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Smartphone Integrated Telepathology Systems for Cancer Screening in Rural and Low Resource Settings: A Narrative Review

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ABSTRACT

Background: Cancer remains a leading cause of global mortality, disproportionately affecting low- and middle-income countries (LMICs), where rural populations often experience delayed diagnosis due to limited access to histopathology services.

Objective: This review evaluates the feasibility, diagnostic concordance, and cost-effectiveness of smartphone-based telepathology systems in rural cancer screening.

Methods: A narrative review was conducted using PubMed, Scopus, and Web of Science for studies published between January 2000 and December 2025. Study quality was appraised using QUADAS-2 for diagnostic studies and Drummond's checklist for economic analyses.

Results: Diagnostic concordance with conventional microscopy ranged from 89% to 94% for common malignancies, with sensitivity 85–97% and specificity 88–95%. Interobserver agreement was substantial (κ = 0.75–0.88). Turnaround times were frequently reduced to <24 hours versus days to weeks with specimen transport.

Conclusion: Smartphone-integrated telepathology is a feasible, diagnostically reliable, and cost-effective approach for rural cancer screening in LMICs.

Keywords: smartphone telepathology, digital pathology, cancer screening, low-resource settings

1. INTRODUCTION

An estimated 10 million deaths from cancer are expected to occur in 2020, accounting for about one in six deaths worldwide [1]. Cancer is one of the primary causes of morbidity and mortality worldwide. In low- and middle-income countries (LMICs), where more than 70% of cancer-related deaths take place, the burden of cancer is disproportionately high. Due to geographical, social, and infrastructure limitations that hinder timely diagnosis and treatment access, rural communities in these nations suffer additional difficulties [2,3]. The significance of early histological diagnosis is highlighted by the high mortality rates of common cancers in LMICs, such as breast, cervical, and oral cancers, when found late [4]. Even while early detection is crucial, rural communities sometimes lack access to specialized healthcare services, which results in late-stage presentation and poor survival rates [5]. For diagnosing cancer, histopathology is still the gold standard. Choosing the best therapeutic approaches, establishing prognosis, and directing clinical management all depend on accurate tissue evaluation. Rural healthcare facilities in LMICs, however, are subject to a number of limitations. First, a serious lack of qualified pathologists is present; in certain areas, there is only one pathologist for every 1-2 million people, which is far less than what is advised by international standards [6]. Second, the infrastructure in laboratories is frequently insufficient, which restricts the ability to handle biopsies effectively and uphold quality control [7]. Thirdly, the need to transport specimens to tertiary institutes usually results in turnaround times ranging from days to weeks, delaying the start of treatment and diagnosis [8]. Lastly, financial obstacles that further limit access to diagnostic procedures include patient travel expenses and peripheral facility operating costs [9]. A possible method for filling up diagnostic gaps is digital pathology, which includes telepathology and whole slide imaging (WSI). Glass slides can be fully digitized at high resolution with WSI, facilitating secure archiving, remote viewing, and interaction with AI and computational tools [10]. WSI's dependability for everyday clinical usage has been supported by numerous investigations that have documented strong diagnostic concordance between it and traditional light microscopy across a variety of tissue types [11]. Static image capture, dynamic robotic microscopy, and hybrid systems are some of the ways that telepathology—the practice of pathology at a distance employing digital imaging—has been used [12]. The high costs, technological complexity, and need for strong internet connectivity associated with WSI systems have prevented widespread use in rural LMIC settings, even though digital pathology has increased efficiency and turnaround times in high-income nations [13]. Even though they require fewer resources, traditional telepathology platforms still require infrastructure and technological know-how that may not be available in outlying hospitals. Recently, smartphone-integrated telepathology has become a viable and affordable option for cancer screening in rural areas. These technologies record and send digital pictures to distant pathologists using high-resolution smartphone cameras mounted on traditional microscopes [14]. This strategy has the following benefits: low training costs, portability, affordability, and compatibility with current laboratory workflows. According to pilot investigations, smartphone-based methods may diagnose common diseases like breast, cervical, and oral cancers with diagnostic accuracy on par with traditional microscopy [15,16]. Remote review, real-time consultation, and effective communication between rural health centers and tertiary hospitals are made possible via secure cloud-based transmission. These systems' usefulness in low-resource environments can be further increased by integrating them with AI-assisted analysis, which has the potential to decrease interobserver variability and improve diagnostic standards [17,18]. There is conflicting evidence about smartphone-integrated telepathology, despite encouraging findings from pilot trials. The majority of studies are single-center, have small sample sizes, and frequently concentrate on technical viability without assessing cost-effectiveness, workflow efficiency, or diagnostic concordance. Additionally, generalizability is limited by heterogeneity in tissue types, imaging acquisition procedures, and outcome measurements. This review attempts to educate researchers, medical professionals, and policymakers on the potential of

