# Province-Wide Deployment of a Telepathology and mHealth System in China: Improving Diagnostic Accuracy and Reducing Inequity

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## Abstract

**Background:** Telepathology has emerged as a transformative digital health solution to address the global shortage of pathologists and the unequal distribution of diagnostic services, particularly in underserved and rural areas. In China, these challenges are especially pronounced in provinces like Henan, which faces high diagnostic demand and limited pathology expertise, contributing to diagnostic inequity across regions.

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**Methods:** An integrated telepathology network was deployed across 120 healthcare institutions using a three-tiered architecture, secure VPN-based transmission, and a browser/server (B/S) framework. The system enabled standardized workflows for whole-slide image acquisition, data transmission, remote diagnostics, and real-time reporting via both web interfaces and a widely adopted mobile platform (WeChat mini-program). System performance was assessed through diagnostic throughput, turnaround time (TAT), concurrency, and retrospective diagnostic accuracy.

**Results:** Since its deployment, the system processed 72,916 diagnostic cases with 355,104 WSIs, averaging nine slides per case. It demonstrated robust performance, supporting 220–300 concurrent users with high stability. The median TAT was 10.06 hours, with 96.41% of cases completed within 72 hours. Diagnostic accuracy improved markedly, with sensitivity and specificity rising from 0.90 and 0.75 (baseline) to 0.96 and 0.95, respectively. The service notably expanded access to county-level hospitals, which accounted for 77.63% of all consultations, reducing diagnostic disparities. Patient costs were reduced by ~50 USD per case, with an estimated annual saving of 405,000 USD.

**Conclusions:** The Henan Province telepathology system illustrates how scalable, province-wide digital health platforms-integrating mHealth components-can improve diagnostic accuracy, efficiency, and equity in resource-limited settings. The model offers practical guidance for other regions facing similar healthcare access challenges. Further studies should examine cost-effectiveness, AI integration, and cross-regional interoperability to support global expansion.

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# Original Manuscript

## Original Paper

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**Keywords:** Telepathology; Diagnostic Equity;Digital Pathology; Remote Diagnostics; Rural Health; Health Systems Innovation.

## Introduction

The digitisation of pathology workflows has revolutionised diagnostic practices. High-throughput slide scanning and standardised data management have enabled unprecedented improvements in service accessibility and inter-institutional collaboration [1]. Digital pathology (DP) offers multiple benefits, including enhanced diagnostic accuracy, faster turnaround times, and increased efficiency in pathology workflows [2],[3],[4],[5]. However, translating these technological advancements into equitable real-world healthcare delivery remains constrained by two systemic barriers: the geographic concentration of pathology expertise and the lack of scalable infrastructure to support cross-regional coordination [6]. In Henan Province, China--a region with a population exceeding 100 million and reporting approximately 279,740 new cancer cases annually [9], these challenges are particularly pronounced. The province faces a critical shortage of pathologists, who constitute only 0.4% of the medical workforce [8]. This shortage leads to significant delays in diagnosis, especially in rural and underserved areas, where patients often face prolonged wait times for pathology reports. These diagnostic delays directly contribute to adverse patient outcomes, including delayed treatment initiation and reduced survival rates, while exacerbating healthcare inefficiencies [7],[9].These diagnostic delays are symptomatic of deeper structural inequities in healthcare access between urban and rural populations.

Telepathology has emerged as a transformative solution to decentralize diagnostic services, offering a viable strategy to overcome these systemic barriers [13],[14],[15]. By leveraging digital slide scanning technologies [17], secure data transmission protocols [18], and remote diagnostic interfaces, telepathology enables cross-regional and cross-institutional collaboration among pathologists [19],[20]. Numerous studies have demonstrated that telepathology systems can effectively reduce turnaround times (TAT), enhance diagnostic accuracy, and optimize resource distribution, making them valuable tools for both routine diagnostics and specialized consultations [16],[21],[22],[23],[24],[25]. For instance, a telepathology diagnostic network established in Tanzania showed TAT performance comparable to conventional intraoperative consultations using optical microscopes [24]. Similarly, the Clinical Telepathology Service (CTS) at the University of California, Los Angeles (UCLA), demonstrated improved diagnostic efficiency and cost savings through its cloud-based infrastructure [12].

However, the scalability of telepathology systems remains a critical barrier to widespread adoption. A recent systematic review revealed that the majority of telepathology initiatives are limited to single institutions or pilot programs, with relatively few achieving province- or state-wide coverage [28]. This limitation arises from multiple technical and organizational challenges, including inconsistent standards for image acquisition, storage, and sharing, which hinder interoperability across regions and institutions [28]. Additionally, the large volumes of data generated by whole slide image (WSI) systems contribute to computational bottlenecks, complicating data processing and analysis [17],[18]. The absence of tiered governance models, which are essential for coordinating multi-level healthcare systems, further constrains the effective management and deployment of telepathology solutions [31],[33]. Moreover, without equitable deployment strategies, such innovations risk widening existing gaps in diagnostic access.

To address these challenges, this study presents the design, deployment, and evaluation of a province-wide telepathology system across 120 healthcare institutions in Henan Province, China. Enabled by dedicated funding from the Henan Provincial Health Commission, the system facilitated the deployment of digital pathology scanners in county- and city-level hospitals. Led by the First Affiliated Hospital of Zhengzhou University, the largest medical institution in China, the system operates under a centralized framework for case management, expert consultation, and data integration, supported by a mobile-enabled interface to expand diagnostic access to remote and rural regions.

This study aims to: (1) design and implement a scalable province-wide telepathology system to enhance equitable access to diagnostic services across healthcare tiers; (2) evaluate its performance in terms of diagnostic efficiency, accuracy, and cost-effectiveness; (3) demonstrate the feasibility of large-scale telepathology expansion in resource-constrained settings; and (4) offer a scalable model that can be replicated in other healthcare systems facing similar challenges. These findings contribute to the growing body of evidence supporting digital health solutions in bridging healthcare gaps and optimizing pathology services worldwide.

# Methods

## System Architecture Design

To address the shortage of pathologists and the uneven distribution of diagnostic resources in Henan Province, China, we designed an integrated province-wide telepathology system optimized for scalability, diagnostic accuracy, and operational efficiency. The system follows a three-tiered hospital architecture, consisting of tertiary-level hubs (provincial hospitals), secondary-level nodes (city-level hospitals), and primary-level healthcare institutions (county-level hospitals). This hierarchical structure enables standardized workflows for digital slide acquisition, data transmission, remote diagnosis, and reporting across 120 healthcare institutions, ensuring equitable access to high-quality pathology services.

The system adopts a Browser/Server (B/S) architecture, chosen for its flexibility, ease of deployment, and compatibility with diverse IT infrastructures in both urban and rural healthcare settings. To support real-time access in resource-constrained environments, we incorporated both web-based platforms and mobile access via a WeChat mini-program. This mobile interface was particularly critical for ensuring remote diagnostic access in rural areas where conventional IT infrastructure is limited. The mini-program was selected due to its widespread adoption in China and seamless integration with existing healthcare communication workflows, eliminating the need for standalone app installations.The system consists of four core modules: Image Acquisition Module, Transmission Link Module, Data Storage Module, and Teleconsultation Platform Module. These modules are tightly integrated to support high-throughput data processing, secure transmission, and efficient telepathology consultations.

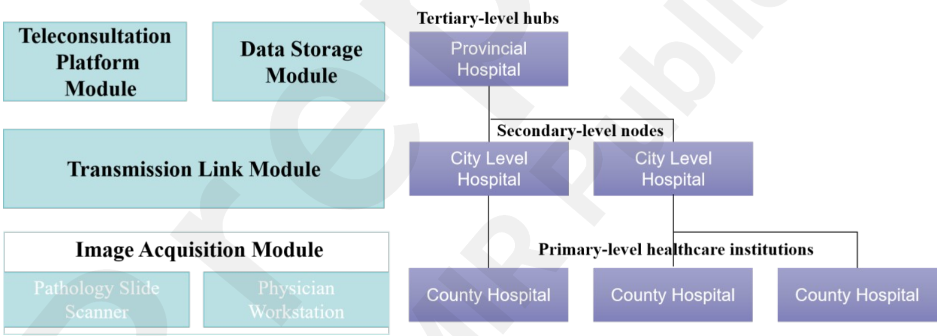


Figure 1. Schematic diagram of system architecture.

