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Telepathology in India – Revolutionizing Pathology Diagnostics through Digital Innovation

Ms. Shweta Thusoo*[1], Ms. Amita Dabholkar[2]

[1*]Assistant Professor, Dr. D.Y. Patil School of Allied Health Sciences, Dr. D.Y. Patil Vidyapeeth, Pimpri, Pune, India

Email ID: Shweta.thusoo@dpu.edu.in

[2]Assistant Professor, Dr. D.Y. Patil School of Allied Health Sciences, Dr. D.Y. Patil Vidyapeeth, Pimpri, Pune, India

***Corresponding Author:**

Ms. Shweta Thusoo**,**

Email ID: Shweta.thusoo@dpu.edu.in

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ABSTRACT

With high-resolution imaging, artificial intelligence (AI), and secure telecommunication systems, telepathology, a revolutionary application of digital technology in pathology, enables remote diagnosis, consultation, and second opinions. Telepathology is revolutionizing the diagnostic environment with advances in Whole Slide Imaging (WSI), cloud storage, and AI-based analytics. This is particularly relevant in countries such as India, where access to specialist pathology services is not well distributed.

Providing immediate and accurate pathology services is very challenging in India with its sizeable and dispersed populace, especially in remote and rural settings. Though government initiatives such as the National Digital Health Mission (NDHM) have paved the path for enhanced telemedicine facilities, several institutions and healthcare establishments have initiated digital pathology initiatives.

The utilization of telepathology in India is still nascent despite such advances. There are still several major hurdles, including the lack of adequate digital infrastructure, prohibitive setup costs, unreliable internet connectivity in outlying areas, and regulatory concerns. In addition, pathologists and laboratory workers must spend a lot of training and change over from the conventional microscopy system to digital pathology. Also necessary are well-crafted regulatory regimes to manage medico-legal and ethical challenges, including data protection and responsibility for diagnosis.

This review article discusses the evolution of telepathology, the current situation in India, the challenges to its widespread application, and the potential means of overcoming them. India can bridge the diagnostic gap and ensure that all have access to quality and affordable healthcare by embracing digital pathology innovations and strengthening telehealth regulations.

Keyword: *Telepathology, Digital Pathology, Remote Diagnostics, Artificial Intelligence in Pathology, Telemedicine in India*..

1. INTRODUCTION

Telepathology, the electronic transmission of pathological images for remote consultation and diagnosis, has witnessed phenomenal growth in the last few decades (1). Telepathology has many benefits, including improved patient care and bridging the rural-urban expertise gap (2). Telepathology evolved from video microscopy research in the early 1950s to becoming a simple diagnostic tool in telemedicine clinical application. Its genesis is due to pioneering feasibility studies on the use of color and other image parameters for diagnosis and a series of studies comparing virtual slide and light microscopy diagnoses (3,4). Telepathology has diagnostic services, education, and teleconferencing as its uses (5).

However, telehealth is faced with immense challenges in the social, political, and technological spaces. Among the most significant challenges are a global lack of competent healthcare professionals, an aging population that increases the demands for health, and a lack of awareness and understanding among policymakers (6). Low-income countries are faced with the coincidence of infectious and noncommunicable diseases, poverty, and limited access to technology and communications infrastructure (7). Additionally, the implementation of telehealth into mainstream health systems is an uphill battle, requiring innovative, resource-saving, and culturally appropriate methods (8).

In India, telepathology has emerged as a potential tool for improving healthcare delivery, but overcoming current regulatory hurdles and limitations is imperative (9). With the development of technology, telepathology is capable of revolutionizing

pathological practice with high sensitivity and specificity in the diagnosis of tissue samples (10). Digital pathology has transformed traditional diagnostic processes by integrating sophisticated imaging technologies, computational algorithms, and artificial intelligence (11). Shifting away from traditional glass slides to digital format enables high-resolution imaging, thus enabling remote consultation, second opinion, and telepathological processes. The digital format enhances the efficiency of laboratory workflow while enabling large storage of data, retrieval, and analysis, thus accelerating the development of advanced diagnostic algorithms (12).