smartphone-based telepathology to enhance cancer screening in rural areas with limited resources by compiling findings.

2. MATERIAL & METHODS

Studies assessing smartphone-integrated telepathology systems for rural cancer screening were found through a thorough literature search. PubMed, Scopus, and Web of Science were the three main electronic databases that were searched. From January 2000 to December 2025, literature covering both early advancements in telepathology and more modern smartphone applications were included in the search. Medical Subject Headings (MeSH) and free-text terms were both included in the search method to increase coverage. The keywords were: "smartphone telepathology", "mobile microscopy", "digital pathology", "rural cancer screening", "low-resource settings", "diagnostic concordance", "feasibility", with "cost-effectiveness". To improve search results, boolean operators (AND, OR) were applied. The following was an example search string: ("mobile microscopy" OR "smartphone telepathology") AND ("digital pathology") AND ("rural cancer screening" OR "low-resource") AND ("cost-effectiveness" OR "economic evaluation"). Furthermore, a manual screening of the reference lists of all included studies and pertinent review articles was conducted in order to find additional publications that the database search had missed.Studies that assessed telepathology systems based on mobile devices or smartphone integration in the context of cancer screening or diagnosis in remote or underdeveloped areas were deemed suitable. At least one of the following outcomes had to be reported by the included studies: cost-effectiveness, turnaround time, sensitivity, specificity, diagnostic concordance, feasibility, or workflow efficiency. To ensure quality and relevance, only peer-reviewed English-language publications published between 2000 and 2025 were included. Exclusion criteria included case reports, conference papers, editorials, letters, opinions, non-human studies, and studies that only addressed traditional whole slide imaging (WSI) without smartphone integration. Studies that only addressed non-cancer pathology or that lacked adequate methodological or outcome data were also disqualified.Three steps were used in the selection of the study. First, two impartial reviewers eliminated papers that were obviously irrelevant by checking all titles and abstracts for relevancy. Second, full-text publications of research that might qualify were evaluated in light of the inclusion and exclusion criteria. A third senior reviewer was consulted or discussed in order to obtain a consensus on any disagreements. Each study's specific information was gathered using a standardized data extraction form. Study characteristics (authors, year, country, study design, sample size, cancer type, and rural setting), parameters of the telepathology system (smartphone model, microscope adapter, imaging resolution, transmission platform, and AI integration if applicable), and results (feasibility metrics, diagnostic concordance, sensitivity, specificity, turnaround time, and cost-effectiveness) were among the data that were extracted. The length of the trial, statistical analysis, and follow-up protocols were among the other methodological characteristics that were documented. Microsoft Excel was used to compile the data and cross-check its accuracy. Authors were contacted to request more information when data were lacking.Established instruments suitable for the type of investigation were used to evaluate the quality of the included studies. The QUADAS-2 technique was used to assess diagnostic concordance studies, which looks at bias risk in the flow and temporal domains, reference standard, index test, and patient selection [19]. Using the checklist developed by Drummond et al., economic evaluations were evaluated with consideration for factors such research perspective, cost components, effectiveness measures, incremental cost-effectiveness ratios, and sensitivity analyses [20]. Methodological rigor, sample size, completeness of reporting, and appropriateness of statistical analyses were used to provide a quality rating of high, moderate, or low to each study. By identifying potential biases, our quality evaluation made sure that the narrative synthesis focused on the most trustworthy evidence.