### *Image Acquisition Module*

This module digitizes traditional pathology slides into high-resolution whole slide images and prepares them for secure transmission. Each participating hospital is equipped with:

*Pathology Slide Scanner*：Model KF-PRO-005 (Konfoong Biotech International Co., Ltd.), capable of scanning slides within 40 seconds at 0.47 μm/pixel (×20 magnification) and within 100 seconds at 0.5 μm/pixel (×40 magnification).

*Physician Workstation*：Powered by Intel Core i5 processors with 8 GB RAM, preloaded with K-Scanner 1.6.0.14 for scanner control and K-Viewer 1.5.3.1 for image browsing and management.

The scanned WSIs are processed using a multi-resolution pyramid structure, optimizing image loading speed and reducing data size without compromising diagnostic quality.

### *Transmission Link Module*

The Transmission Link Module ensures that digitized pathology images can be transmitted from the applying hospital to higher-level hospitals. Considering data security and transmission rates, the system utilizes the 5G fixed-mobile convergence medical private network, previously established by

The Henan telemedicine center of china and covering Henan Province, as the transmission link. Digitized pathology slides scanned are uploaded to the central server for storage and diagnosis through this private network. The architecture of this private network is illustrated in Figure 2:

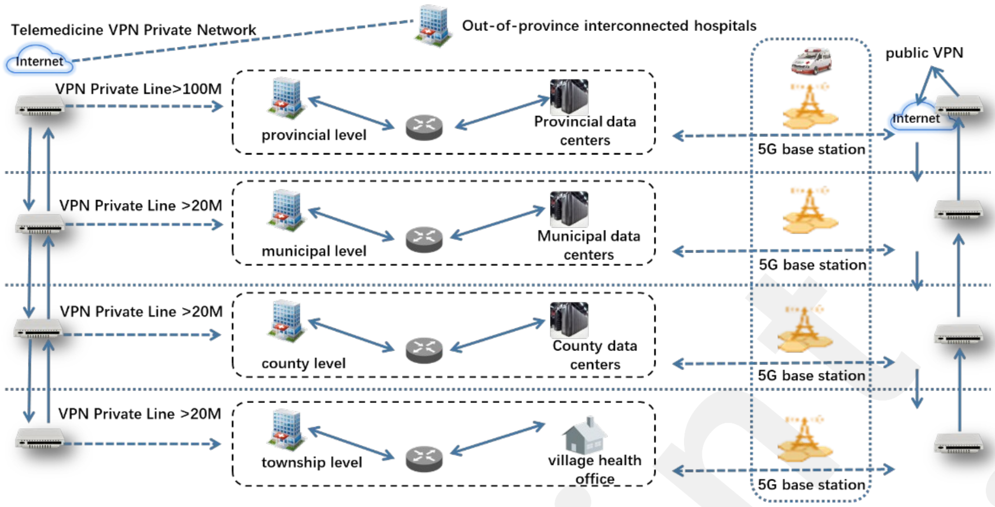


Figure 2. Architecture diagram of 5G fixed-mobile converged medical private network.

The telemedicine private network can be classified into wired transmission networks, 5G telemedical transmission networks, and IoT (Internet of Things) transmission networks. The wired network is primarily used in fixed office scenarios and easily accessible medical institutions, such as large hospitals for teleconsultations, telepathology, remote education, and applications in medical institutions at the county level and above. The 5G telemedical transmission network mainly supports dynamic scenarios, off-hospital scenes, and the access of medical institutions in remote areas, including remote ward rounds, remote emergency services, remote ECG, remote ultrasound, and access for village and town health clinics. The construction and application of this private network provide effective network support for the transmission of remote pathological slides.

## Data storage module

The Data Storage Module is designed to ensure the secure, scalable, and efficient storage of WSIs, diagnostic reports, and patient records. To enhance storage efficiency and fault tolerance, we employ Erasure Coding (EC) technology, which works by dividing data into multiple fragments and generating parity blocks distributed across different storage nodes. In the event of data corruption or hardware failure, EC enables data reconstruction from the remaining fragments, ensuring high availability and data integrity with minimal storage overhead [34].

For data backup, the system adopts a master-slave data synchronization strategy, implementing asynchronous replication to ensure the consistency and integrity of data. Additionally, binary log (Binlog) technology is utilized to record all database changes, allowing for rapid data recovery in the event of a system failure. The backup mechanism employs a mixed-based replication (MBR) model, combining the advantages of statement-level and row-based replication, ensuring efficient and stable data backups.

## Teleconsultation platform module

The Teleconsultation Platform is the core of the system, supporting remote pathology consultations, diagnostic reporting, and inter-institutional case discussions. The software architecture (Figure 3) is organized into four layers:

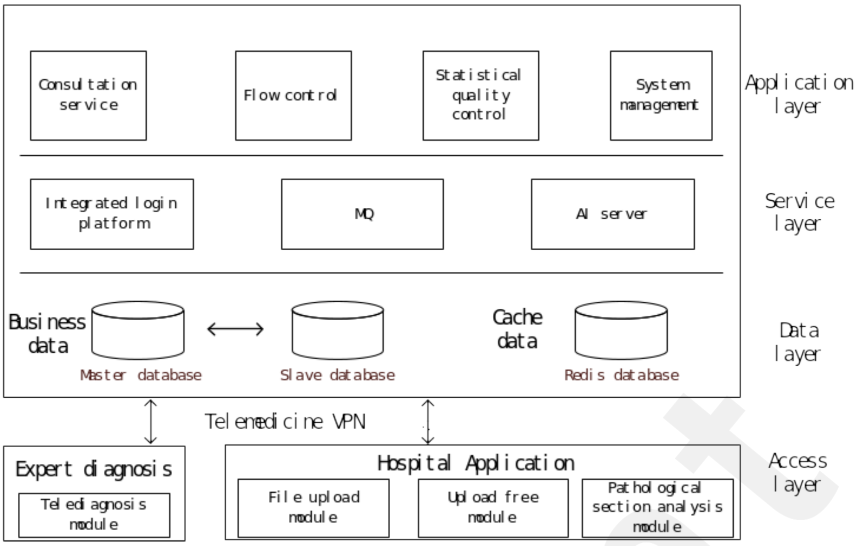

Figure 3. Teleconsultation platform architecture diagram.

*The Access Layer* connects requesting hospitals with expert terminals, enabling seamless interaction and workflow integration. Within this layer, the Upload Free Module eliminates the need for manual file uploads by integrating directly with local digital pathology scanners, ensuring automatic and efficient transmission of WSIs. Additionally, the Pathological Section Analysis Module performs preliminary analysis, including image quality assessment, segmentation, and lesion detection, aiding triage personnel in prioritizing cases. To optimize performance, WSI images undergo segmentation, compression, and pyramid layer processing, allowing for rapid loading and smooth scaling of high-definition images. Experts can access, analyze, and report cases either through a web browser or via the WeChat mini-program, enhancing flexibility and accessibility.

*The Data Layer* is responsible for managing both business-related data and cache data to ensure system stability and efficiency. Business data is stored within a MySQL relational database, maintaining structured and secure data management, while cache data, such as user authentication tokens and system configuration information, is stored using Redis, an in-memory database designed to facilitate high-speed data access and enhance system performance.

*The Service Layer* provides the system's core functionalities, encompassing consultation process management, diagnostic reporting, and quality control statistics. To ensure seamless communication between different modules, Message Queue (MQ) technology is implemented, allowing for asynchronous data transmission. This enables efficient handling of high-volume concurrent requests, ensuring that teleconsultation processes remain reliable and scalable without system bottlenecks.

*The Application Layer* provides various application functionalities and permissions tailored for triage personnel, system administrators, primary hospital doctors, and others, catering to their specific roles and access levels.

