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REVIEW ARTICLE

# Next-Generation Tumor Targeting: Tackling Treatment Inaccessibility with MRI-Integrated Cryoablation Technologies

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Cancer is one of the most important causes of death around the world, and effective treatment of the tumor is still one of the most difficult issues, especially in the developing world with limited resources. The traditional methods of treatment like surgery, chemotherapy, and radiotherapy are costly, may have complications and may be unavailable in under-resourced areas. Cryoablation is a minimally invasive therapeutic technique that precisely freezes and destroys the tumor tissue without damaging adjacent normal tissues. New developments in the combination of magnetic resonance imaging (MRI) and cryoablation systems have greatly improved the accuracy of treatment, real-time monitoring, and safety of the procedure. MRI-guided cryoablation allows for precise localization of the tumor surface, visualization of the ice-ball spread and complete destruction of the tumor with minimal collateral tissue damage. Clinical results have been encouraging with this technology in many forms of cancer such as liver, kidney, prostate, breast and bone tumors. Additionally, MRI-integrated cryoablation can provide opportunities for personalized cancer care and increased access via outpatient procedures and shorter recovery times. This review will highlight the principles, technological advancements, clinical applications, advantages, challenges, and future directions of MRI-integrated cryoablation as a next-generation method to improve access to effective tumor-targeted therapies around the world.

**Keywords:** Cryoablation; Magnetic Resonance Imaging; Tumor Targeting; Minimally Invasive Therapy; Cancer Treatment Accessibility

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## 0.1 List of Abbreviations

| Abbreviation | Full Form |
|---|---|
| AI | Artificial Intelligence |
| CT | Computed Tomography |
| FDA | Food and Drug Administration |
| HIFU | High-Intensity Focused Ultrasound |
| MRI | Magnetic Resonance Imaging |
| PET | Positron Emission Tomography |
| RFA | Radiofrequency Ablation |
| ROI | Region of Interest |
| US | Ultrasound |
| WHO | World Health Organization |

## 1 Introduction

Cancer is a huge worldwide public health problem with millions of new cancer cases and cancer deaths occurring every year (1, 2). Even for cancers that have benefitted from tremendous progress in diagnosis and treatment, inequities in the delivery of effective cancer treatments are a significant barrier to equitable health outcomes. For many patients, especially those living in a low and middle-income country, the access to healthcare is constrained by a lack of facilities, lack of specialist oncology services, prohibitive treatment costs and delayed diagnosis. All these difficulties add to survival problems and a poor quality of life for affected populations (3, 4). Therefore, new treatment strategies that promise to be clinically effective, easily available, minimally invasive, and flexible in a variety of healthcare settings are desired. **Figure 1**

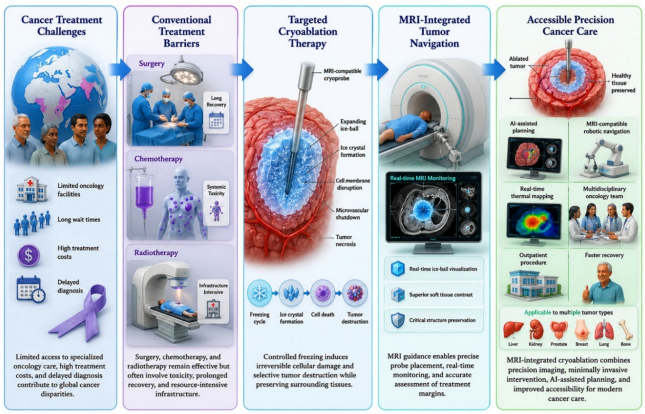


**Fig. 1** BioRender-style graphical abstract illustrating the evolution from global cancer treatment barriers to MRI-integrated cryoablation. The workflow highlights healthcare disparities, limitations of conventional therapies, cryoablation mechanisms, MRI-guided precision targeting, and accessible next-generation precision oncology.

Oncological treatment has long been based on traditional methods such as surgery, chemotherapy and radiotherapy. Although these modalities are extremely useful in terms of therapeutic benefit, they may be accompanied by considerable drawbacks (5, 6). Surgical operations involve long hospitalisation and recovery, chemotherapy may lead to systemic toxicity and side-effects and radiotherapy requires a high level of infrastructure which is not available in many healthcare providers. In addition, such treatment modalities might not be appropriate for elderly patients, patients with multiple comorbidities or patients with tumors in anatomically demanding areas. These restrictions have led researchers and clinicians to seek other approaches that can provide more effective targeted destruction of tumors, while minimizing complications and the burden on the healthcare system.

