Alpha particles, due to their high linear energy transfer (LET), produce dense ionization tracks that are particularly lethal to tumor cells, even at low doses [16,18].

#### 3.3.2. Targeted cellular uptake and receptor binding

In targeted radionuclide therapy, therapeutic atoms are delivered via molecules that bind selectively to cancer cell receptors. For instance, Lutetium-177-labeled DOTATATE targets somatostatin receptors on neuroendocrine tumors, ensuring that radiation is primarily confined to malignant cells. This receptor-ligand specificity reduces systemic toxicity and allows for higher therapeutic doses at the tumor site [17].

#### 3.3.3. Thermal ablation via nanoparticles

Metallic nanoparticles, especially gold and iron-based, can be activated by external energy sources such as near-infrared (NIR) laser light or alternating magnetic fields. Upon activation, these particles generate localized heat, leading to the destruction of tumor cells through membrane disruption, protein denaturation, and induction of apoptosis, a process known as hyperthermia. Photothermal therapy using gold nanoparticles is particularly effective because of their efficient light absorption and high biocompatibility [10, 11].

#### 3.3.4. Enhancement of radiation sensitivity (radiosensitization)

High atomic number (Z) elements like gold and hafnium amplify the effects of external radiotherapy through increased production of secondary electrons (Auger electrons and photoelectrons) during photon interactions. This process enhances the radiation dose deposited within the tumor and increases the formation of reactive oxygen species (ROS), further damaging cellular macromolecules [19].

#### 3.3.5. Immune modulation and bystander effects

Recent studies have shown that some atom-based therapies can stimulate immune responses against tumors. For example, localized radiation can induce immunogenic cell death, releasing tumor antigens and danger-associated molecular patterns (DAMPs) that activate dendritic cells and cytotoxic T cells. This phenomenon may contribute to systemic tumor regression, known as the abscopal effect [19].

### 3.4. Advantages and limitations of atom-based cancer therapies

Atom-based therapies have revolutionized the landscape of oncology by providing highly targeted and minimally invasive treatment options. However, despite their numerous strengths, these approaches also face technical, biological, and regulatory limitations that must be addressed to ensure widespread clinical

adoption. This section summarizes the key advantages and current challenges associated with atomic and nuclear-based cancer treatments [4].

3.4.1 Advantages

3.4.1.1. High Specificity and Targeted Action

One of the most significant advantages of atom-based therapies, particularly radiopharmaceuticals and nanoparticle-mediated interventions, is their ability to selectively target tumor cells. By exploiting specific cellular receptors or tumor microenvironment features, these treatments deliver cytotoxic effects precisely to malignant tissues, reducing collateral damage to healthy organs [4].

3.4.1.2. Minimal invasiveness

Unlike surgery or systemic chemotherapy, many atom-based therapies (e.g., targeted radionuclide therapy or brachytherapy) can be administered with minimal or no invasive procedures. This not only reduces patient discomfort but also shortens recovery time and hospital stays [13].

3.4.1.3. Potential for theranostics

Several radiopharmaceuticals offer combined diagnostic and therapeutic functionality (theranostics), such as Lutetium-177 and Technetium-99m derivatives. This dual capability enables real-time imaging of tumor response and allows dynamic adjustment of treatment plans [13].

3.4.1.4. Efficacy against resistant or deep-seated tumors

Particle therapies such as proton and heavy ion therapy are especially effective in treating tumors that are difficult to reach surgically or resistant to conventional photon-based radiotherapy. Their precise depth control and high linear energy transfer (LET) make them suitable for complex tumor anatomies [13].

3.4.2. Limitations

3.4.2.1. Limited accessibility and high cost

Atom-based therapies, especially those involving cyclotron-generated isotopes or particle accelerators, require sophisticated infrastructure and trained personnel. The high setup and maintenance costs restrict availability to specialized centers, particularly in low-resource settings [7].

3.4.2.2. Complex dosimetry and safety concerns

Accurate dosing of radioactive agents remains a critical challenge. Both underdosing and overdosing can lead to suboptimal outcomes or severe toxicity. Additionally, handling and disposal of radioactive materials require strict safety protocols and regulatory compliance [7].

3.4.2.3. Biological heterogeneity and resistance

Tumor heterogeneity and changes in receptor expression over time can compromise the efficacy of targeted atom-based therapies. Furthermore, some cancer types may not express sufficient levels of targetable molecules, limiting the applicability of certain radiopharmaceuticals [7].

3.4.2.4 Limited long-term data

Although many atom-based therapies have shown promising short-term results, long-term clinical data on survival outcomes, late toxicity, and secondary malignancies are still lacking for several newer agents and techniques [7].

## 4. Discussion

Atom-based therapies have significantly enriched the landscape of cancer treatment by introducing a new level of precision, selectivity, and multimodal potential. The clinical success of established agents such as Iodine-131 in thyroid cancer and Lutetium-177 in neuroendocrine tumors validates the effectiveness of radionuclide-based strategies. Likewise, emerging nanotechnological approaches using gold or iron oxide nanoparticles show immense promise for noninvasive tumor targeting and controlled cell destruction. However, these benefits must be interpreted within the broader context of oncological care, which is increasingly moving toward integration, personalization, and cost-effectiveness [1].