## System Functionality Overview

During the functional design phase of the system, a multidisciplinary design discussion group was established to ensure that the system effectively met the needs of different stakeholders. This group consisted of six members, including one pathologist from the First Affiliated Hospital of Zhengzhou University, representing the requirements of tertiary hospitals, two pathologists from primary healthcare institutions who articulated user needs from a clinical perspective, one project manager overseeing system development, and two software developers responsible for technical implementation. To validate the system's diagnostic reliability, a clinical study was conducted in which pathologists compared WSI-based diagnoses with conventional glass slide diagnoses across various case types. Expert feedback was collected on image interpretability, usability, and diagnostic confidence using both the browser-based platform and the WeChat mini-program. The results demonstrated a high concordance between digital and conventional diagnoses, confirming the system's suitability for clinical application.

Based on functional requirements, users were categorized into four distinct roles within the telepathology framework, ensuring an optimized workflow that facilitates seamless collaboration between requesting personnel, triage personnel, diagnostic experts, and system administrators.

- *Requesting personnel:* Primarily from county-level (primary) and city-level (secondary) hospitals, initiate telepathology processes by digitizing and scanning pathology slides, completing patient medical records, and submitting telepathology requests to higher-level institutions. This decentralized design enabled even low-resource county hospitals to initiate telepathology consultations independently, contributing to more equitable diagnostic access.
- *Triage personnel:* As pathologists within city-level (secondary) and provincial-level (tertiary) hospitals, they are responsible for pre-analytical quality control and case allocation. By leveraging their in-depth knowledge of their hospital's pathology experts and their areas of specialization, they ensure that each case is assigned to the most suitable specialist within the institution.
- *Diagnostic experts:* Consisting of pathologists within city-level and provincial-level hospitals, analyze the assigned digital slides and generate diagnostic reports, either providing a direct diagnosis or escalating particularly complex cases to a higher-level institution when necessary.
- *Administrators:* They oversee the integrated telepathology system, managing user roles and permissions, ensuring data security, and maintaining system functionality to guarantee a seamless telepathology workflow.

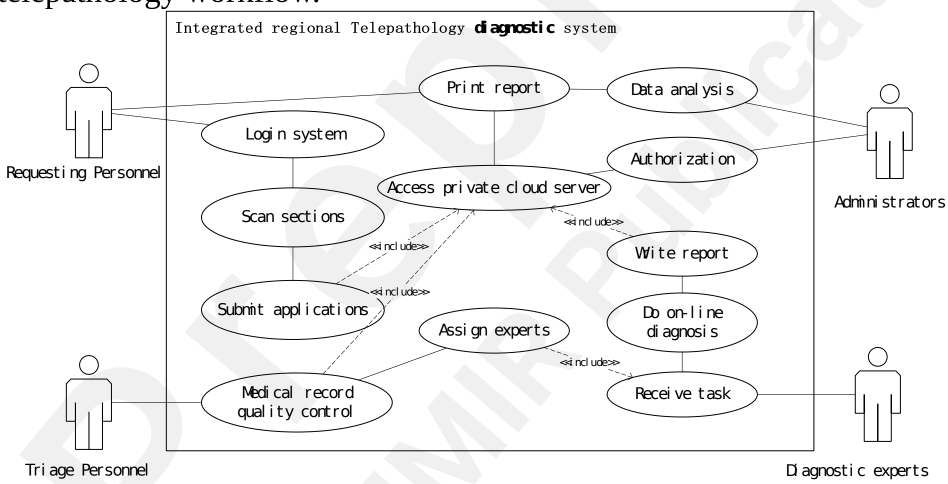


Figure 4. Use case diagram for overall system process design.

## Operational Workflow and User Interaction

The integrated telepathology system is designed to streamline the end-to-end diagnostic workflow, encompassing three primary functionalities: Application Initiation, Triage, and Diagnostic Review. These functionalities are supported by an intuitive user interface (UI) that facilitates efficient interaction between primary healthcare providers, triage coordinators, and diagnostic experts. This section provides a detailed description of the system's operational flow, user roles, and key technical features.

### *Application Initiation Workflow*

The initiation of a consultation application is core function performed by requesting personnel at primary healthcare institutions. This process involves several key steps: logging into the system, scanning pathology slides, and completing the consultation application form. The output of this function is the transmission of consultation application data via the VPN network to the telemedical private cloud server at the Henan Telemedicine center of china. This information is then made accessible to triage personnel and diagnostic experts at tertiary medical institutions for review and further processing. The use case diagram for this function is illustrated in Figure 5.

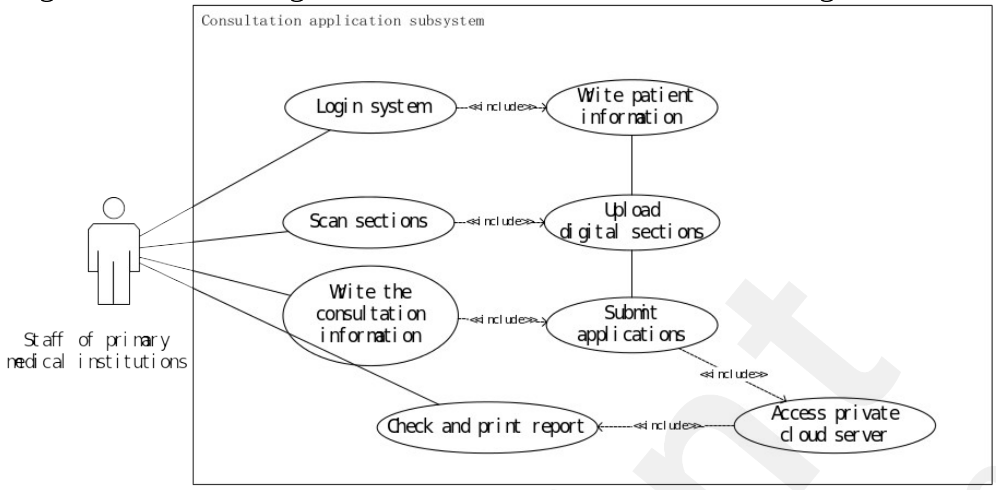


Figure 5. Workflow diagram for telepathology consultation request submission.

## *Triage Workflow and Quality Control*

The triage function is performed by pathologists serving as triage personnel within tertiary medical institutions, playing a pivotal role in ensuring the integrity of the diagnostic process. This function involves conducting pre-analytical quality control on received telepathology applications, which includes:

- Assessing the quality of scanned slides to ensure they meet diagnostic standards, including adequate resolution, proper staining, and the absence of significant artifacts that may compromise interpretation.
- Verifying the completeness of clinical information, ensuring that relevant patient history, laboratory findings, and any necessary supporting documentation are provided to facilitate accurate diagnosis.

If the scanned slides or clinical information are insufficient, triage personnel may request additional data or a resubmission before assigning the case to the most appropriate diagnostic expert based on the specific pathology subspecialty required.

As practicing pathologists, triage personnel possess a strong foundation in pathology and maintain an in-depth understanding of the expertise and current workload of their colleagues within the institution. This knowledge enables them to efficiently allocate cases, ensuring that each case is reviewed by the most qualified specialist while optimizing resource utilization. The workflow diagram illustrating this process is depicted in Figure 6.

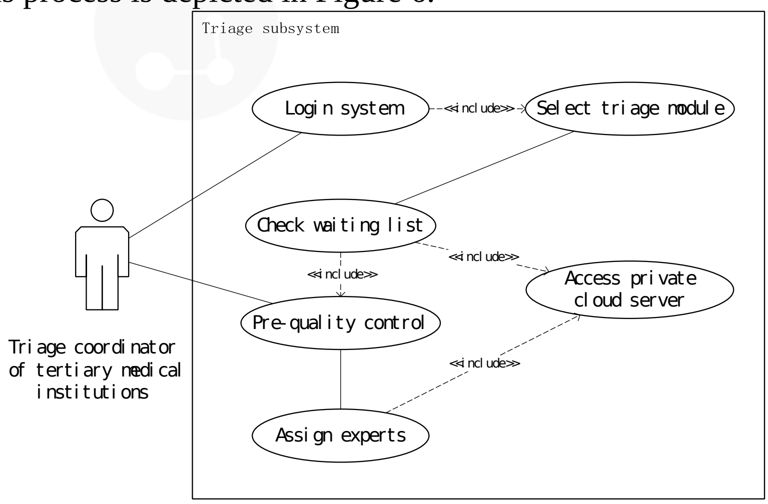

Figure 6. Workflow diagram for case triage and quality control in telepathology.