One of the most important advancements in digital pathology is its harmonization with artificial intelligence (AI) and machine learning (ML), which eliminate tedious tasks like diseased feature detection, biomarker measurement, and tissue segmentation (13). Through automation, they minimize inter-observer variability and enhance diagnostic quality. AI-powered algorithms are most useful in tricky cases, guiding pathologists toward recognizing subtle patterns that may escape detection in naked-eye (14).

Telepathology, the fusion of digital pathology and telemedicine, was a novel method by which remote sharing, reading, and interpretation of pathological material may be performed by utilizing digital communication and high-resolution imaging systems (15)

Advances in Telepathology Technology

Telepathology enables distant diagnosis and case review by pathologists, hence linking resource-limited areas to specialized pathological care (16). Success of the process has been aided by advances in Whole Slide Imaging (WSI), cloud storage technology, AI-enabled image interpretation, and secure telecommunication platforms (17). The technology has been of immense use in areas like oncology, hematology, infectious diseases, and histopathology, where timely and accurate diagnosis is critical to successful patient care (18).

There are three basic models of telepathology:

1. Static-Image Telepathology involves capture and transmission of individual microscopic images to facilitate remote consultation. While this method is cost-effective, it is limited by the potential to miss important diagnostic areas (19).

2. Real-time dynamic telepathology employs robotic microscopy or live video streaming to allow pathologists to remotely investigate slides and provide immediate diagnoses (20).

3. Whole Slide Imaging (WSI) Telepathology is the most advanced model, which entails high-resolution scanning of the entire digitized slides that are remotely examined, analyzed through artificial intelligence, and stored (21).

The use of telepathology presents various benefits:

• Improved Diagnostic Precision and Efficiency – Digital pathology instruments enable pathologists to analyze tissue samples at very high resolutions, which gives them the ability to properly magnify and shrink individual regions. This level of detail tends to exceed what conventional microscopes can do, thereby reducing the likelihood of human error (22).

• Enhanced Collaboration – Telepathology facilitates collaboration among different experts, bridging almost the limitation brought about by geographical distance. The implementation of this collaborative effort guarantees a holistic understanding of the case, which further affects treatment and improves patient outcomes (17).

• Educational Tool – Telepathology is also a valuable educational tool because it allows pathologists to share knowledge and experience. Trainee pathologists have the opportunity to engage in observing and learning from experienced pathologists' diagnostic work, resulting in the acquisition of vast amounts of knowledge and increased professional (23).

Despite its numerous benefits, telepathology faces several challenges:

• High Costs – Installation of telepathology systems requires high expenditure on information technology infrastructure and related services (12).

• Legal and Regulatory Challenges – Challenges occur with respect to adherence to legal and regulatory guidelines, especially concerning cross-border consultations (5).

• Technical Limitations – A number of technical issues, such as system reliability, image resolution, and compatibility among different systems, can hinder the effective application of telepathology (3).

• Resistance to Change – Some pathologists will resist adopting telepathology because of familiarity with traditional methods or skepticism over new technology (18).

Telepathology in India: Current Status and Practice

India, with its high geographical heterogeneity and wide health disparity between the urban and rural regions, is faced with the challenge of providing timely and quality pathology services across geographies. The paucity of trained pathologists, particularly in tier-2 and tier-3 cities and rural health centers, exacerbates the delay in diagnosis (24). The National Medical Commission (NMC, formerly the Medical Council of India) reports a serious shortage of pathologists compared to the

growing demand, thereby rendering telepathology an appropriate substitute for traditional diagnostic practices (20).

Various Indian public and private healthcare centers have launched digital pathology and telepathology initiatives to address this gap. Some of the notable implementations include:

• The National Digital Health Mission (NDHM): NDHM, initiated by the Government of India, facilitates digitization in medical care, such as pathology services. Formed on August 15, 2020, and subsequently rechristened the Ayushman Bharat Digital Mission (ABDM) in September 2021, its goal is to provide quality healthcare that is accessible, affordable, and available anywhere and anytime (NDHM, 2021). ABDM seeks to build an integrated digital health environment by interlinking patient records, diagnostics, and treatment history, enabling smooth telepathology integration (6).

• Tata Memorial Centre and AIIMS Initiatives: AIIMS and Tata Memorial Centre have implemented digital pathology platforms for teleconsultation in histopathology, especially in the context of cancer. The institutions have incorporated Whole Slide Imaging (WSI) technology, allowing pathologists to remotely access high-resolution digital slides, shortening delays in diagnosis and enhancing cancer care (7).

