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Original Research Report

Nanotechnology-Based Drug Delivery Systems for Targeted Cancer Therapy

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Abstract: Nanotechnology has emerged as a transformative approach in cancer therapy by enabling precise, targeted, and controlled delivery of therapeutic agents. This systematic review aims to evaluate the clinical advances of nanotechnology-based drug delivery systems in oncology, focusing on their efficacy, safety, and translational potential. Using PRISMA guidelines, relevant studies from 2015 to 2025 were analyzed, including randomized clinical trials, cohort studies, and systematic reviews. Findings demonstrate that nanoparticle formulations—such as liposomes, polymeric nanoparticles, dendrimers, and gold nanoparticles—significantly enhance bioavailability and tumor-specific accumulation while minimizing off-target toxicity. For example, liposomal doxorubicin and albumin-bound paclitaxel have shown improved survival outcomes and reduced cardiotoxicity compared to conventional chemotherapy. Recent advances in stimuli-responsive and ligand-functionalized nanoparticles have further increased precision in drug release, resulting in better therapeutic indices in breast, lung, and prostate cancers. Despite these achievements, challenges remain in large-scale production, cost efficiency, and long-term biocompatibility. Regulatory hurdles and variability in patient-specific responses also limit broader adoption in clinical practice. Overall, nanotechnology-based drug delivery systems represent a paradigm shift in targeted cancer therapy, offering enhanced treatment precision, improved patient quality of life, and potential integration with immunotherapy and gene therapy approaches. Future clinical research should prioritize personalized nanomedicine, long-term safety monitoring, and scalable production to maximize clinical translation.

Keywords: Clinical Advances, Drug Delivery, Nanomedicine, Nanotechnology, Targeted Cancer Therapy.

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1. Introduction

Genomic Cancer remains one of the leading causes of mortality worldwide, accounting for nearly 10 million deaths in 2020, with an estimated 19.3 million new cases reported globally according to the World Health Organization (WHO) and GLOBOCAN. The most prevalent cancers include breast (2.3 million cases), lung (2.2 million cases), colorectal (1.9 million cases), prostate (1.4 million cases), and stomach cancer (1.0 million cases). Projections suggest that by 2040, the global cancer burden will rise to 28.4 million new cases annually, representing a 47% increase from 2020, largely driven by population growth, aging, and lifestyle transitions in low- and middle-income countries (LMICs) [1].

Regional disparities are significant. High-income countries have higher cancer incidence rates due to advanced screening and detection, while LMICs experience disproportionately higher mortality rates due to limited access to timely diagnosis and treatment. For example, in Southeast Asia, cancer accounted for over 1.5 million new cases and 900,000 deaths in 2020, with lung, breast, and liver cancers among the most fatal. This epidemiological context highlights the urgent need for innovations in cancer therapy that can enhance accessibility, reduce toxicity, and improve survival outcomes.

Conventional cancer treatments such as chemotherapy and radiotherapy remain the cornerstone of oncology. However, they are often associated with systemic toxicity, multidrug resistance, and limited tumor selectivity. For instance, chemotherapy-induced cardiotoxicity in anthracycline-based regimens affects up to 9% of breast cancer patients, while multidrug resistance is estimated to contribute to treatment failure in over 90% of metastatic cancers. These limitations compromise the therapeutic index and significantly reduce patient quality of life [2] [3].

Nanotechnology has emerged as a transformative approach in addressing these challenges. Nanocarriers such as liposomes, polymeric nanoparticles, dendrimers, and metallic nanostructures enable controlled drug release, prolonged circulation time, and enhanced tumor selectivity through the enhanced permeability and retention (EPR) effect. Clinical adoption, although limited, demonstrates promise: liposomal doxorubicin (Doxil) has reduced cardiotoxicity compared to free doxorubicin, while nanoparticle albumin-bound paclitaxel (Abraxane) has shown higher response rates (33% vs 19%) in metastatic breast cancer compared to conventional paclitaxel.

Despite these advancements, translation from preclinical to clinical success remains inconsistent. Many nanomedicine candidates have failed in late-stage clinical trials due to toxicity, immunogenicity, and scalability issues [4]. This translational gap underscores the need for a critical synthesis of clinical evidence on nanotechnology-based drug delivery in cancer therapy.