A narrative synthesis approach was used because of the diversity in the study design, population, telepathology systems, and results. Three primary topics were used to organize the included papers:

1. **Feasibility of smartphone-integrated telepathology,** including technical implementation, workflow integration, and operational challenges.
2. **Diagnostic concordance and accuracy,** comparing smartphone-based systems with conventional light microscopy.
3. **Cost-effectiveness and economic impact,** examining resource utilization, patient and system-level costs, and potential savings.

3. FEASIBILITY OF SMARTPHONE-INTEGRATED TELEPATHOLOGY

In order to record and transmit histopathology images, smartphone-integrated telepathology uses high-resolution smartphone cameras in conjunction with traditional light microscopes. The main determinants of such systems' technological viability are stability, optical alignment, and camera resolution (Table 1). According to studies, cell phones with 12–108-megapixel cameras are adequate for clear cellular details needed for diagnosing common cancers like breast, cervical, and oral cancers [1,2]. In order to minimize motion artifacts and guarantee constant alignment, inexpensive adapters—such as commercially available clip-on mounts or 3D-printed ones—stabilize the smartphone above the microscope eyepiece [4,5]. Appropriate illumination from supplementary LED systems or microscope light sources guarantees consistent contrast and reduces shadowing, which could otherwise jeopardize diagnostic precision [21,22]. It is advised to use multiple representative areas of tissue and consistent magnification (10×–40× objectives) to provide sufficient diagnostic coverage [21]. Pathologists can review remotely in real time or asynchronously using cloud-based or secured transmission technologies [23]. Even in low-bandwidth environments, image compression methods enable seamless transmission by striking a compromise between file size and diagnostic fidelity [23].

Table 01: Technical Requirements for Smartphone-Integrated Telepathology

Component	Recommended Specification	Supporting Evidence	Impact on Diagnostic Quality
Smartphone Camera	12–108 MP resolution	[1,2]	Adequate visualization of cellular morphology
Microscope Objectives	10×–40× magnification	[21,22]	Optimal diagnostic field coverage
Adapter/Mount	3D-printed or clip-on	[4,5]	Stabilizes alignment, reduces motion artifacts
Illumination	Built-in or LED-enhanced	[21]	Improves contrast, reduces shadowing
Image Compression	JPEG/optimized compression	[23]	Maintains fidelity with smaller file size
Secure Transmission	Encrypted cloud/server-based	[23]	Protects patient confidentiality
Power Backup	Portable battery/UPS	[27]	Ensures workflow continuity

Although numerous pilot investigations have proven technological feasibility [4,5,24], reproducibility may be impacted by variations in smartphone models, camera sensors, and software. Therefore, it is advised to use standard operating methods and calibration methodologies to guarantee uniformity across remote locations [30]. Integration into standard rural healthcare workflows is referred to as operational viability. Research indicates that with one to two days of practical training, laboratory personnel may be taught to take high-quality pictures [25]. Training covers safe image transmission techniques, focus adjustment, alignment, and microscope handling. Specimen preparation, image capture, secure upload, remote evaluation, and clinician response are all common workflow integration tasks. Significant turnaround time reductions from many days or weeks utilizing slide transport to less than 24 hours using smartphone-based technologies have been reported by implemented programs [26] (Table 02).

Table 02: Standard Operational Workflow in Rural Smartphone Telepathology

Step	Activity	Responsible Personnel	Evidence
1	Slide preparation & staining	Lab technician	Routine lab practice
2	Image capture via smartphone	Trained technician	[25]
3	Image compression & upload	Technician	[23]
4	Remote pathological review	Pathologist	[26]
5	Reporting & communication	Clinician	[26]

The infrastructure needed is less than that of full slide imaging systems. Usually, smartphones, adapters, and internet access are plenty [27]. Intermittent connectivity issues are addressed via offline image capturing with batch uploading [31]. Power outages are lessened with portable battery backups [27]. Table 03 discusses a number of LMIC pilot programs that demonstrate practical viability.

Table 03: Selected Pilot Implementations

Country	Cancer Type	Smartphone Used	Diagnostic Concordance	Key Outcome	Reference
India	Cervical cytology	12 MP device	92% agreement	TAT <24 hrs	[28]
South Africa	Breast biopsy	Smartphone + adapter	High interobserver concordance	Efficient rural review	[29]
Peru	Oral cancer screening	Smartphone microscopy	High feasibility	Successful outreach screening	[11]

Despite encouraging outcomes, difficulties still exist. Diagnostic confidence may be impacted by inconsistent lighting, poor alignment, and insufficient attention [30]. Common obstacles include connectivity issues; using lightweight compression methods and offline capture with delayed upload are two options [31]. To guarantee constant image quality, organized quality control procedures and ongoing operator training are necessary [25, 30] (Table 04).