### Diagnostic Function Design

The diagnostic function is executed by experts at tertiary hospitals, specifically pathologists, who access the system via a computer interface or the WeChat mini-program. Upon logging in, they review the assigned telepathology cases, analyzing digital pathology slides and accompanying clinical data to provide a comprehensive pathological diagnosis. The diagnostic report includes a pathological description, grading, staging, results of immunohistochemistry (IHC), and additional relevant findings.

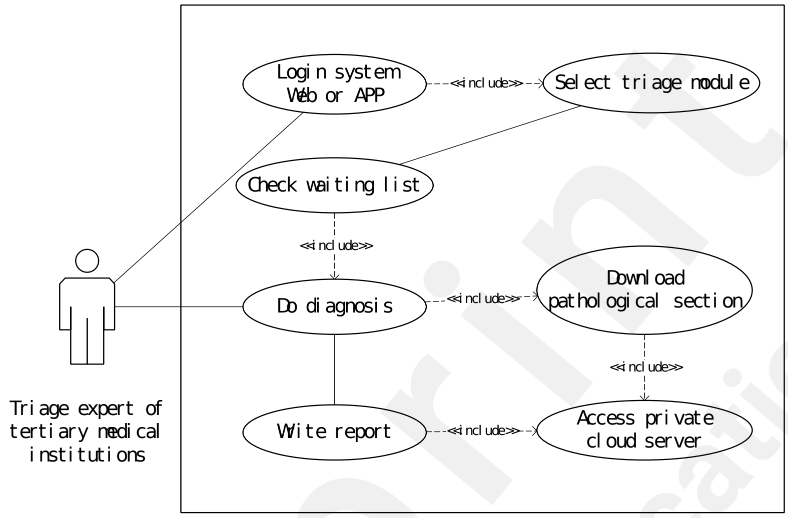


Figure 7. Workflow diagram for remote pathology diagnosis and reporting.

When an expert at a tertiary hospital determines that additional IHC staining is required, they can submit an IHC request through the system, specifying the recommended IHC markers for further testing. This request is automatically recorded in the system and made accessible to the originating hospital. The originating hospital performs the IHC staining locally, digitizes the stained slides, and uploads them back to the original case record within the platform. The tertiary hospital expert then reviews the newly uploaded IHC-stained slides, incorporating the findings into a supplementary diagnostic report to ensure a comprehensive pathology assessment.

## Results

## System Deployment and Operational Integration

The telepathology system was successfully deployed within the Henan Telemedicine Center's private cloud infrastructure, leveraging a secure Virtual Private Network (VPN) to facilitate encrypted data transmission across 120 integrated healthcare institutions at the provincial, municipal, and county levels. This architecture ensures robust data security, transmission stability, and interoperability, which are critical for maintaining diagnostic accuracy during remote consultations.

The deployment of digital pathology scanners followed a stepwise approach to ensure systematic integration, validation, and training across hospitals. In 2015, the Henan Provincial Health Commission initiated a province-wide infrastructure assessment to evaluate hospital readiness for telepathology implementation. The procurement and phased installation of 120 scanners began in 2016, prioritizing tertiary hospitals first, followed by city and county level hospitals, based on workload demand and digital infrastructure readiness. Pathologists and technicians were trained in scanner operation, quality control, and troubleshooting. By 2017, scanners were fully integrated into routine workflows, with ongoing monitoring and performance optimization to maintain consistency in image acquisition.

To accommodate various clinical scenarios, the system supports both web-based interfaces and mobile access via a WeChat mini-program. The mobile integration significantly enhances accessibility, particularly in rural and resource-limited regions, where mobile technology adoption is high. The user interface (UI) was optimized for both platforms to streamline diagnostic workflows, reduce user friction, and improve the turnaround time for pathology consultations (Figure 8).

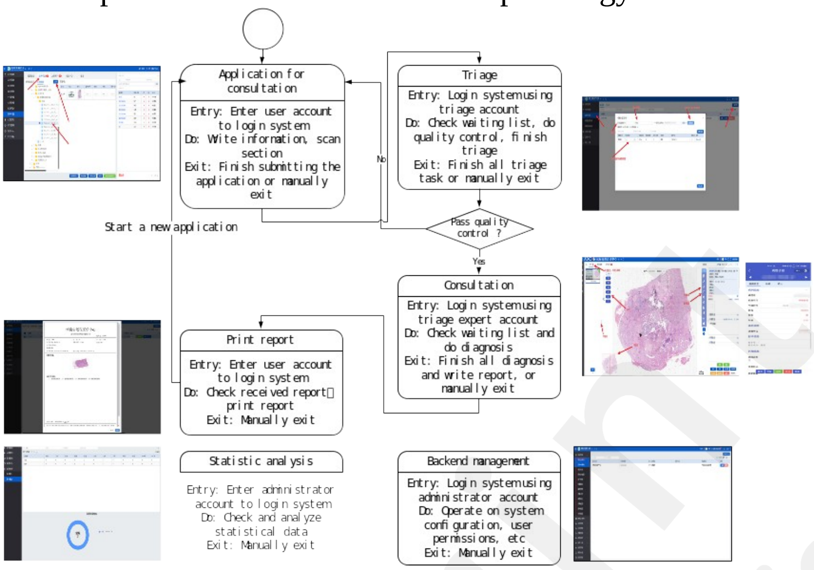


Figure 8. System user interface design for web and WeChat mini-program.

Since deployment, the system has facilitated 72,916 telepathology consultations, averaging approximately 22 cases per day. A total of 355,104 WSIs have been processed. The cumulative data volume has reached 220.1 TB, with each slide averaging 0.62GB. However, slide storage size varies depending on scanning resolution, typically ranging from 500 MB to 2 GB, with 20× scans occupying 500 MB to 1 GB and 40× scans ranging from 1 GB to 2 GB. The system supports multiple whole-slide image formats, including KFB, TMAP, MDS, MDSX, SDPC, MRXS, SVS, SCN, and NDPI, which utilize pyramidal storage for efficient multi-resolution viewing. Unlike DICOM, which is primarily used for radiology, these formats support multi-layered, ultra-high-resolution whole-slide imaging, ensuring optimal fidelity for pathological assessment.

The system is hosted on Henan Telemedicine Center’s private cloud, employing a distributed storage system for high availability, redundancy, and secure access. Diagnosed slides are archived rather than deleted, ensuring long-term availability for clinical review, quality control, and research. To optimize storage, frequently accessed images remain in high-performance storage, while older slides are moved to cost-efficient archival storage, maintaining scalability as telepathology adoption grows.

## Diagnostic Process Implementation

Since deployment, the telepathology system has streamlined diagnostic workflows across 120 healthcare institutions, enabling seamless collaboration between county, city, and provincial-level hospitals. The system has facilitated the efficient submission, triage, and assignment of pathology cases, ensuring that cases requiring expert consultation are promptly routed.

The WeChat mini-program has been widely adopted to facilitate remote access and case review, allowing pathologists to view WSIs and provide feedback even outside traditional workstations. However, medical-grade monitors remain the preferred choice for primary diagnosis, while the mobile platform serves as a supplementary tool for preliminary assessments and report verification.

Healthcare professionals receive ongoing training and technical support to ensure effective system utilization. Annual training conferences provide updated guidance and case discussions. A comprehensive operations manual is available for reference, covering image acquisition, quality control, and reporting workflows. Additionally, a real-time WeChat-based support chat group allows users to seek assistance, report issues, and provide feedback, ensuring timely resolution of operational challenges.

To optimize medical resource distribution, the system utilizes a tiered healthcare architecture, incorporating provincial, municipal, and county-level medical institutions. County-level institutions may escalate complex cases directly to provincial-level or route them through municipal-level institutions. Municipal hospitals act both as requestors and providers, while provincial hospitals primarily manage complex case diagnostics.