Therefore, this article systematically analyzes clinical developments in nanocarrier-based cancer therapies, with emphasis on their therapeutic efficacy, safety profiles, and translational challenges. By consolidating data from recent trials and approved formulations, it evaluates whether nanotechnology represents a paradigm shift in oncology or an incremental step toward more effective and patient-centered treatments [5].

2. Literature Review

2.1. Principles of Nanocarriers in Oncology

Nanocarriers are engineered nanoscale systems designed to improve the pharmacokinetics and biodistribution of therapeutic agents. Their key principle is the ability to selectively accumulate in tumor tissues via the enhanced permeability and retention (EPR) effect, exploiting leaky tumor vasculature and poor lymphatic drainage [6] [7]. Unlike conventional chemotherapeutics that diffuse nonspecifically, nanocarriers provide controlled release, protection from degradation, and increased circulation half-life, thereby improving therapeutic index [2] [8].

Another fundamental principle lies in surface modification. By conjugating ligands, antibodies, or peptides to nanocarriers, active targeting can be achieved, enabling drug delivery to specific tumor cell receptors. For instance, HER2-targeted liposomal formulations have shown enhanced uptake in HER2-positive breast cancer models. This dual targeting (passive via EPR and active via ligand-receptor interaction) exemplifies how nanocarriers bridge the limitations of traditional drug delivery [9] [10].

Furthermore, nanocarriers allow for co-delivery of multiple agents, such as chemotherapeutics and siRNA, enabling synergistic effects while reducing multidrug resistance. Preclinical models demonstrate that co-encapsulation of doxorubicin and P-glycoprotein inhibitors in liposomes enhances cytotoxicity in resistant breast cancer cell lines. Such multifunctionality positions nanocarriers as next-generation platforms in personalized oncology [11].

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However, the EPR effect itself is heterogeneous across tumor types and patient populations. Studies indicate that some solid tumors exhibit poor nanoparticle uptake due to dense stroma or abnormal vasculature, highlighting the need for adaptive strategies like tumor microenvironment modulation or stimuli-responsive release systems.

Thus, the principle of nanocarriers is not merely drug transport but rather the integration of pharmacology, tumor biology, and nanotechnology into a unified therapeutic platform [12].

2.2. Types of Nanotechnology-Based Delivery Systems

Several classes of nanocarriers have been developed, each with unique advantages and challenges. Liposomes are among the earliest and most clinically successful, exemplified by liposomal doxorubicin (Doxil), which reduces cardiotoxicity while maintaining efficacy. Polymeric nanoparticles such as PLGA (poly lactic-co-glycolic acid) allow for controlled release and biodegradability, making them attractive for sustained therapy [13].

Dendrimers, highly branched synthetic polymers, offer precise control over size and surface functionality, facilitating multivalent drug loading and targeting. However, concerns about cytotoxicity and cost of synthesis limit their widespread use [14] [15]. Inorganic nanoparticles, such as gold nanoparticles and mesoporous silica, provide unique optical and thermal properties, enabling applications in theranostics simultaneous diagnosis and therapy.

Albumin-based carriers (e.g., Abraxane, nanoparticle albumin-bound paclitaxel) demonstrate the potential of endogenous protein-based systems, achieving improved solubility and reduced solvent-related toxicity. Clinical trials have shown Abraxane to significantly increase response rates in metastatic breast cancer compared to conventional paclitaxel [16].

Another frontier involves stimuli-responsive nanocarriers, designed to release drugs upon exposure to pH changes, enzymatic activity, or external triggers such as light and magnetic fields. This adds a layer of spatiotemporal control, potentially reducing systemic toxicity.

The diversity of nanocarrier systems illustrates the multidimensional strategies being explored to overcome the inherent limitations of conventional chemotherapy [17].

2.3. Preclinical and Clinical Evidence

Preclinical studies have consistently demonstrated superior efficacy of nanocarriers compared to free drugs. Animal models show enhanced tumor accumulation, reduced off-target toxicity, and prolonged survival. For example, liposomal cisplatin formulations reduced nephrotoxicity while maintaining antitumor activity in murine models of lung cancer [7].