Cryoablation is a novel minimally invasive procedure that uses very cold temperatures to cause permanent damage to the cells and necrosis of the tumor. Cryoprobes are placed into the lesion during this process and repeated cycles of rapid freezing create ice crystals within cells, causing cell membrane damage, damage to the microvascular circulation, and eventually destruction of the tumor. Cryoablation has many benefits over conventional surgery, such as less pressure on the body during surgery, less chance of complications, shorter hospital stays and quicker recovery (7, 8). Furthermore, the method can be applied as needed and could be used in conjunction with systemic treatments to increase the effectiveness of the overall treatment.

The correct placement of the probe and monitoring of the ablation zone are crucial for successful cryoablation. Thus, for successful treatment, imaging guidance is key. Traditionally, ultrasound and computed tomography have been utilized for cryoablation procedures, but may not be adequate for imaging the margins of a tumor and the depth of tissue freezing (9, 10). MRI is now a better choice for imaging because of its superior soft tissue contrast, ability to image in multiple planes and real-time visualization of the changing ice ball throughout treatment. The use of MRI-guided cryoablation contributes to a greater accuracy and safety of the procedure as it enables the ability to target the tumors with precision, monitor the treatment process and protect the surrounding critical structures.

Further, recent technological advances have enhanced the ability of MRI and cryoablation systems to be integrated into a strong platform for next generation tumor targeting. The combination of the most up-to-date imaging software, MRI compatible cryoprobes, AI-supported planning devices, and real-time thermal evaluations have contributed to the precision of treatment and therapeutic success (11, 12). These advances have been the impetus to adopt cryoablation for a myriad of cancer applications including those of the liver, kidney, prostate, breast, lung and musculoskeletal system.

MRI integrated cryoablation technology is a next generation technology with the potential to alleviate the problem of inaccessibility for treatment and deliver high quality clinical care at a lower cost (13-15). All this technology can be used to push the world further towards improving the care of cancer patients, decreasing gap between diagnosis and effective treatment, and increasing the accessibility to and personalization of precision image-guided, minimally invasive tumor destruction solutions. **Table 1**

**Table 1** Summary of key features, clinical benefits, imaging capabilities, accessibility advantages, and future innovations associated with MRI-integrated cryoablation compared with conventional cancer treatment approaches in precision oncology.

| Aspect | Conventional Cancer Therapy | Cryoablation | MRI Integration | Key Advantages | Clinical Impact |
|---|---|---|---|---|---|
| Treatment Approach | Surgery, chemotherapy, radiotherapy | Minimally invasive freezing | Real-time image guidance | Precise tumor destruction | Improved local control |
| Procedure Invasiveness | Moderate to high | Low | Enhanced accuracy | Reduced tissue damage | Faster recovery |
| Hospital Stay | Often prolonged | Shorter | Better procedural planning | Reduced healthcare burden | Outpatient potential |
| Imaging Capability | Limited intraoperative monitoring | Requires guidance | Superior soft-tissue visualization | Accurate margin assessment | Improved safety |
| Eligible Patients | Limited in high-risk groups | Suitable for frail patients | Personalized treatment planning | Preserves organ function | Broader accessibility |
| Future Innovations | Conventional technologies | Advanced cryoprobes | AI-assisted MRI monitoring | Precision oncology integration | Expanded cancer applications |

## 2 MRI-Integrated Cryoablation: Principles and Technological Foundations

### 2.1 *The basic principles of cryoablation for cancer treatment*

Cryoablation is a less-invasive treatment method where very cold temperatures are used to kill off cancerous cells (16, 17). The technique entails imaging-guided insertion of special cryoprobes into the tumor tissues. Compressed gases, which cause fast cooling, cause the formation of ice crystals in the cells both inside and outside the cells, causing mechanical damage to the membranes and organelles. The freeze–thaw cycles also repeatedly injure the cancer's blood vessels, leading to the death of the cancer cells. Cryoablation does not require removal of nearby healthy tissue as traditional surgical resection does and has less morbidity associated with it. The formation of the visible ice-ball during treatment gives the clinician a direct indication of the ablation zone, thus allowing a better control of the procedure (18, 19). Cryoablation has proven effective for several different types of solid tumors, such as the liver, kidney, prostate, breast and lung. The minimally invasive procedure, short recovery period and suitability for high risk patients has made it a more and more appealing choice in today's oncology. **Figure 2**