• Private Sector Investments: Large private healthcare organizations such as SRL Diagnostics, Metropolis Healthcare, and Apollo Hospitals are heavily investing in artificial intelligence-based pathology solutions and cloud reporting systems. Apollo Hospitals has integrated artificial intelligence with Microsoft and embarked on digital transformation in their healthcare delivery process. Artificial intelligence-based diagnostic solutions offer the ability for automated detection of abnormalities, thereby reducing human error and increasing operational efficiency (8).

• IIIT Hyderabad and NIMS Collaboration: Indian Institute of Information Technology (IIIT) Hyderabad in collaboration with Nizam's Institute of Medical Sciences (NIMS) has initiated an innovative project in digital pathology. With the introduction of a digital scanner in NIMS, traditional histopathological slides are converted into digital images, thus enabling the development of an Indian Pathology Dataset. The project enables pathology research and aids in the development of AI-based diagnostic tools tailored for the Indian populace (Maleki Varnosfaderani & Forouzanfar, 2024)(10).

Telepathology Adoption Challenges in India

While the potential is present, telepathology's utilization in India has several challenges:

1. Infrastructure Limitations: The majority of rural health centers lack the necessary IT infrastructure, such as high-speed internet and digital scanners, to facilitate telepathology implementation (9).

2. Legal and Regulatory Barriers: Compliance with telemedicine and digital pathology regulations and laws remains a challenge. There is a need for clear guidelines for cross-border consultation in pathology and data protection (5).

3. Excessive Implementation Costs: Establishing telepathology infrastructure involves significant amounts of money to spend on technology, training staff, and maintenance, which might be difficult for small healthcare organizations (3).

4. Limited Digital Literacy: The majority of physicians, particularly from rural regions, lack proper training in operating digital pathology machines, which requires extended training courses (15).

Despite tremendous advances in telemedicine, telepathology still has a long way to go before it becomes an integral part of the Indian healthcare system. Although digital pathology has been promising in reducing diagnostic delays and expanding access to specialist opinions, several barriers still exist that limit its universal use. These are infrastructural constraints, regulatory hurdles, workforce skill gaps, and interoperability issues. The future of telemedicine and telepathology depends on the elimination of these barriers, which is crucial for the development of an efficient and streamlined diagnostic pathway. Adequate training of the healthcare personnel and provision of infrastructure to realize the full potential of telepathology will be critical (25)26).

1. Technological Barriers – The biggest deterrent in the implementation of telepathology in India is the high cost of implementation. Whole Slide Imaging (WSI) scanners, the driving force behind the digitalization of pathological slides, call for huge up-front investments. Moreover, high-resolution digital image requirements necessitate high storage space, and internet transmission requires high bandwidth, often not provided by rural hospitals and diagnostic centers. The absence of proper internet facilities in remote localities further detracts from real-time consultations, and pathologists find it difficult to offer prompt diagnoses (16,21).

2. Legal and Regulatory Problems – Lack of universally accepted national procedures for telepathology practice is a major problem. India lacks a properly established regulatory system to effectively deal with medico-legal issues, protect patient data, and provide protection in terms of liability for remote diagnostic practices. Compliance with the Health Insurance Portability and Accountability Act (HIPAA) and similar patient data protection acts is important to establish safe telepathology platforms. Additionally, there is uncertainty regarding the legal admissibility of digital pathology reports as documents, which is a problem for accountability in case of diagnostic errors (5,27).

3. Workforce Training and Acceptance – The shift from conventional glass slide microscopy to digital pathology involves

extensive retraining of pathologists, technicians, and healthcare administrators. A considerable number of professionals resist the use of telepathology, primarily due to unfamiliarity with digital equipment and diagnostic accuracy concerns. To address these challenges, it is essential to develop extensive training programs that incorporate AI-enhanced diagnostic tools, digital image analysis, and telecommunication technologies. Integrating telepathology training into medical education curricula and continuing medical education (CME) programs can facilitate greater acceptance among healthcare professionals (3,28).