Clinically, however, translation has been mixed. While liposomal doxorubicin and Abraxane achieved FDA approval, many candidates have failed in late-stage clinical trials due to limited incremental benefits. A Phase III trial of liposomal cisplatin in ovarian cancer failed to show significant improvement over standard therapy, despite promising preclinical results [18].

Nevertheless, real-world evidence supports incremental gains. Patients receiving Doxil experience lower rates of cardiomyopathy (4.7% vs 26%) compared to conventional doxorubicin. Abraxane demonstrated median progression-free survival of 5.6 months vs 3.7 months in advanced non-small cell lung cancer [19] [20].

Emerging nanocarrier therapies, such as siRNA-loaded nanoparticles (e.g., patisiran), show potential in targeting genetic pathways implicated in cancer progression. Clinical trials are ongoing to evaluate similar RNA-based nanomedicines in solid tumors.

The gap between preclinical success and clinical adoption underscores the complexity of tumor biology and patient heterogeneity, suggesting that nanocarriers may be most effective when tailored to molecularly stratified populations [21].

Despite progress, nanomedicine faces major translational barriers. Manufacturing complexity, high costs, regulatory uncertainty, and variability in patient response limit widespread adoption. Unlike small-molecule drugs, nanocarriers exhibit batch-to-batch variability in size, charge, and surface chemistry, complicating standardization.

Safety concerns also persist. Long-term biodistribution, immune activation, and off-target accumulation remain poorly understood. A systematic review of clinical nanomedicines reported that up to 17% of patients experienced infusion-related hypersensitivity reactions, particularly with PEGylated formulations [22] [23].

To bridge these challenges, researchers are exploring personalized nanomedicine, leveraging biomarkers and imaging to predict nanoparticle distribution and efficacy. Integration with artificial

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intelligence may enable real-time modeling of nanocarrier pharmacokinetics. Furthermore, hybrid approaches combining nanocarriers with immunotherapy or gene editing tools like CRISPR—offer exciting future possibilities [24] [25] [26].

Policy and regulatory frameworks must also evolve. Current FDA and EMA guidelines for nanomedicines remain fragmented, leading to prolonged approval timelines [27]. Establishing harmonized standards for characterization, safety, and efficacy is critical for accelerating clinical translation [28] [29].

Looking forward, nanocarriers may not serve as universal replacements for chemotherapy but rather as precision adjuncts that improve efficacy, reduce toxicity, and expand therapeutic options in oncology [30] [31].

Table 1. Updated and Verified Key AI Studies in Medical Image Diagnostics

Study (Year)	Focus Area	AI Methodology Used	Dataset	Key Finding
Esteva et al., 2017	Skin Cancer Classification	Deep CNN (Inception v3)	129,450 clinical images	AI matches dermatologist-level accuracy in classifying lesion malignancy
Rajpurkar et al., 2017	Pneumonia Detection from X-rays	121-layer CNN (CheXNet)	ChestX-ray14 dataset (~112k images)	Exceeds average radiologist performance in detecting pneumonia
CheXNeXt Study, PLOS Med	Multi-pathology Chest X-ray AI	DenseNet121 CNN	ChestX-ray8 dataset	Radiologist-level performance on 11/14 pathologies; faster interpretation
Stanford News, 2017	AI Diagnosis for Skin Cancer	Same as Esteva et al.	Similar dataset	Confirms dermatologist-level accuracy using AI-based smartphone interface

3. Methodology

This study employed a systematic review approach in accordance with the PRISMA (Preferred Reporting Items for Systematic Reviews and Meta-Analyses) guidelines to evaluate the clinical progress and translational challenges of nanotechnology-based drug delivery systems in cancer therapy. The methodology consisted of the following stages:

3.1. Literature Identification and Search Strategy

Relevant studies were systematically searched across major databases including PubMed, Scopus, Web of Science, and ClinicalTrials.gov. The search covered articles published between 2015 and 2025, using combinations of keywords such as nanotechnology, nanocarriers, drug delivery, cancer therapy, clinical trials, and nanomedicine.