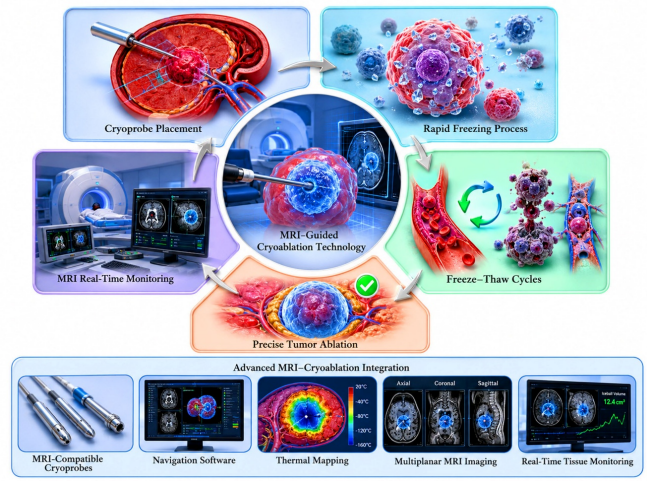


**Fig. 2** Schematic illustration of MRI-guided cryoablation technology showing cryoprobe placement, rapid cellular freezing, freeze–thaw-induced tumor destruction, real-time MRI monitoring, and precise tumor ablation, supported by advanced MRI-compatible navigation and thermal mapping systems.

### 2.2 *Combined MRI-Cryoablation systems*

Cryoablation systems are being combined with magnetic resonance imaging (MRI) and this combination is a huge leap forward in image-guided cancer therapy (5, 20). MRI has better soft tissue contrast and multiplanar imaging than other imaging techniques like ultrasound and computed tomography. These benefits are to help localized the boundaries of the tumor and surrounding critical anatomic structures before and during the treatment. MRI can also be used to watch the ice-ball formation occur, and to assure that a tumour is completely enclosed and healthy tissue is not at risk (21, 22). New technological advances include magnetic resonance imaging (MRI)-compatible cryoprobes, cutting-edge software for navigation and the most recent innovations in thermal mapping technology which may allow for more precise and consistent treatment. Visualization of tissue modification during the entire procedure increases confidence of the procedure and helps to prevent incomplete ablation. Moreover, MRI guidance is especially useful in the targeting of tumors within anatomically complex areas, where accurate targeting is crucial (9, 23). This integration has vastly contributed to both the results of treatment and application of the cryoablation to many cancer types. **Table 2**

**Table 2** Summary of the fundamental principles, mechanisms, MRI-guidance features, clinical advantages, and limitations of MRI-integrated cryoablation, highlighting its role in precise, minimally invasive, image-guided cancer treatment.

| Component | Principle | Mechanism | MRI Contribution | Clinical Benefit | Limitation |
|---|---|---|---|---|---|
| Cryoprobe Insertion | Image-guided targeting | Probe placement into tumor | Precise anatomical localization | Accurate treatment delivery | Requires expertise |
| Rapid Freezing | Extreme low temperature | Intracellular ice crystal formation | Real-time visualization | Effective tumor destruction | Risk of incomplete coverage |
| Freeze–Thaw Cycles | Repeated thermal injury | Membrane and organelle damage | Monitoring ablation zone | Enhanced cell death | Procedure duration |
| Vascular Injury | Microvascular disruption | Ischemia and necrosis | Assessment of treatment extent | Long-term tumor control | Variable tissue response |
| MRI-Compatible Systems | Integrated imaging and therapy | MRI-safe cryoprobes and navigation | Superior soft-tissue contrast | Improved procedural precision | Higher equipment cost |
| Thermal Mapping | Temperature monitoring | Ice-ball tracking and margin control | Real-time treatment guidance | Reduced collateral damage | Infrastructure requirements |