4. Interoperability Challenges – One of the key technical challenges in telepathology is the absence of standardization across various digital pathology platforms. Various hospitals and diagnostic centers use different software and imaging systems, thereby complicating the integration of telepathology with existing hospital information systems (HIS) and electronic medical records (EMR). Compatibility needs to be established, and data exchange needs to be smooth between these platforms to maximize workflow efficiency and facilitate remote pathology services. For facilitating the widespread use of telepathology, industry-wide initiatives to develop standardized imaging formats and communication protocols are essential (15,29).

Outlook and the Way Forward

The future of telepathology in India looks good with the advent of artificial intelligence-based diagnostic tools, fifth generation (5G) telecommunications, and cloud computing making it possible for use on a large scale. Artificial intelligence tools in pathology, such as computer-assisted image analysis and deep learning, can assist in enhancing the speed and accuracy of disease diagnosis such as cancer, tuberculosis, and blood disorders. Additionally, government initiatives and investment in digital health infrastructure will be crucial in overcoming the challenges in the adoption of telepathology (2,17,27)(30).

Anticipated Developments

Despite these challenges, the future of telepathology in India appears bright, thanks especially to ongoing advances in virtual microscopy technology. Virtual microscopy enables pathologists to access and examine remotely high-definition digital images of tissue samples, thereby providing opportunities for teleconsultation, education, and effective diagnostic processes (15). This new methodology promotes collaboration among specialists, accelerates the process of obtaining second opinions, and increases pathology services to under-resourced regions. The application of artificial intelligence and machine learning in digital pathology is likely to improve diagnostic accuracy and operational efficiency. Moreover, government-initiated programs such as the ABDM, and partnerships between research institutions and health providers, are likely to further accelerate the growth of telepathology services. With ongoing progress in cloud storage technology, high-definition imaging capability, and telecommunication networks, telepathology is bound to revolutionize diagnostic pathology in India, thereby increasing the availability of quality healthcare across the nation (22).

Telepathology Impact Induced by AI

Artificial Intelligence (AI) has emerged as a key driving force in telepathology, with enhanced diagnostic quality, reduction of human errors, and workflow process optimization. AI-driven algorithms in digital pathology have revolutionized the analysis, interpretation, and storage of pathological specimens. AI enables automated image analysis, biomarker detection, and real-time decision support, thus enhancing the efficacy and accessibility of telepathology (1).

1. Diagnosis and Analysis with AI-Powered Imaging Software with artificial intelligence functionality can detect abnormalities, classify diseases, and perform quantitative measurements of tissue samples. Sophisticated machine learning algorithms are highly accurate in identifying histopathological patterns, thus assisting pathologists in diagnosing various conditions, such as cancer, infectious diseases, and autoimmune diseases. Automation with this approach eliminates inter-observer variability and ensures consistency in the outcome of diagnosis. Evidence shows that workflows that integrate AI in pathology increase diagnostic accuracy and reduce turnaround time for critical cases (7,22).

2. Minimization of Diagnostic Errors and Improved Efficiency Another important advantage of artificial intelligence (AI) in telepathology is its ability to minimize human errors. AI computer programs can detect areas of interest on digital slides, thus avoiding pathologists from overlooking minor abnormalities. Through the automation of repetitive tasks like cell counting, tissue separation, and biomarker measurement, AI enables pathologists to focus on more challenging and emergent cases. This improvement results in improved workflow efficiency, allowing laboratories to handle more cases with increased(6,8).

3. Artificial Intelligence-Based Decision Support Systems Artificial intelligence-based decision support systems support pathologists by providing evidence-based recommendations for diagnosis and treatment planning. These systems use large sets of annotated pathology images to generate insights that guide clinical decision-making activities. Moreover, AI can predict the progression of disease and suggest individualized treatment options based on histopathological data. The use of AI in telepathology is especially crucial in resource-limited settings, where there are limited expert pathologists (9,10).

4. Telepathology in Remote and Rural Areas Telepathology systems based on artificial intelligence are helping reduce healthcare inequality between rural and urban areas. Through the enablement of real-time, AI-assisted remote diagnosis,

remote healthcare providers can avail specialist pathological examination without having to physically relocate slides. AI can also be used to conduct the initial screening of cases and rank them according to severity, enabling severe cases to be addressed on time. This is especially relevant in oncology, where timely diagnosis has a significant bearing on treatment (11)(5).