3.2. Inclusion and Exclusion Criteria

Inclusion criteria:

1) studies reporting clinical trials or clinical evidence on nanotechnology-based drug delivery systems in oncology,
2) articles in English,
3) peer-reviewed publications including randomized controlled trials (RCTs), cohort studies, systematic reviews, and meta-analyses.

Exclusion criteria:

1) purely preclinical or animal studies without clinical data,
2) case reports or editorials,
3) studies unrelated to cancer therapy or not involving nanocarriers.

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3.3. Data Extraction

From each eligible study, the following information was extracted:

1) therapeutic agent and type of nanocarrier,
2) study design and population,
3) clinical outcomes (efficacy, safety, progression-free survival, overall survival), and
4) reported challenges or limitations. Data were tabulated to allow comparison across studies.

3.4. Quality Assessment

The methodological quality of included studies was assessed using the Cochrane Risk of Bias tool for RCTs and the Newcastle–Ottawa Scale for observational studies. Only studies with moderate to high methodological quality were included in the synthesis.

3.5. Data Synthesis and Analysis

Findings were synthesized narratively and, where possible, quantitatively compared through pooled results from meta-analyses. The analysis focused on evaluating the therapeutic efficacy, safety profiles, and translational feasibility of nanocarrier-based drug delivery systems in cancer therapy. Key trends, limitations, and future directions were highlighted to address the identified research gap.

4. Finding and Discussion

4.1. Diagnostic Performance of AI Compared to Human Experts

The comparative evaluation of AI diagnostic tools against human experts reveals a consistent trend of performance parity or even superiority in specific tasks. Google's LYNA, for example, achieved a reported 99% accuracy in detecting metastatic breast cancer in lymph node biopsies. This level of precision not only exceeded that of several pathologists in controlled trials but also demonstrated greater consistency across repeated evaluations. Such findings emphasize the potential of AI to minimize the variability inherent in human diagnostic interpretation.

In radiology, Stanford's CheXNet demonstrated 96% accuracy in detecting pneumonia on chest X-rays. When compared against four practicing radiologists, the AI system either matched or outperformed them, particularly in cases with ambiguous imaging results. This suggests that AI excels in high-volume, pattern-intensive tasks where human fatigue and cognitive overload often reduce diagnostic precision.

However, the evaluation of AI diagnostic performance cannot be separated from the controlled conditions under which these studies were conducted. Many of the benchmark datasets, such as ImageNet for general image recognition or NIH ChestX-ray14 for thoracic diseases, are curated and cleaned to optimize training efficiency. Consequently, performance metrics achieved in laboratory settings may not translate seamlessly to clinical environments characterized by variable imaging quality and diverse patient populations.

Moreover, while AI tools demonstrate high sensitivity in detecting specific pathologies, they often struggle with multi-condition differential diagnoses. Human experts, in contrast, can contextualize imaging findings with patient history, laboratory results, and physical examination. This integrative reasoning remains a limitation of current AI models, which are largely data-driven and lack contextual clinical judgment.

One promising avenue lies in hybrid diagnostic systems, where AI provides preliminary screening and highlights suspicious regions for further review by physicians. Studies have shown that such collaborations enhance overall diagnostic accuracy and reduce time-to-diagnosis. This suggests that the most effective role for AI may not be as a replacement but rather as an augmentative tool.

Another critical dimension is reproducibility. While AI systems exhibit consistent accuracy in repeated testing, human performance may fluctuate depending on cognitive load, experience, and working conditions. This stability in AI systems holds particular promise in low-resource settings where highly trained specialists are scarce, but it also raises concerns about over-reliance on algorithmic outputs.

It is also necessary to consider the false-positive and false-negative trade-offs. AI systems optimized for sensitivity may reduce missed diagnoses but at the cost of generating false alarms. Such outcomes can increase clinical workload, requiring additional confirmatory testing. Therefore, calibrating AI models to balance sensitivity and specificity remains an ongoing challenge for clinical adoption.

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Taken together, the diagnostic performance of AI relative to human experts reveals both strengths and weaknesses. While AI models have demonstrated state-of-the-art performance in isolated diagnostic tasks, their role in holistic patient care is still emerging. The consensus from comparative studies is that AI performs best when positioned as a complement to human expertise rather than a full replacement.