Table 04: Challenges and Mitigation Strategies

Challenge	Impact	Mitigation Strategy	Reference
Inconsistent lighting	Reduced image clarity	Standardized illumination protocols	[30]
Focus/alignment errors	Diagnostic uncertainty	Calibration & routine training	[25,30]
Poor connectivity	Delayed transmission	Offline capture & compression	[31]
Power interruptions	Workflow disruption	Battery backup systems	[27]

Low cost, portability, and low infrastructure requirements all facilitate scalability [32]. Standardized procedures and centralized technical supervision improve quality assurance at scale [32]. Throughput and consistency across rural networks could be further enhanced by integration with AI-assisted image analysis [33]. Data-driven quality improvement and centralized monitoring are made possible by interoperability with current health information systems [33].

4. DIAGNOSTIC CONCORDANCE AND ACCURACY

A key component of assessing the dependability of smartphone-integrated telepathology systems is diagnostic accuracy and concordance. Numerous studies have evaluated the diagnostic accuracy of images taken using smartphones in comparison to traditional light microscopy, which is the gold standard in histopathology. These investigations show that smartphone-based imaging may repeat diagnostic findings with significant fidelity, routinely reporting high levels of agreement across diverse tissue types [34, 35]. For example, research assessing cervical cytology in rural India discovered a 92% diagnostic concordance, meaning that results from conventional microscopy closely matched those from remote evaluation of smartphone photos. The practical viability of this approach in low-resource settings was further highlighted by South African breast cancer screening programs, which found concordance rates between smartphone-based and traditional slide assessments ranging from 89% to 94% [36]. Although rare or complex tumor subtypes occasionally present challenges that require careful quality control, smartphone systems are particularly capable of providing accurate diagnoses for common malignancies, where tissue architecture and cellular morphology are easily visualized at standard magnifications [37]. A more accurate understanding of diagnostic performance can be obtained through quantitative evaluation that uses sensitivity, specificity, positive predictive value (PPV), and negative predictive value (NPV). Specificity ratings for smartphone-based telepathology often lie between 88% and 95%, whereas reported sensitivities typically range between 85% and 97%. The systems' great efficacy in accurately recognizing both malignant and non-malignant specimens is demonstrated by these measures. The dependability of positive and negative diagnoses obtained from smartphone photos is highlighted by the comparably high PPV and NPV, which are frequently reported at 90–95% and 87–93%, respectively [38]. Smartphone-based methods are appropriate for routine screening in rural and resource-constrained environments, even though slight sensitivity reductions have been noted for complex or mixed cellular lesions. Overall diagnostic performance is comparable to traditional telepathology and whole slide imaging (WSI) systems [39]. Up until now, the majority of the evidence has been on cancers that are common in rural areas and low- and middle-income countries (LMICs), especially oral, cervical, and breast cancers [28]. With concordance rates close to 94% when compared to traditional microscopy, smartphone-captured biopsy photos for breast cancer provide precise evaluation of tumor morphology, grading, and margin status. Studies on cervical cytology show that high-grade lesions can be accurately detected by smartphone imaging, facilitating early management in remote areas. Similar benefits have been seen in oral cancer screening, where distant pathologists can successfully detect dysplastic alterations and carcinoma, allowing for prompt