## System Performance Evaluation

To evaluate the system‘s technical performance, a stress test was conducted using the Apache Benchmark Tool. Simulated environments with 100 concurrent users performing 100 requests each were used to assess system responsiveness, scalability, and load-bearing capacity under both typical and peak usage conditions.

Table 1. System performance metrics under concurrent load.

| Requests | Response Times(ms) | | | | | | | Throughput | Network (KB/sec) | |
|---|---|---|---|---|---|---|---|---|---|---|
| Label | Average | Min | Max | Median | 90th pct | 95th pct | 99th pct | Transactions/s | Received | sent |
| Consultation Request Interface | 5766.62 | 2568 | 7619 | 5987.50 | 7013.10 | 7144.85 | 7497.85 | 25.78 | 114.72 | 48.81 |
| Application List View Page | 2348.18 | 190 | 3237 | 2442.00 | 2859.50 | 2988.70 | 3206.30 | 58.88 | 646.77 | 30.24 |
| Pending Diagnosis List Page | 2356.92 | 200 | 3017 | 2545.00 | 2838.30 | 2891.75 | 3001.79 | 59.00 | 648.10 | 30.59 |
| Diagnosis Page | 2728.16 | 423 | 4359 | 3038.00 | 3793.00 | 4031.70 | 4353.06 | 43.87 | 15.72 | 50.08 |

The data derived from the system performance evaluation reveal significant capabilities in handling concurrent operations across various interfaces:

(1)Consultation Request Interface: The system can respond to 25.78 requests per second, which supports approximately 125 users operating online simultaneously.

(2)Application List View Page: The system is capable of handling 58.88 requests per second, allowing for about 300 users to be active online at the same time.

(3)Pending Diagnosis List Page: The system's response rate is 59 requests per second, indicating capacity for approximately 300 users to operate online simultaneously.

(4)Diagnosis Page: The system manages 43.87 requests per second, suggesting it can accommodate an estimated 220 users online simultaneously.

The results demonstrate that the telepathology system can maintain high performance even under substantial user loads. The integration of a dedicated VPN, coupled with the optimized B/S architecture, ensures that diagnostic workflows are not compromised during peak operational periods. These capabilities are critical for large-scale deployments in healthcare systems with fluctuating demands.

## Real-World Impact and Clinical Outcomes

To evaluate the real-world impact of the provincial telepathology system, we conducted a comprehensive analysis of system usage, diagnostic efficiency, patient demographics, clinical outcomes, and economic benefits. The data analyzed in this section were primarily derived from the telepathology system itself, which continuously records information from remote pathology consultations.

*Data Collection and Sources*: The primary data sources for this analysis included:

- System-Recorded Case Data: Diagnostic cases were extracted from digitized pathology slides submitted by primary healthcare institutions, with tertiary hospital pathologists providing remote diagnoses. The system recorded case volumes, institutional contributions, and turnaround times, allowing for evaluation of system efficiency and diagnostic accessibility.

- Patient Demographic and Diagnostic Data: Information on age, sex, and diagnostic classifications (benign vs. malignant cases) was retrieved from system-generated pathology reports to assess changes in diagnostic trends.
- Retrospective Diagnostic Accuracy Assessment: A subset of 1,027 cases was retrospectively analyzed, comparing lower-level hospital diagnoses with expert-reviewed telepathology diagnoses, calculating sensitivity and specificity improvements.
- Economic Impact Estimation: Cost-saving estimates were derived based on travel distances, transportation costs, and consultation fees that would otherwise be incurred by patients traveling to tertiary hospitals for in-person diagnoses.

These data collectively provide a comprehensive assessment of the system's impact on diagnostic accessibility, efficiency, and accuracy, particularly in rural and resource-limited settings.

*System Utilization and Expansion:* The scanners deployed in hospitals were used for both routine in-house pathology workflows and telepathology consultations, but only selected cases were uploaded for remote expert review. The telepathology system was not intended to replace all local diagnostic workflows; rather, it served as a platform for second-opinion consultations and specialized expert input when necessary. Cases uploaded for telepathology consultations primarily included diagnostically complex cases requiring additional expert interpretation, subspecialist consultation requests for specific pathology types, and frozen section cases where rapid intraoperative decision-making was required. This selective approach ensured efficient utilization of digital pathology resources while allowing hospitals to retain routine diagnostics locally. By integrating telepathology into the existing diagnostic framework, hospitals could leverage the expertise of higher-level institutions without overloading the digital infrastructure with routine cases that did not require external review.

Since its implementation, the telepathology system has been integrated into 120 healthcare institutions across Henan Province. From 2016 to 2024, a total of 72,916 diagnostic cases were completed, with municipal hospitals contributing 16,313 cases (22.37%) and county-level hospitals accounting for 56,603 cases (77.63%). This distribution not only illustrates extensive adoption, but also reflects the system's success in addressing diagnostic inequity by shifting specialist services closer to rural and underserved communities.

Analysis of annual service volumes revealed a significant upward trend. Municipal hospitals experienced a growth from 240 cases in 2016 to 3,503 cases in 2021, representing a 1360% increase. Similarly, county-level hospitals saw an increase from 2,095 cases in 2016 to 8,317 cases in 2019, reflecting a 297% growth. Despite fluctuations in service volumes in later years, the overall trend indicates sustained adoption and utilization across healthcare tiers (Table 2).

Table 2. Annual diagnostic service volume by hospital level (2016–2024).

| Hospital level | 2016 | 2017 | 2018 | 2019 | 2020 | 2021 | 2022 | 2023 | 2024 |
|---|---|---|---|---|---|---|---|---|---|
| City-Level | 240 | 657 | 1060 | 923 | 2100 | 3503 | 2970 | 2439 | 2421 |
| County-level | 2095 | 3673 | 6202 | 8317 | 7490 | 6536 | 6198 | 8267 | 7825 |

These findings suggest that the telepathology system has effectively enhanced diagnostic capacity, particularly in county-level institutions where pathology services were previously limited.

*Diagnostic Efficiency and Turnaround Time*: The system's efficiency was assessed based on turnaround time, defined as the interval from whole-slide image submission to diagnostic report issuance. The median TAT was 10.06 hours for routine cases, with 54.28% (39,579 cases) diagnosed within 12 hours and 96.41% (70,298 cases) completed within 72 hours.

For frozen section consultations, where rapid diagnostic turnaround is critical, the system facilitated real-time notifications to pathologists upon case submission. From 2016 to 2024, a total of 508 frozen section cases were processed through the telepathology system, with an average time from request to diagnosis of approximately 16 minutes and 6 seconds. This highlights the system's ability to support time-sensitive intraoperative pathology decisions and enhance surgical workflow efficiency.

*Patient Demographics and Diagnostic Distribution*：A total of 72,916 patient cases were analyzed to assess demographic patterns and diagnostic outcomes. Among these cases, 43.58% (31,777) were male and 56.42% (41,139) were female. Regarding pathological diagnoses, 48.80% (35,583 cases) were benign, while 51.20% (37,333 cases) were malignant. Compared to a baseline dataset from 2020, there was an observed increase in the proportion of male patients by 2.49% (from 41.09%) and a decrease in benign lesion diagnoses by 3.38% (from 52.18%).

The distribution of diagnosed specimen types further highlights the system's broad applicability. The most frequently analyzed samples were uterine (19.6%), gastrointestinal (17.54%), and esophageal (8.38%) tissues. Other common specimen categories included breast (5.92%), lung/mediastinum (5.71%), and male genital organs (5.33%). A diverse range of less frequent specimens, such as thyroid (3.46%), head and neck (2.55%), and respiratory tract (2.30%), further demonstrates the system's ability to support comprehensive pathology diagnostics across multiple anatomical sites. While biopsy specimens are included in the dataset, the system currently categorizes cases by anatomical site rather than by procedural type (biopsy vs. resection), and detailed specimen classification is not yet available. Future system updates may incorporate specimen-type classification to further enhance data granularity.