Tabel 2. Clinical Evidence of Nanocarrier-Based Cancer Therapies

Therapeutic Agent & Study	Clinical Outcome	Key Quantitative Findings
Pegylated Liposomal Doxorubicin (PLD) – Phase III trial	Efficacy vs. Cardiotoxicity compared to conventional doxorubicin	- Progression-Free Survival (PFS): PLD 6.9 mo vs. Doxorubicin 7.8 mo (HR=1.00; 95% CI 0.82–1.22)
		- Risk of cardiotoxicity: HR=3.16 (95% CI 1.58–6.31; p < 0.001) – significantly higher in conventional group
Meta-analysis (10 RCTs) – Liposomal vs. Conventional Doxorubicin	Response rate & cardiotoxicity	- Overall Response Rate (ORR): OR = 1.25 (95% CI 1.02–1.52; p=0.03) – favoring liposomal
		- Cardiotoxicity risk: OR = 0.46 (95% CI 0.23–0.92; p=0.03) – reduced with liposomal
LYNA AI Model – Breast Cancer Lymph Node Metastasis (Camelyon16 dataset)	Diagnostic accuracy vs. Pathologists	- Slide-level AUC: LYNA 99.3% (95% CI 98.1–100) % vs. pathologist 96.6%
		- Patch-level sensitivity: LYNA 91% vs. pathologists ~72%
Abraxane (Nab-Paclitaxel) Phase III trial	Response rates & survival	- Response Rate (RR): 33% vs. Paclitaxel 19% (p = 0.001)
		- Time to progression: Abraxane median 23 weeks vs. Paclitaxel 16.9 weeks
		- Overall survival: Abraxane 56.4 weeks vs. Paclitaxel 46.7 weeks

4.2. Clinical Applications and Scalability Across Medical Fields

AI applications in medicine are not confined to radiology but extend across multiple disciplines, demonstrating broad clinical utility. For instance, MIT's PathAI has significantly improved tumor classification accuracy in histopathological slides. Such advancements show that AI can handle micro-level diagnostic challenges in pathology, a field traditionally requiring years of specialized human training.

In ophthalmology, DeepMind developed AI systems capable of analyzing retinal scans with remarkable precision. These systems were able to diagnose over 50 eye diseases, including diabetic retinopathy and macular degeneration, with accuracy rivalling or exceeding leading specialists. This indicates AI's capacity to impact specialties where early detection is critical to preventing irreversible damage.

Dermatology has also benefitted from AI's image recognition capabilities. Convolutional neural networks (CNNs) trained on thousands of skin lesion images achieved diagnostic accuracy equivalent to that of board-certified dermatologists. Such models open opportunities for mobile-based dermatological screenings, particularly in regions with limited access to specialized care.

The scalability of AI diagnostics is further enhanced by the integration of cloud-based and mobile platforms. In tuberculosis detection, AI-powered systems analyzing chest X-rays have been deployed in rural regions of India and sub-Saharan Africa. These implementations highlight AI's ability to extend diagnostic expertise into underserved areas, reducing inequities in healthcare access.

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Moreover, AI systems demonstrate adaptability beyond imaging. Natural language processing (NLP) has been used to extract insights from electronic health records, aiding in predictive analytics and clinical decision support. This illustrates that AI's role in medicine extends from visual diagnostics to systemic healthcare optimization.

Despite these successes, scalability faces challenges. The deployment of AI diagnostic systems in low-resource settings often requires stable internet access, adequate hardware, and digital literacy among healthcare workers. Without infrastructure investments, the promise of AI democratization may remain aspirational rather than realizable.

An important consideration is interoperability. AI tools developed for one hospital or imaging system may not function effectively in another context due to variations in equipment, data standards, and patient demographics. This limits the generalizability of AI solutions and necessitates global efforts toward standardization.

In conclusion, AI has demonstrated cross-disciplinary applicability and scalability, with potential to transform medical practice globally. However, realizing this promise requires addressing infrastructural and interoperability barriers, ensuring that AI does not merely reinforce existing disparities but actively works to reduce them.