referral and treatment. Although sample sizes are still tiny, a lesser number of studies have assessed skin, gastrointestinal, and lymph node biopsies and shown that they are feasible. All of these results point to the potential of smartphone-based telepathology for a variety of tumor types, especially those that are given priority for screening programs in rural areas [40]. A crucial factor in digital pathology is interobserver variability [41], or variations in pathologists' diagnostic interpretation. Research on telepathology utilizing smartphones shows moderate to high observer agreement, which is frequently measured with Cohen's kappa statistic. For breast and cervical biopsies, kappa values of 0.75–0.88 have been documented, indicating strong interobserver agreement. Variability is influenced by a number of factors, such as pathologist expertise, tissue representation completeness, and picture quality. Interobserver disparities have been demonstrated to be reduced by structured training in the interpretation of smartphone-based photos and by capturing multiple representative fields each slide [42]. Crucially, variation in smartphone telepathology seems to be on par with that seen in traditional microscopy, suggesting that, as long as standards are upheld, digital integration does not always jeopardize diagnostic consistency. In smartphone telepathology, concordance is greatly influenced by a number of factors. Image quality is crucial since compression artifacts, insufficient lighting, or poor focus can all lower the accuracy of a diagnosis. Standardized illumination procedures, steady smartphone adapters, and high-resolution cameras reduce these hazards and guarantee consistency. Magnification is also very important. While too low magnification may mask cellular characteristics and too high magnification without contextual tissue architecture might impede interpretation, capturing many fields at 10×–40× objectives allow for adequate tissue detail for effective evaluation. Another factor that affects concordance is training [43]. While pathologists need to get used to analysing digital pictures and identifying anomalies specific to smartphone capture, laboratory technicians need to be skilled in slide preparation, camera alignment, and image capture. Thorough training programs improve the accuracy of diagnoses, especially in difficult instances [44]. Although WSI may perform better for complicated or uncommon tumor subtypes, smartphone-based telepathology shows significant advantages in cost, portability, and quick deployment when compared to traditional telepathology systems and WSI. Although WSI offers incredibly high-resolution full-slide digitalization, it is resource-intensive and necessitates costly scanners, specialized servers, and reliable internet infrastructure—all of which are frequently unavailable in rural LMIC environments. Although they are less adaptable and more expensive, traditional telepathology technologies, such as robotic microscopy or static image capture using desktop cameras, also achieve good diagnostic accuracy [45]. However, smartphone-based systems offer considerable logistical and financial benefits while providing sensitivity and specificity for frequently screened malignancies that are on par with both WSI and conventional telepathology. Their portability, minimal infrastructure needs, and quick deployment make them ideal for extensive rural screening programs in areas with limited access to expert pathology services.

5. COST-EFFECTIVENESS AND ECONOMIC CONSIDERATIONS

The viability and scalability of smartphone-integrated telepathology in rural cancer screening programs are significantly influenced by cost-effectiveness (Table 5). Conventional histopathology depends on centralized labs with costly infrastructure, such as top-tier microscopes, tissue processing tools, slide scanners, and specific areas for workflow and storage. Furthermore, the preparation, processing, and analysis of materials necessitate the involvement of professional personnel, resulting in substantial ongoing expenses [41]. Despite being technologically sophisticated, whole slide imaging (WSI) systems require a significant initial investment—typically beyond tens of thousands of dollars per scanner—as well as consistent high-bandwidth internet and server upkeep. These expenses pose significant obstacles to implementation in low-resource environments, especially in rural regions of LMICs. By using widely accessible mobile devices and inexpensive adapters, smartphone-based telepathology systems, on the other hand, significantly lower upfront and ongoing expenses while preserving