*Economic Impact:* Before the implementation of telepathology services, patients in county hospitals seeking expert pathology consultation typically had to travel to tertiary hospitals with their glass slides and medical records, incurring transportation costs, lost wages, and long wait times. Alternatively, some hospitals mailed slides for consultation, but this method was slow and inefficient, often leading to delayed diagnoses.

With telepathology, biopsy slides are now digitized locally and reviewed remotely by experts at tertiary institutions, eliminating the need for physical transport and reducing the financial burden on patients. This service is provided at no cost, saving patients an estimated 378.5 RMB (~50 USD) per case 7, with an annual cost reduction of approximately 405,000 USD. These economic benefits are particularly significant for rural patients, for whom travel costs previously posed a major barrier to timely healthcare access. In many cases, telepathology consultations replaced costly and time-consuming travel to urban hospitals, further narrowing the urban-rural diagnostic gap.

*Diagnostic Accuracy and Clinical Outcomes:* To assess diagnostic accuracy, we conducted a retrospective analysis of 1,027 cases, selected based on the availability of preliminary diagnoses from lower-level hospitals and corresponding expert-reviewed diagnoses within the telepathology system. The expert pathologists' diagnoses at tertiary hospitals were considered the gold standard for comparison.

Diagnostic performance was evaluated using sensitivity, specificity, and AUC (area under the curve) as key metrics. The results demonstrated that lower-level hospital diagnoses had a sensitivity of 0.90 and specificity of 0.75, whereas telepathology-assisted diagnoses showed improved sensitivity (0.96) and specificity (0.95) when compared against the gold standard. This represents a sensitivity increase of 6.7% and a specificity improvement of 26.7%, reflecting the system's ability to enhance diagnostic precision, reduce discrepancies, and support evidence-based clinical decision-making.

These improvements are attributed to standardized workflows, real-time expert consultations, and advanced image management technologies, reinforcing the telepathology system's role in quality assurance and diagnostic accuracy enhancement.

## Discussion

## Principal Results

This study presents the design, deployment, and evaluation of a province-wide telepathology system across 120 healthcare institutions in Henan, China. The system addresses diagnostic disparities by leveraging a secure VPN, Browser/Server architecture, and a mobile-accessible WeChat mini-program to improve accessibility, efficiency, and diagnostic accuracy.

The implementation significantly improved diagnostic accessibility, with 72,916 telepathology consultations completed. Notably, the system redistributed diagnostic capacity to lower-tier hospitals, allowing them to serve cases that previously required urban referral-thus directly mitigating inequities in access. County-level hospitals, previously lacking pathology expertise, contributed 77.63% of cases, highlighting the system's role in bridging healthcare gaps. The median diagnostic turnaround time was 10.06 hours, with 54.28% of cases completed within 12 hours and over 96% within 72 hours, demonstrating a substantial reduction in diagnostic delays. Mobile health integration through the WeChat mini-program further reduced delays, enabling real-time expert access.

The system also enhanced diagnostic accuracy. A retrospective analysis of 1,027 cases showed that sensitivity improved from 0.90 to 0.96, and specificity increased from 0.75 to 0.95, reducing diagnostic discrepancies. This can be attributed to standardized workflows, real-time expert consultation, and improved image management technologies.

The telepathology system demonstrated robust technical scalability and performance stability, supporting 220-300 concurrent users without compromising diagnostic efficiency. The Apache Benchmark stress tests confirmed the system's ability to handle high volumes of simultaneous requests, with peak response rates of up to 59 transactions per second. The optimized B/S architecture eliminates the need for complex client-side installations, ensuring seamless system access across diverse devices and operating environments. Additionally, the secure VPN infrastructure guarantees data encryption, confidentiality, and integrity, essential for maintaining patient privacy during data transmission. The integration of mobile health technology through the WeChat mini-program extends the system's reach to remote areas with limited IT infrastructure, ensuring consistent performance even under suboptimal network conditions. Similar findings have been reported for cloud-based telepathology systems, which provide scalability and flexibility for managing large datasets and adapting to evolving healthcare demands 29. These findings highlight the system's readiness for large-scale deployments, making it adaptable to other provinces in China or similar resource-limited settings globally. Its demonstrated ability to extend services to historically underserved regions suggests high potential for addressing diagnostic inequity on a broader scale.

## Limitations

Despite these achievements, several challenges were encountered during implementation, including technical, operational, and personnel-related issues. Scanner calibration inconsistencies and variations in staining protocols initially resulted in occasional scanning failures and image artifacts. To address this, standardized quality control procedures and routine scanner calibration were implemented. Additionally, the large size of whole-slide images (500MB-2GB per slide) created data transmission constraints, particularly in hospitals with limited network bandwidth. This was mitigated through lossless image compression and tiered storage management, ensuring optimized storage allocation while preserving diagnostic fidelity.

From an operational standpoint, county-level pathologists required additional training in digital pathology workflows, prompting the establishment of structured training programs, a comprehensive operations manual, and a WeChat-based real-time support network. These measures collectively ensured seamless system integration while minimizing disruptions to routine pathology workflows.

## Economic and Healthcare Benefits

The telepathology system has also demonstrated significant economic benefits. By eliminating the need for in-person consultations at tertiary hospitals, the system reduced transportation and consultation costs for patients. On average, each patient saved approximately 378.5 RMB (~50

USD), leading to an estimated annual cost reduction of 405,000 USD. These findings align with prior research on the economic benefits of telepathology. A Canadian study reported annual savings of 26,000 CAD in courier fees and 60,000 CAD in travel costs associated with traditional pathology services [35]. Similarly, UCLA's telepathology network reduced courier expenses by 24 USD per expedited trip while lowering the financial burden of employing specialty pathologists for low-volume services [36]. Furthermore, the system's ability to redistribute diagnostic workloads optimizes healthcare resources. County-level hospitals, which traditionally lacked specialized pathology services, now handle a substantial proportion of diagnostic cases, reducing the burden on provincial-level facilities and improving healthcare equity.

## Comparison with Prior Work

While the telepathology system has demonstrated substantial benefits, several limitations should be acknowledged. However, residual disparities in digital infrastructure and workforce distribution may limit equity gains in the most remote settings, warranting further targeted investments. The study was conducted in Henan Province, which may limit the generalizability of findings to regions with different healthcare infrastructures or socio-economic conditions. The retrospective analysis of diagnostic accuracy was based on cases referred through the telepathology system, which may not fully represent the broader spectrum of pathology cases in routine clinical practice. Although cost savings were estimated, a formal cost-effectiveness analysis considering long-term economic outcomes and healthcare resource utilization was not performed. International collaborations and strategic partnerships have been shown to facilitate telepathology adoption by providing essential resources, training, and infrastructure support, which could enhance diagnostic capabilities in regions facing similar challenges [37].

To address these limitations and further enhance the system's impact, future research should focus on comprehensive cost-benefit and cost-effectiveness studies to evaluate the long-term economic impact of telepathology on healthcare systems. Incorporating AI-powered diagnostic tools for automated image analysis, decision support, and error detection could further improve diagnostic accuracy and efficiency. Expanding system deployment to other provinces and exploring cross-border telepathology networks would facilitate international collaborations and global pathology consultations. Furthermore, developing standardized training programs for pathologists and laboratory technicians will ensure consistent diagnostic quality across all healthcare tiers.

## Conclusions

The Henan Province telepathology system has significantly improved diagnostic accessibility, efficiency, and accuracy. Its scalability, cost-effectiveness, and technical robustness make it a viable model for resource-limited settings globally. By addressing healthcare disparities—particularly between rural and urban institutions—and optimizing pathology workflows, the system represents a transformative advancement in digital pathology and telemedicine. The integration of mobile health platforms further extended diagnostic services to underserved populations, making the model not only scalable but also equitable. This approach may serve as a blueprint for reducing diagnostic inequity in other decentralized healthcare systems worldwide.