One of the central themes emerging from this review is the growing shift toward theranostics, the combined use of diagnostic and therapeutic tools within the same atomic platform. This concept not only allows for individualized treatment planning but also improves real-time monitoring and adjustment of therapeutic regimens. However, widespread implementation remains limited by technical and logistical barriers, particularly in low-resource settings where access to radionuclide production and regulatory support is inadequate [5].

A notable advantage of atom-based treatments is their ability to address radioresistant or inoperable tumors, offering a viable alternative when conventional therapies fall short. For instance, heavy ion and proton therapies provide superior depth control and minimize exposure to surrounding tissues, making them ideal for treating tumors near vital structures. Yet, despite their clear clinical benefits, these modalities are expensive and geographically restricted, often available only in advanced cancer centers [13].

Moreover, atom-based strategies are not without biological limitations. Tumor heterogeneity, changes in receptor expression, and resistance to oxidative stress can limit the effectiveness of targeted therapies or reduce the uptake of nanoparticles. This underscores the need for improved biomarker discovery, better patient stratification, and adaptive treatment protocols that evolve with tumor dynamics [7].

The future success of this field also depends on interdisciplinary collaboration, linking nuclear medicine, oncology, immunology, and material sciences. Recent studies suggest that combining atom-based therapies with immunotherapeutic agents may yield synergistic effects, turning localized treatments into systemic anti-tumor responses. However, this area is still in its infancy and requires extensive preclinical and clinical validation [19].

In conclusion, while atom-based therapies have already demonstrated considerable promise, their optimal use will require a balanced approach that considers efficacy, safety, cost, accessibility, and patient-centered outcomes. Future research should prioritize simplifying production, enhancing tumor selectivity, minimizing toxicity, and expanding the reach of these therapies beyond specialized centers [1].

## 5. Future perspectives

The future of atom-based cancer therapies lies in the convergence of multiple scientific disciplines, including nuclear medicine, molecular biology, nanotechnology, and immunotherapy. As our understanding of tumor biology deepens and technological capabilities expand, novel strategies are being developed to overcome current limitations and unlock the full therapeutic potential of atomic interventions [5].

### 5.1. Personalized and precision medicine

Advancements in genomics and molecular diagnostics are paving the way for more personalized atom-based treatments. By tailoring radiopharmaceuticals to specific tumor mutations or expression profiles, clinicians can enhance treatment specificity and improve patient outcomes. Theranostic agents, which allow simultaneous imaging and therapy, will play a central role in this personalized approach [6, 14].

### 5.2. Combination with immunotherapy

There is growing interest in combining atom-based therapies with immunotherapy. Preclinical and early clinical studies have shown that ionizing radiation can promote immunogenic cell death, increase tumor antigen presentation, and modulate the tumor microenvironment to enhance immune response. Strategies such as combining radionuclide therapy with immune checkpoint inhibitors or cancer vaccines are currently under investigation [19].

### 5.3. Development of novel radioisotopes

Research is underway to discover and produce new therapeutic isotopes with optimized physical and biological properties. Alpha emitters such as Actinium-225 and Astatine-211 are gaining attention due to their high linear energy transfer and short path length, offering potent tumoricidal effects with minimal

systemic toxicity. Innovations in isotope production and radiolabeling technologies are expected to broaden the clinical arsenal [9].

5.4. Advanced nanoplatforms for multimodal therapy

Next-generation nanoparticles are being designed for multifunctional use, simultaneously enabling targeted drug delivery, hyperthermia, radiosensitization, and imaging. These smart nanoplatforms often integrate atomic elements such as gold, hafnium, or gadolinium, and can be engineered to respond to specific stimuli within the tumor microenvironment. This will likely lead to more effective and safer therapies with real-time monitoring capabilities [10].

5.5. Expanding access and infrastructure

Efforts are also underway to democratize access to atom-based cancer therapies by developing cost-effective production methods for radioisotopes, miniaturizing accelerator technology, and enhancing global radiopharmacy networks. Streamlining regulatory pathways and establishing clear clinical guidelines will be essential to support broader adoption [7].

## 6. Conclusion

Atom-based therapies represent a transformative advancement in the fight against cancer. By harnessing the physical, chemical, and biological properties of specific atomic elements, particularly radioactive isotopes and metal-based nanoparticles, these approaches enable highly targeted, minimally invasive, and effective treatment strategies. Techniques such as radiopharmaceutical therapy, particle beam therapy, and nanoparticle-assisted hyperthermia have already shown significant clinical success in a variety of malignancies, including thyroid, prostate, neuroendocrine, and bone cancers.

Despite their promise, several challenges remain. These include limited infrastructure, high treatment costs, safety concerns regarding radiation exposure, and the need for further long-term clinical data. Addressing these issues will require interdisciplinary collaboration, regulatory refinement, and continued investment in research and development.

Looking ahead, the integration of atomic technologies with personalized medicine, immunotherapy, and nanotechnology is likely to redefine the standard of care in oncology. With continued innovation and clinical validation, atom-based therapies are poised to become a cornerstone in the multimodal management of cancer, offering patients more precise, effective, and individualized treatment options.

## Declarations

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