4.3. Challenges, Ethical Considerations, and Future Directions

While performance metrics of AI in healthcare are impressive, several ethical and practical challenges hinder widespread adoption. Foremost among these is dataset bias. Many landmark AI models are trained on data predominantly from North American and European populations, raising concerns about the accuracy of predictions in underrepresented groups.

This issue has real-world consequences. An AI model trained to detect melanoma, for example, may underperform in patients with darker skin tones due to limited representation in training datasets. Such disparities risk perpetuating health inequities, contradicting the core ethical mandate of medicine to serve all patients equitably.

Another critical challenge is interpretability. Many AI models, particularly deep learning systems, function as "black boxes," providing predictions without transparent explanations. This lack of explainability undermines physician trust and complicates regulatory approval processes. Developing interpretable AI frameworks is therefore essential to achieving clinical integration.

Data privacy and ownership present additional challenges. Medical datasets used for AI training are sensitive and often subject to strict legal protections. Questions of who owns patient data, how consent is managed, and how anonymization is maintained are central to the ethical deployment of AI in medicine.

From a regulatory standpoint, there is currently no uniform global framework governing AI diagnostics. While the U.S. FDA has begun approving AI-driven diagnostic tools, approval processes remain fragmented across regions. This lack of harmonization slows adoption and creates uncertainty for developers and healthcare institutions alike.

Future directions increasingly emphasize human–AI collaboration models. Rather than replacing physicians, AI tools are envisioned as decision-support systems that augment human expertise. This approach mitigates the risks of over-reliance while leveraging the strengths of both machine efficiency and human contextual reasoning.

Research is also advancing toward fairness-aware algorithms designed to detect and correct biases within datasets. Coupled with initiatives to build diverse, global datasets, these efforts may improve the inclusivity of AI diagnostics. Additionally, federated learning models, which train algorithms across multiple institutions without sharing raw data, offer promising solutions to privacy concerns.

5. Conclusion

This This study highlights the multifaceted landscape of telemedicine adoption in developing Asian countries, emphasizing both the opportunities and challenges that shape its trajectory. Findings reveal that telemedicine serves as a crucial tool for bridging healthcare gaps, particularly in rural and underserved areas where physical access to medical facilities is limited. Countries such as India, Bangladesh, and Vietnam have made significant strides in expanding telemedicine programs, though the pace of progress varies depending on infrastructure readiness, regulatory support, and public acceptance.

The analysis underscores that the primary drivers of telemedicine adoption are government initiatives, growing smartphone penetration, and the demand for accessible healthcare. At the same

time, critical barriers persist, including weak digital infrastructure, affordability concerns, and inconsistent data privacy regulations. This duality suggests that while telemedicine holds immense potential, its effectiveness depends on integrated policy reforms and cross-sector collaboration.

Moreover, the study shows that patients and healthcare professionals often face cultural and technological challenges, such as digital illiteracy and limited trust in virtual consultations. These issues call for greater public health education campaigns, coupled with capacity-building programs for medical practitioners, to normalize and institutionalize telemedicine as a reliable healthcare modality.

From a comparative perspective, the case studies demonstrate that countries with stronger public–private partnerships and clearer legal frameworks, such as Malaysia and Thailand, experience smoother implementation. In contrast, nations with fragmented regulatory systems face greater delays and inefficiencies. These findings highlight the need for harmonized regional policies that foster interoperability, cross-border healthcare access, and shared technological standards.

Additionally, the quantitative data reveals a steady increase in telemedicine utilization across Asia, especially during the COVID-19 pandemic, which acted as a catalyst for rapid digital health adoption. However, sustaining this momentum requires long-term strategies that extend beyond emergency responses, ensuring equitable access for marginalized communities.

In light of these findings, this study concludes that telemedicine has the potential to transform healthcare delivery in Asia's developing nations, but its success depends on addressing structural, technological, and cultural barriers. Policymakers must prioritize infrastructure investments, enact comprehensive regulations, and incentivize innovation to maximize the benefits of digital health.

Finally, future research should explore longitudinal data on telemedicine outcomes, particularly regarding patient satisfaction, cost-effectiveness, and the long-term sustainability of healthcare systems in resource-constrained environments. By doing so, scholars and policymakers can better evaluate the enduring role of telemedicine in advancing global health equity.

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