## Acknowledgements

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## Conflicts of Interest

None declared

## Abbreviations

B/S: Browser/Server
CTS: Clinical Telepathology Service
EC: Erasure Coding
IHC: Immunohistochemistry
MQ: Message Queue
mHealth: Mobile Health
TAT: Turnaround Time
UCLA: University of California, Los Angeles
VPN: Virtual Private Network
WSI: Whole Slide Image

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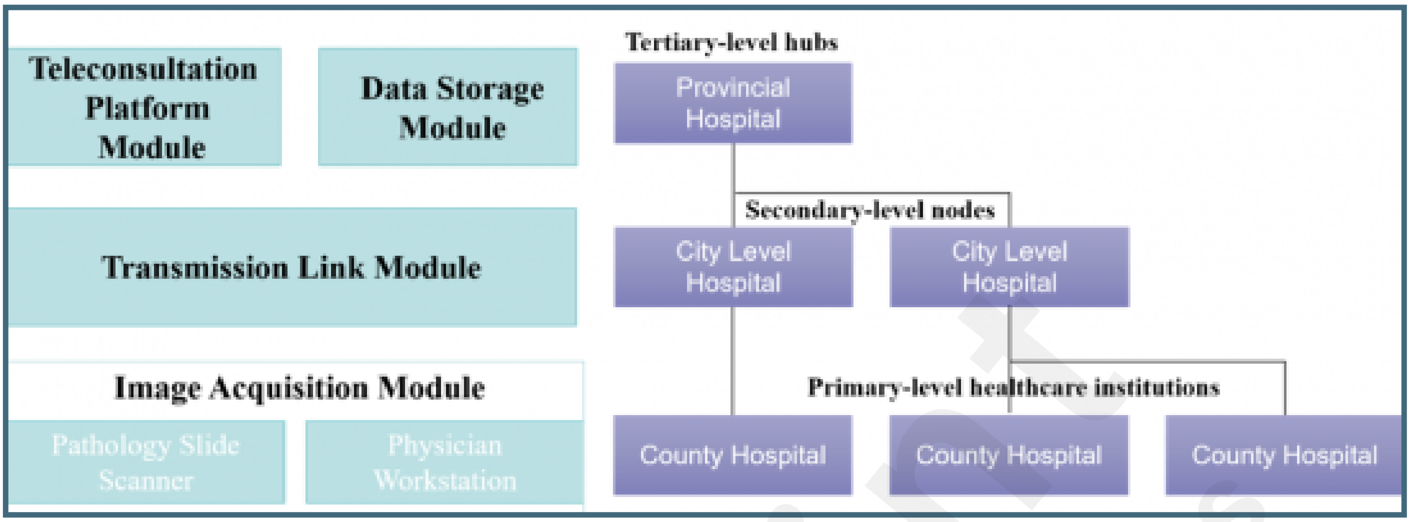
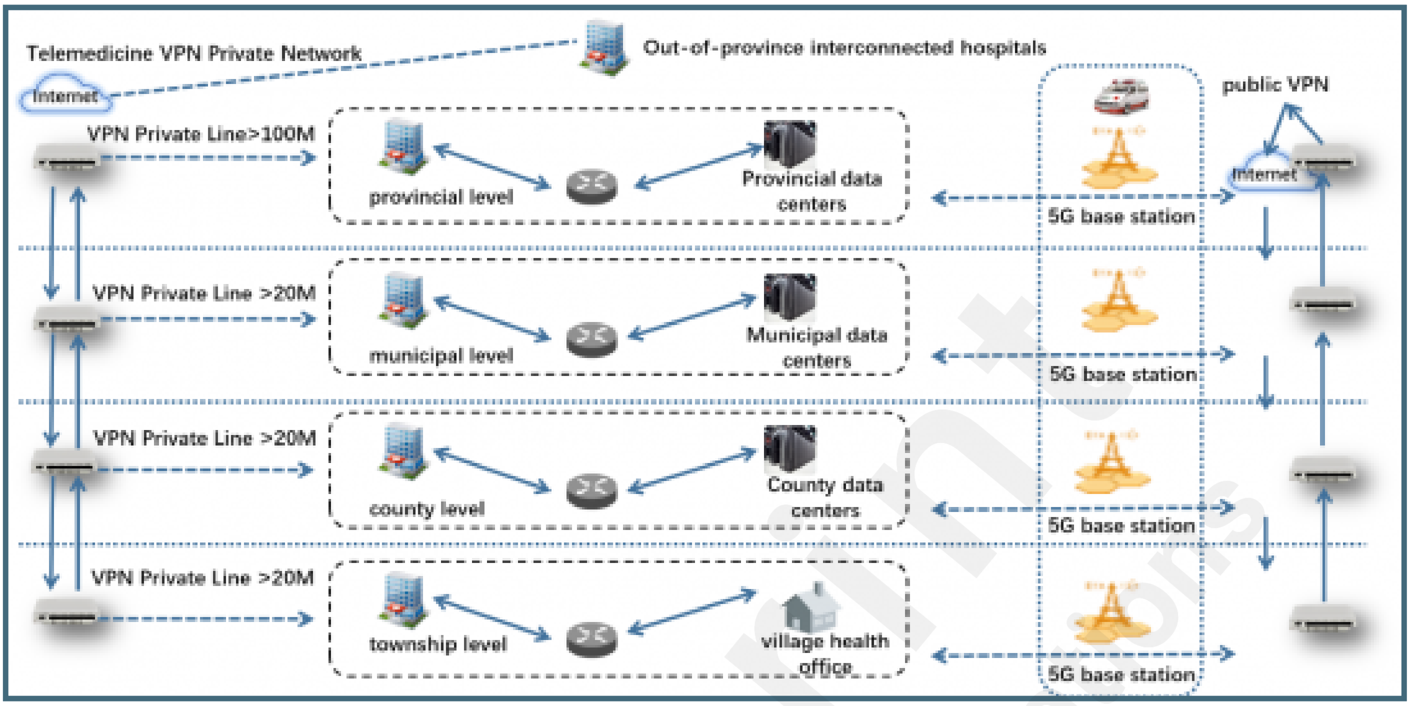
# Supplementary Files

# Figures

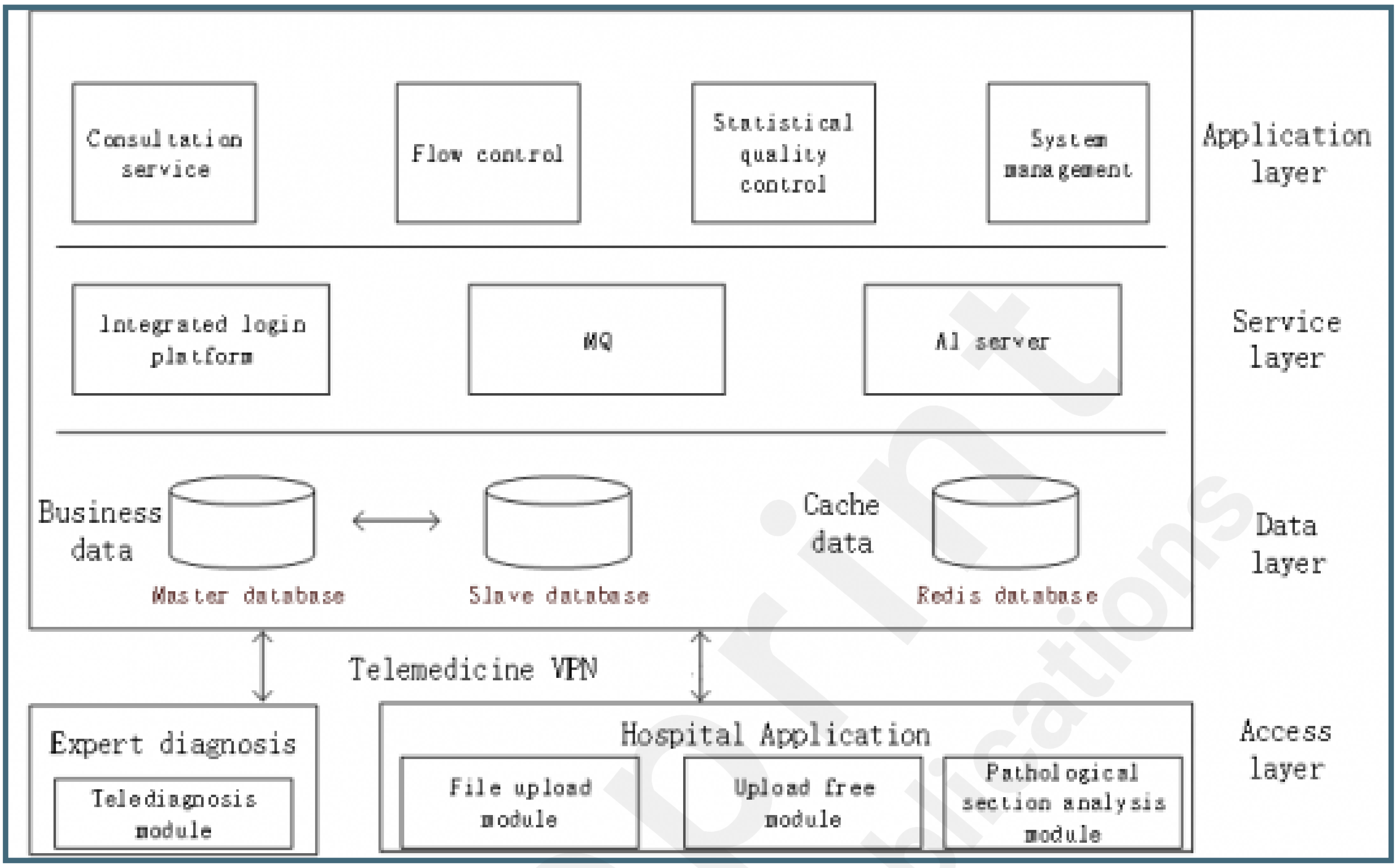
Schematic diagram of system architecture.