## 3 Clinical Applications & Accessibility Advantages

### 3.1 *Clinical Applications in various types of Tumors*

The MRI guided cryoablation has become a promising treatment for various types of malignant and benign tumors (24-26). The method is nephron-sparing and has excellent local tumour control in renal tumours. MRI-guided cryoablation can help accurately target prostate cancer in the treatment of the disease, and helps maintain urinary and sexual function. When surgery is not an option, liver tumors, such as primary hepatocellular carcinoma and metastatic lesions, can be effectively treated (5, 27, 28). Cryoablation has also been effective in the treatment of breast tumors and recurrent chest-wall cancers (malignancies) especially in patients that are not good candidates for traditional surgical treatments. Cryoablation is gaining popularity in the treatment of painful bone metastases and is being used for select primary bone tumors in musculoskeletal oncology. This precision in visualizing treatment margins using MRI guidance can greatly enhance treatment outcomes (9, 29, 30). There are increasing clinical data showing that MRI-guided cryoablation is as effective as proven local treatments in selected patients with the added benefits of being less invasive and having a shorter recovery time. **Figure 3**

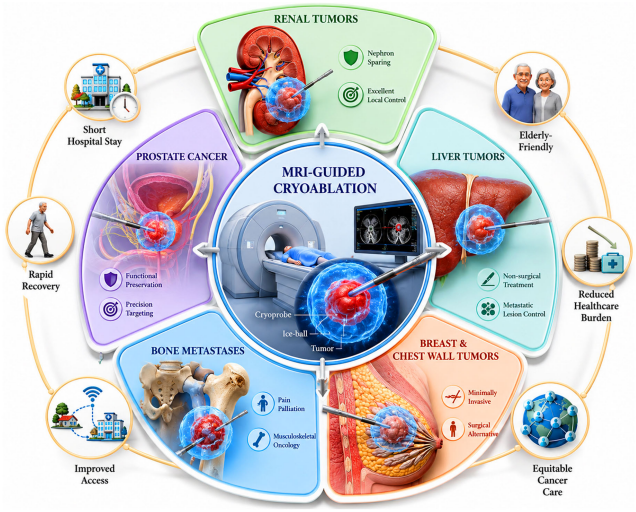


**Fig. 3** Schematic illustration of MRI-guided cryoablation showing clinical applications in renal, prostate, liver, breast, and bone tumors, alongside accessibility advantages including shorter hospitalization, faster recovery, improved access, reduced healthcare burden, and equitable cancer care.

### 3.2 Inaccessibility *of Treatment and Healthcare Disparities*

A great benefit of MRI integrated cryoablation is that it can help overcome some of the major challenges to cancer treatment accessibility (11, 31). Geographic and lack of specialist availability, long wait times and expensive conventional cancer treatments are issues that many patients encounter. MRI guided cryoablation is a less invasive procedure that may have a shorter hospital stay and quicker recovery than surgery. Lower procedural mortality helps to lower the use of health care resources and promotes ambulatory or short-stay care (14, 32). These characteristics can help facilitate access to care, especially in health-care systems with capacity issues. Moreover, the use of cryoablation might be indicated for elderly patients and those who have multiple comorbidities and are not suitable for more invasive surgery (33). Imaging is increasingly used and available and as the expertise in the procedure grows, the role of MRI-guided cryoablation may help minimize inequities in access to cancer treatment. Incorporating its use into more multidisciplinary oncology programs could help to deliver advanced cancer care resources more equitably around the world. **Table 3**

**Table 3** Summary of major clinical applications and accessibility advantages of MRI-guided cryoablation across multiple tumor types, highlighting therapeutic benefits, patient suitability, imaging precision, and healthcare system impact.

| Tumor Type | Clinical Role | Key Advantage | MRI Guidance Benefit | Patient Group | Outcome |
|---|---|---|---|---|---|
| Renal Tumors | Nephron-sparing treatment | Preserves kidney function | Precise tumor localization | Early-stage RCC patients | Excellent local control |
| Prostate Cancer | Focal tumor ablation | Preserves urinary and sexual function | Accurate treatment margins | Localized disease | Reduced morbidity |
| Liver Tumors | Alternative to surgery | Minimally invasive approach | Real-time lesion visualization | Non-surgical candidates | Effective tumor destruction |
| Breast Tumors | Local tumor control | Cosmetic tissue preservation | Precise targeting | High-risk surgical patients | Faster recovery |
| Bone Metastases | Pain palliation and tumor control | Symptom relief | Accurate ablation zone monitoring | Advanced cancer patients | Improved quality of life |
| Healthcare Accessibility | Expands treatment access | Shorter hospitalization | Efficient image-guided intervention | Elderly/comorbid patients | Reduced health care burden |