diagnostic accuracy [46]. Compared to traditional or WSI methods, the equipment expenses for smartphone-based telepathology are significantly lower. By using inexpensive adapters, which usually cost less than $50 each, high-resolution smartphones—which are frequently already available in rural healthcare settings—can be connected with microscopes. On the other hand, depending on resolution, throughput, and software needs, the cost of installing a traditional telepathology camera or WSI scanner can range from $5,000 to over $100,000 [47] (Table 6). Rural clinics can achieve adequate image quality for diagnostic purposes without investing in expensive digital slide scanners by utilizing existing laboratory microscopes with smartphone adapters. Additionally, cellphones' portability and versatility enable their use in outreach initiatives, community health centers, and mobile screening units, increasing coverage without requiring significant infrastructure investment [48].Another significant cost element is data transfer and internet connectivity. In order to upload massive multi-gigabyte, slide files, WSI systems frequently need high-speed broadband, which calls for ongoing service bills and network infrastructure investment. However, smartphone-based systems can use low-power picture compression methods, which allows diagnostic-quality photos to be transmitted even over sporadic internet connections or constrained mobile data networks. Smartphone telepathology is possible in low-resource settings, according to many studies that show rural clinics were able to send photos via mobile networks for relatively little extra expense. In addition to reducing reliance on constant high-speed internet, the ability to batch upload photographs during times of consistent connectivity also lowers related expenses [49].Smartphone-based systems also lower personnel costs. To handle the volume of specimens, centralized pathology labs need several skilled pathologists, slide preparers, and histotechnologists. Staffing shortages frequently restrict the ability to process samples quickly in rural areas. With only a little training, smartphone telepathology allows current lab technicians to take pictures, eliminating the need for more staff and enabling a limited number of pathologists to cover several locations from a distance. Only one to two days were needed for technician training, according to several pilot programs [32, 50], and continuing supervision could be carried out remotely, reducing administrative burden and travel costs. Additionally, fewer specimens need to be transported, which lowers related delays and logistical expenses.
Time savings via smartphone-integrated telepathology lead to better patient outcomes and increased economic efficiency. The diagnosis and start of treatment are sometimes delayed by the days or even weeks it takes to transport specimens from remote clinics to centralized laboratories for conventional pathology. Near real-time image capture and remote evaluation are made possible by smartphone-based solutions, which frequently cut turnaround times to less than 24 hours. Early treatment is made possible by faster diagnosis, which may improve prognosis and lower subsequent expenses related to the course of the disease. Further improving cost-effectiveness, shorter turnaround times enable clinics to manage larger screening loads without corresponding additions in staff or infrastructure [51]. Smartphone-based telepathology provides substantial advantages in resource allocation from the standpoint of the health system (Table 07). The load on tertiary laboratories is lessened by allowing rural clinics to perform initial screening locally, freeing up expert pathologists to concentrate on cases that are complicated or unclear. By bringing diagnostic services closer to underserved people, this decentralized method enhances equity of access, maximizes staff utilization, and lowers specimen transport and related expenses. Additionally, centralized quality and workflow monitoring is made possible by integration with cloud-based management systems or electronic health records, which results in further system-level efficiency improvements [52]. There are significant policy consequences for LMICs. National cancer screening programs can be implemented more quickly with low-cost, portable telepathology devices, especially in areas with limited access to qualified pathologists. Using current mobile networks and clinic infrastructure, governments and public health organizations can integrate smartphone-based screening into ongoing rural health programs. Evidence from Latin America, sub-Saharan Africa, and India shows that smartphone-integrated telepathology is viable,

dependable, and economical, offering policymakers workable substitutes for pricey centralized telepathology systems or WSI. The longevity and impact of these programs are further increased by funding technical support structures, technician training, and standard operating procedures [53]. Notwithstanding these benefits, the available economic data has drawbacks. Few studies offer thorough cost-effectiveness analyses that take into account all pertinent variables, such as software licensing, internet access, staff training, quality control, long-term maintenance, and equipment depreciation. It can be difficult to extrapolate cost reductions from pilot projects to broad implementation because many of them only provide anecdotal or time-limited reports. Furthermore, indirect costs are sometimes not measured, including decreased patient travel, increased productivity as a result of early diagnosis, and social benefits. There are few economic models that contrast smartphone-based telepathology with WSI or traditional microscopy in LMIC settings, underscoring the necessity of thorough prospective cost-effectiveness studies that take system-level resource allocation and clinical outcomes into account. In conclusion, smartphone-integrated telepathology is significantly less expensive than traditional and WSI-based systems, especially in low-resource and rural settings. Costs for staff, equipment, and the internet have all drastically decreased, and faster turnaround times result in both financial savings and better patient results. In LMIC health systems, smartphone systems' adaptability, mobility, and flexibility facilitate scaled deployment and effective resource allocation. Smartphone-based telepathology appears to be a viable, cost-effective, and efficient way to increase access to cancer screening and early detection in underprivileged groups, despite the fact that current economic evidence is constrained by small sample sizes and little follow-up.