5. Future and Ethical Horizons The prospects of artificial intelligence in telepathology are good, with ongoing research focused on developing sophisticated deep learning algorithms capable of replicating the diagnostic ability of human pathologists with near-expert accuracy. Ethical concerns like algorithmic bias, patient privacy, and excessive reliance on AI need to be managed cautiously. While AI can improve the capability of pathologists, ensuring that ultimate diagnostic conclusions are arrived at under human supervision needs to be guaranteed for accountability and patient safety (3,15).

State-supported programs and aid

The Indian government has also recognized the potential of digital health technologies and has moved to promote telepathology through policies and initiatives. The launch of the Ayushman Bharat Digital Mission (ABDM), previously the National Digital Health Mission (NDHM), is aimed at digitizing the health record and creating an integrated data-sharing system for improving patient care. It is expected that the program will further the use of telepathology through the integration of digital pathology platforms with electronic health records (EHR) and telemedicine services (31).

The Digital India initiative has contributed significantly to the development of telehealth infrastructure through the expansion of broadband connectivity, the adoption of cloud computing, and the inclusion of digital technologies in healthcare processes.

Policy Recommendations for Advancing Telepathology

For ensuring the full potential of telepathology in India, a combined effort of government agencies, private healthcare organizations, and technology developers is required. A range of policy recommendations can facilitate the extensive application of telepathology and provide assurance of its successful integration:

1. Telepathology Standardization of Practice – The government needs to establish national telepathology guidelines delineating standardized processes for image acquisition, storage, transmission, and reporting. The standardized processes need to comply with international standards of digital pathology to ensure interoperability and exchange of information between institutions (3,27).

2. Investment in digital pathology infrastructure, i.e., whole slide imaging (WSI) scanners, cloud-based storage systems, and artificial intelligence-based image analysis software, is crucial for both the public and private sectors. Granting financial incentives, grants, and subsidies to hospitals and diagnostic centers incorporating telepathology can accelerate its adoption (1,15).

3. Training and Capacity Building – The integration of digital pathology and AI training into medical curricula and continuing medical education (CME) programs will improve workforce readiness. Pathologists, laboratory technicians, and health IT professionals need to be provided with hands-on training in telepathology workflows and AI-aided diagnostics (28,29).

4. Enhancing Data Privacy and Security Laws – Enhancing cybersecurity measures and enacting robust data privacy regulations will be critical in safeguarding patient information. Implementing end-to-end encryption, blockchain-based data handling, and HIPAA-compliant telepathology software will boost trust and utilization (3,5).

5. Public-Private Partnerships (PPP) and Collaborations – Establishing partnerships among public authorities, private healthcare facilities, research centers, and technology firms can promote innovative advances in telepathology. PPP models may facilitate mass deployment of AI-based digital pathology solutions, subsequently improving access to remote diagnostics in underprivileged populations (6,8).

6. AI and Regulatory Framework Integration – AI-enabled diagnostic devices need to be clinically validated and approved by regulatory bodies prior to mass implementation. Robust guidelines for AI-driven pathology and the responsible use of AI will reduce anxiety about algorithm bias and diagnostic performance (7,9).

7. Telepathology networks – Establishing national and regional telepathology networks of urban tertiary health facilities and connecting them with rural health facilities can, in a way, fill the diagnostic gap. Governmental support to create cloud computing-based repositories for pathology data and telemedicine centers can further increase access to expertise in pathology at the specialized level (10,11).

2. CONCLUSION

Telepathology is a revolutionary diagnostic medicine technology, overcoming India's geographical handicap and lack of trained pathologists. With the integration of digital pathology with telemedicine and use of AI-based tools, telepathology increases diagnostic accuracy, minimizes delays, and allows remote expert consultation. India has made some strides with initiatives such as the Ayushman Bharat Digital Mission (ABDM), but cost, rural infrastructure limitations, and regulatory ambiguities continue. These are met with strategic investments, policy interventions, and coordination between government

agencies, private healthcare providers, and technology innovators. With continued efforts towards improving infrastructure, standardizing procedures, and maintaining data security, telepathology can revolutionize diagnostics, enhance healthcare accessibility, and make India a digital pathology leader globally.

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