## 4 Future Perspectives and Emerging innovations

### 4.1 *Artificial Intelligence and Precision targeting of tumor cells*

With the rapid advancement of artificial intelligence (AI) in the field of oncology, the potential applications of AI to improve MRI-integrated cryoablation procedures are not far off (34, 35). Tumors can be segmented and treatment plans can be generated using AI algorithms to help the clinician optimize cryoprobe placement and predict treatment outcomes. Large clinical datasets can be used to train machine learning models to recognize subtle imaging patterns that could impact the success of the procedure and likelihood of recurrence. Automated image analysis can enhance the consistency and minimize the operator variability in treatment planning. Real time monitoring with AI support might also help to improve the safety of the procedure by forecasting the ice ball's growth and taking into account potential risks for nearby critical structures (36, 37). Furthermore, predictive analytics can suggest personalized approaches for treating patients based on their tumor features and profiles. There are three powerful technologies converging at the next step – MRI, cryoablation and AI, all of which have the potential to be more precise, efficient, and therapeutic. Ongoing tests and research of AI systems is likely to be key to next generation tumor targeting strategies (38, 39). **Figure 4**

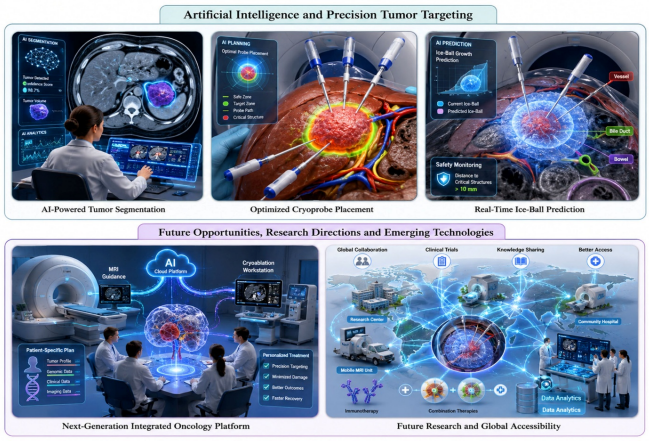


**Fig. 4** BioRender-style illustration depicting future MRI-integrated cryoablation innovations, highlighting AI-assisted tumor segmentation, optimized cryoprobe placement, real-time ice-ball prediction, integrated precision oncology platforms, and global accessibility initiatives for personalized cancer treatment.

### 4.2 *Checking the Future Opportunities and Research Directions and Challenges*

MRI-integrated cryoablation has a tremendous potential for the future but the difficulties that may need to be overcome to achieve this in a wide-spread clinical practice are still present (40, 41). The implementation in resource constrained environments can be limited by cost, infrastructure and skills required. Research priorities are still the need for procedures to be standardized and long-term outcomes assessed. More multicenter trials are required for comparison with other local therapy techniques like radiofrequency and microwave ablation and high intensity focused ultrasound therapy (42, 43). Large, future studies of combination therapy between cryoablation and immunotherapy, targeted therapy and radiotherapy for augmenting anticancer responses should also be considered. Advances in MRI technology, designs of cryoprobes and robotic navigation systems could potentially boost the accuracy and reach of treatments (44, 45). In addition, cost-effectiveness analysis would be useful to help assess the cost-effectiveness of MRI-guided cryoablation in various healthcare systems. These are only a few of the obstacles to overcome in order to fully realize the potential of this novel technology and advance its use in personalized cancer treatment (46, 47). **Table 4**

**Table 4** Summary of emerging innovations, research priorities, clinical opportunities, and implementation challenges associated with MRI-integrated cryoablation, highlighting artificial intelligence, technological advancements, accessibility considerations, and future directions in precision oncology.