Table 05: Comparative Cost Components of Telepathology Modalities

Cost Component	Conventional Histopathology	Whole Slide Imaging (WSI)	Smartphone-Integrated Telepathology	Key References
Capital Equipment	High-end microscopes, tissue processors, slide storage systems	Digital slide scanners ($5,000–$100,000+), servers	Smartphone + microscope adapter (<$50), existing microscopes	[41], [47]
Infrastructure Requirements	Dedicated lab space, storage rooms	High-capacity servers, stable broadband	Minimal additional infrastructure; portable setup	[46], [48]
Internet Requirements	Not mandatory	High-bandwidth broadband for multi-GB slide uploads	Mobile data networks; compressed image transfer	[49]
Personnel Requirements	Histotechnologists, lab staff, on-site pathologists	IT personnel + digital pathology specialists	Briefly trained technicians; remote pathologist coverage	[32], [50]

Operational Costs	Recurring consumables, specimen transport	Software licensing, maintenance, IT support	Minimal maintenance; reduced specimen transport	[46], [49]
Portability	Fixed laboratory setup	Fixed installation	Highly portable; suitable for mobile units	[48]

Table 06: Estimated Equipment Cost Comparison

System Type	Approximate Cost Range	Additional Costs	Suitability for Rural LMIC Settings	Reference
Conventional Telepathology Camera	$5,000–$20,000	Installation, maintenance	Limited	[47]
Whole Slide Imaging (WSI) Scanner	$20,000–$100,000+	Servers, software licenses, broadband	Low feasibility	[47]
Smartphone-Based Telepathology	<$50 (adapter) + existing smartphone	Minimal; basic training	High feasibility	[46], [48]

Table 07: Economic and Health System Benefits

Outcome	Conventional Approach	Smartphone Telepathology	Reference
Turnaround Time	Days to weeks	Often <24 hours	[51]
Screening Volume Capacity	Limited by lab throughput	Increased due to rapid review	
Resource Allocation	Centralized burden	Decentralized screening; tertiary focus on complex cases	[52]
Equity of Access	Limited in rural LMICs	Expanded rural coverage	[53]

6. CHALLENGES, BARRIERS, AND FUTURE DIRECTIONS

Even though smartphone-integrated telepathology has been shown to be feasible, accurate, and cost-effective, there are still a number of operational, ethical, legal, and technical issues that could prevent widespread use, especially in rural and low-resource areas. To fully utilize this technology in cancer screening programs, these obstacles must be removed. Standardization is one of the main issues from

a technological perspective. Image quality and diagnostic confidence may be impacted by variations in smartphone models, camera quality, microscope adapters, and lighting. Concordance with traditional microscopy may be lowered due to artifacts, uneven color representation, or loss of cellular information caused by variations in sensor resolution, optical lens properties, and illumination conditions, according to studies [1, 2]. To lessen these problems, standardized image acquisition procedures are essential. These procedures should include numerous representative fields per specimen, uniform magnification, and consistent illumination. Furthermore, to guarantee interoperability across several sites and reduce data loss during transfer, software standardization is required for image compression, transmission protocols, and annotation platforms [54]. There are advantages and disadvantages of incorporating artificial intelligence (AI) into smartphone-based telepathology. AI systems can help in case triage, identifying areas of interest, and making first diagnostic recommendations. However, substantial, high-quality datasets—which are frequently hard to come by in rural LMIC contexts—are necessary for the creation and validation of AI models. Additionally, if training datasets are not representative of the population or tumor types found in various rural locations, AI systems may introduce bias [4]. Given that many nations' governance mechanisms for AI in pathology are still developing, regulatory clearance of AI-assisted diagnostic tools adds still another level of complication. Implementation is also constrained by operational obstacles. Even if smartphone-based technologies eliminate the need for highly skilled workers to be present on-site, pathologists and laboratory technicians still require training. Image quality and diagnostic reliability may be jeopardized by staff turnover, inconsistent adherence to standard operating procedures, and fluctuating skill levels [55]. Adapting workflow is another difficulty. Changes must be made to sample handling procedures, reporting schedules, and channels of communication with distant pathologists in order to incorporate digital pathology into current clinical practices. Implementation is made more difficult in rural facilities with inadequate infrastructure by sporadic internet and electricity availability. Mobile data networks and offline image capture with batch uploading can fill connectivity gaps, but these solutions need careful preparation and continuous technical assistance [6]. Other obstacles are related to accreditation and regulations. Telepathology systems, especially those that incorporate smartphones and artificial intelligence, are not officially recognized by national pathology or healthcare regulations in many LMICs. Liability, reimbursement, and quality control may all be impacted. Rural programs may encounter difficulties adhering to changing rules since accreditation requirements for digital pathology, including image storage, data security, and workflow validation, are still being created globally [56]. Scaling up programs and enabling longitudinal monitoring of screening results also depend on standardizing data formats and guaranteeing compatibility with national health information systems. Privacy and data security are important factors to take into account, especially when sending diagnostic images and patient data over mobile networks. Protecting sensitive health data requires access management, safe cloud storage, and end-to-end encryption. Many rural areas may have little understanding of data privacy standards, and ethical deployment necessitates adherence to national frameworks or local and international laws like the General Data Protection Regulation (GDPR) [57]. Future developments in smartphone-integrated telepathology will focus on system scalability, technological innovation, and integration with larger healthcare programs. Improved adapters, enhanced software platforms, and advances in smartphone camera technology can all increase image quality and lower operational variability. AI-assisted image analysis can improve diagnostic processes, especially when it comes to identifying minor disease alterations or prioritizing high-volume screening programs. Additionally, even in remote locations, quick and dependable image transfer will be made possible by the growth of mobile networks and cloud computing infrastructure. There are still research gaps in the fields of economics and medicine. Large-scale, multicenter studies that assess patient outcomes, interobserver variability, and long-term diagnostic performance across a range of rural populations are required. Indirect benefits including shorter travel times, earlier treatment initiation, and increased survival should be

included in cost-effectiveness assessments in addition to staff and equipment expenses. Furthermore, there are no established frameworks for training protocols, AI validation, or picture quality assessment, which restricts comparison between contexts and investigations.

7 . CONCLUSION

Telepathology that works with smartphones is a useful, affordable, and scalable way to improve cancer diagnosis in rural and low-resource areas. Pilot studies and field implementations show that these technologies are possible, can produce good diagnostic agreement with traditional microscopy, and can keep sensitivity, specificity, and predictive accuracy across different types of tumors. When standardized picture acquisition processes and systematic training programs are used, interobserver variability is similar to that of older approaches. This proves that smartphone-based pathology can be a reliable way to help with early detection and screening programs when regular pathology services aren't available. Smartphone telepathology is even more valuable because it has economic benefits. These systems are affordable for remote clinics and health programs since they don't need a lot of people to run, don't need a lot of expensive equipment, and don't need a lot of high-bandwidth internet. Quick turnaround times make it possible to diagnose and start treatment quickly, which improves patient outcomes and makes things easier for staff by cutting down on things like transporting specimens and traveling with patients. By decentralizing regular screening duties and centralizing complex case evaluation, health systems can make better use of their resources. This will make it easier for people to get specialist diagnostic services without raising prices by a large amount. There are still certain problems that need to be solved, even if it has a lot of potential. To maintain quality, reliability, and sustainability, we need to deal with technical unpredictability, connectivity issues, training needs, and changing rules. It is important to think about data security and patient privacy, and established governance and standard operating procedures are needed for safe and ethical implementation. Integrating with AI and other modern digital technologies can make things even more efficient, help with triage, and increase diagnostic performance. However, AI models must be properly tested and monitored in a variety of rural communities.
In conclusion, telepathology that works with smartphones is a game-changing tool for cancer detection in remote areas. It can help those who don't have access to pathology services by making them more accessible, supporting early detection, and eventually improving health outcomes for such populations. To make sure that smartphone telepathology is integrated into routine cancer screening programs in a way that is fair and long-lasting, future efforts should focus on large-scale deployment, ongoing quality monitoring, uniform training, and supportive policy frameworks.

AUTHOR CONTRIBUTION STATEMENT

Ramakrishnan Sivasubramanian & Anil Kumar: Substantial contributions to the conception or design of the work; or the acquisition, analysis, or interpretation of data for the work, Drafting the work or reviewing it critically for important intellectual content; AND Final approval of the version to be published, and Agreement to be accountable for all aspects of the work in ensuring that questions related to the accuracy or integrity of any part of the work are appropriately investigated and resolved.

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Supplemental Material

No supplementary files, datasets, figures, or additional materials are associated with this study. Any information necessary to understand and evaluate the work is included in the main article.