| Area | Current Status | Emerging Innovation | Expected Benefit | Major Challenge | Future Priority |
|---|---|---|---|---|---|
| Tumor Segmentation | Manual MRI assessment | AI-based automated segmentation | Improved accuracy | Data variability | Validation studies |
| Treatment Planning | Operator-dependent planning | Machine learning-guided planning | Optimized probe placement | Algorithm reliability | Clinical integration |
| Real-Time Monitoring | MRI visualization of ice-ball | AI-assisted growth prediction | Enhanced safety | Computational complexity | Real-time implementation |
| Therapeutic Strategies | Cryoablation alone | Combination with immunotherapy/radiotherapy | Stronger anticancer response | Clinical evidence gaps | Multicenter trials |
| Technical Development | Conventional cryoprobes | Robotic navigation and advanced probes | Greater precision | High equipment costs | Technology optimization |
| Healthcare Accessibility | Limited specialized centers | Cost-effective MRI-guided platforms | Expanded patient access | Infrastructure requirements | Economic evaluation |

## 5 Discussion

MRI-integrated cryoablation is a breakthrough in image-guided oncology which allows the best of both technologies – cryogenic tissue destruction and MRI – to be used together. The technology overcomes various drawbacks of existing cancer treatment methods, especially for patients who are not surgical candidates or for patients with tumors situated in complex anatomy. The ability to accurately visualize the tumor margins and monitor the ice-ball formation in real-time allows the clinicians to precisely ablate while reducing damage to healthy tissues. MRI guidance provides superior soft-tissue contrast and procedural confidence, especially in organs in which lesions are hard to delineate, compared with ultrasound- and CT-guided procedures. Emerging data demonstrates MRI-guided cryoablation to have the potential of excellent local tumor control rates, low morbidity following cryoablation and short recovery and rehabilitation. Also, because the surgery is minimally invasive, it can be done and managed as an outpatient, saving the extra expenses and risks of prolonged hospitalization. However implementation on a large scale is still face to challenges including infrastructure, cost of equipment and training. To fully realize the clinical and societal potential of this exciting therapeutic platform, these challenges will need to be overcome.

## 6 Future Directions

Continuous innovations in imaging, robotics and artificial intelligence and precision oncology will shape the future of MRI-integrated cryoablation. AI has the potential to improve the accuracy and reproducibility of this procedure with the help of AI-driven treatment planning solutions that will support lesion segmentation, probe positioning, and the prediction of the outcome of ablation interventions. The potential of using robotic-assisted navigation with MRI-compatible cryoprobes may further reduce human operator interaction and help reach hard-to-reach tumors. Newer technologies such as real time thermal mapping and automatic monitoring of ice balls could lead to treatments that are more efficiently controlled and less likely to have inadequate ablation. The future should also include studies of the potential synergism of cryoablation and immunotherapy, targeted therapy and personalized medicine in order to increase the systemic antitumor response. There is a potential for cancer care to be different and the ability of moving smaller, low cost MRI systems that can be deployed more easily to regional and local cancer care systems may help to address this. Large-scale multicenter clinical trials, health-economic evaluations and studies of long-term outcomes will be necessary to define the role of MRI-guided cryoablation in the wider cancer management pathways, and to establish standardized protocols and their integration into comprehensive management pathways.

## 7 Conclusion

MRI-integrated, cryoablation is a novel, promising next-generation technique for tumour targeting, and is a very minimally invasive procedure with very accurate MRI guidance. With this technology, the boundaries of the tumor can be precisely seen and will give real-time feedback during the ablation process, thus making the treatment more effective and harming less healthy tissues surrounding the tumor. The benefits of this treatment when compared to ‘old fashion' treatments are the minimal morbidity of the treatment itself, quick recovery, patient comfort, as well as repeat treatments if needed. Perhaps most importantly, though, MRI-guided cryoablation may render inaccessible cancer undeniably accessible – and it could turn out to be less invasive and more cost-effective way of treating the disease. Whilst there are issues about infrastructure, technical skills and economic viability, there is reason to believe that there will be technological advancements that will enhance accessibility and clinical uptake. Moving forward, as artificial intelligence technology and robotic manipulation and personalized therapy continue to advance, it has the potential to grow to other forms of cancer. To conclude, MRI-integrated cryoablation is a pioneering technology in the realm of precision oncology, showing great potential for improving patient outcomes and promoting access to effective cancer treatment on a global scale.

### 7.1 CRediT Author Statement

Stalin Arulsamy, Kumarappan Chidambaram, A. Santhana Krishna Kumar conceptualization of the study, drafted the manuscript and designed the figures, and manuscript review and editing. All authors reviewed the manuscript.

### 7.2 Declaration Statement

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper

## Conflicts of Interest

All authors declare that there are no conflicts of interest associated with the publication of this manuscript.

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