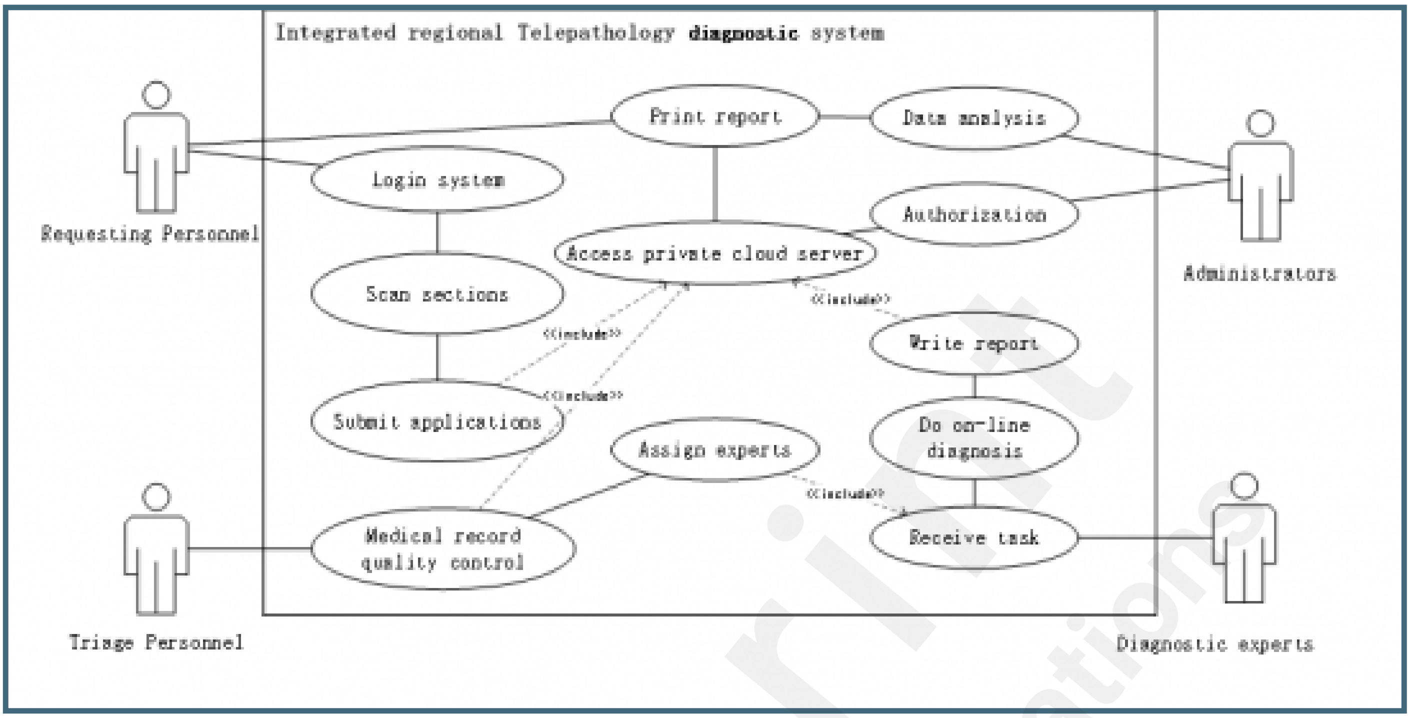
Architecture diagram of 5G fixed-mobile converged medical private network.



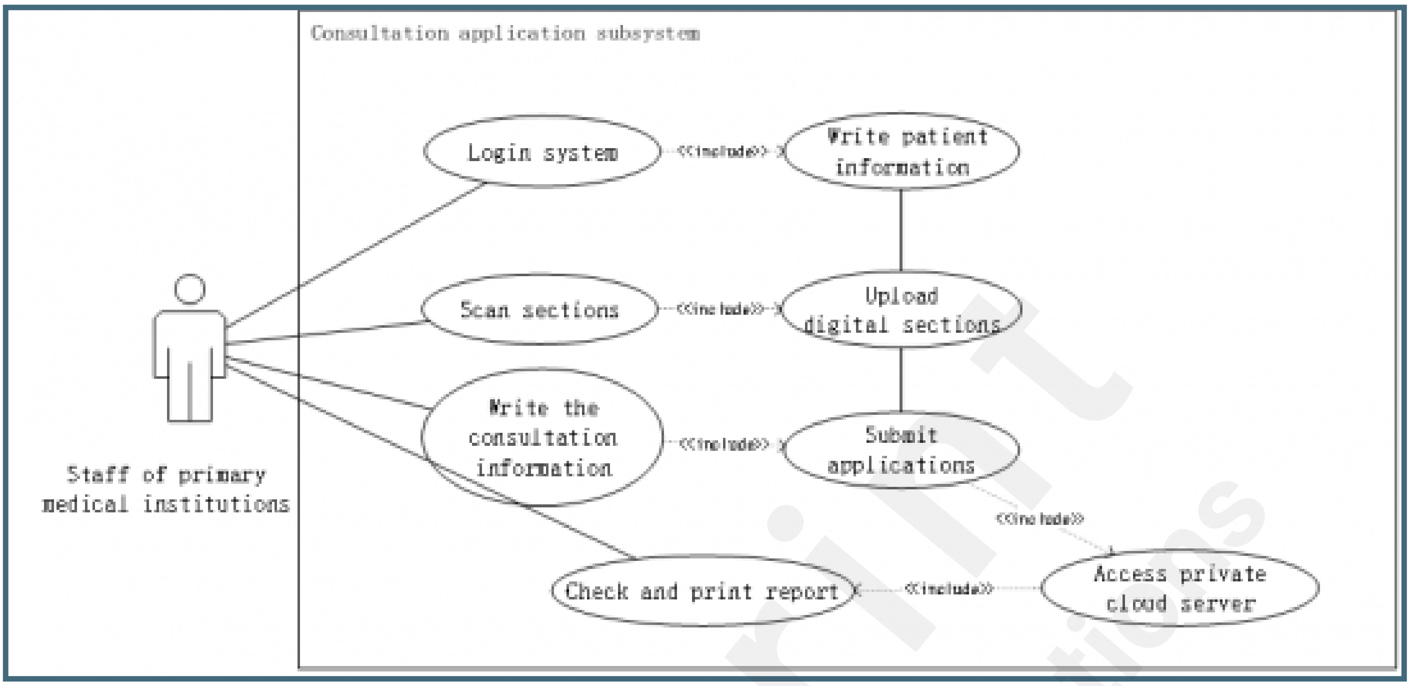
Teleconsultation platform architecture diagram.



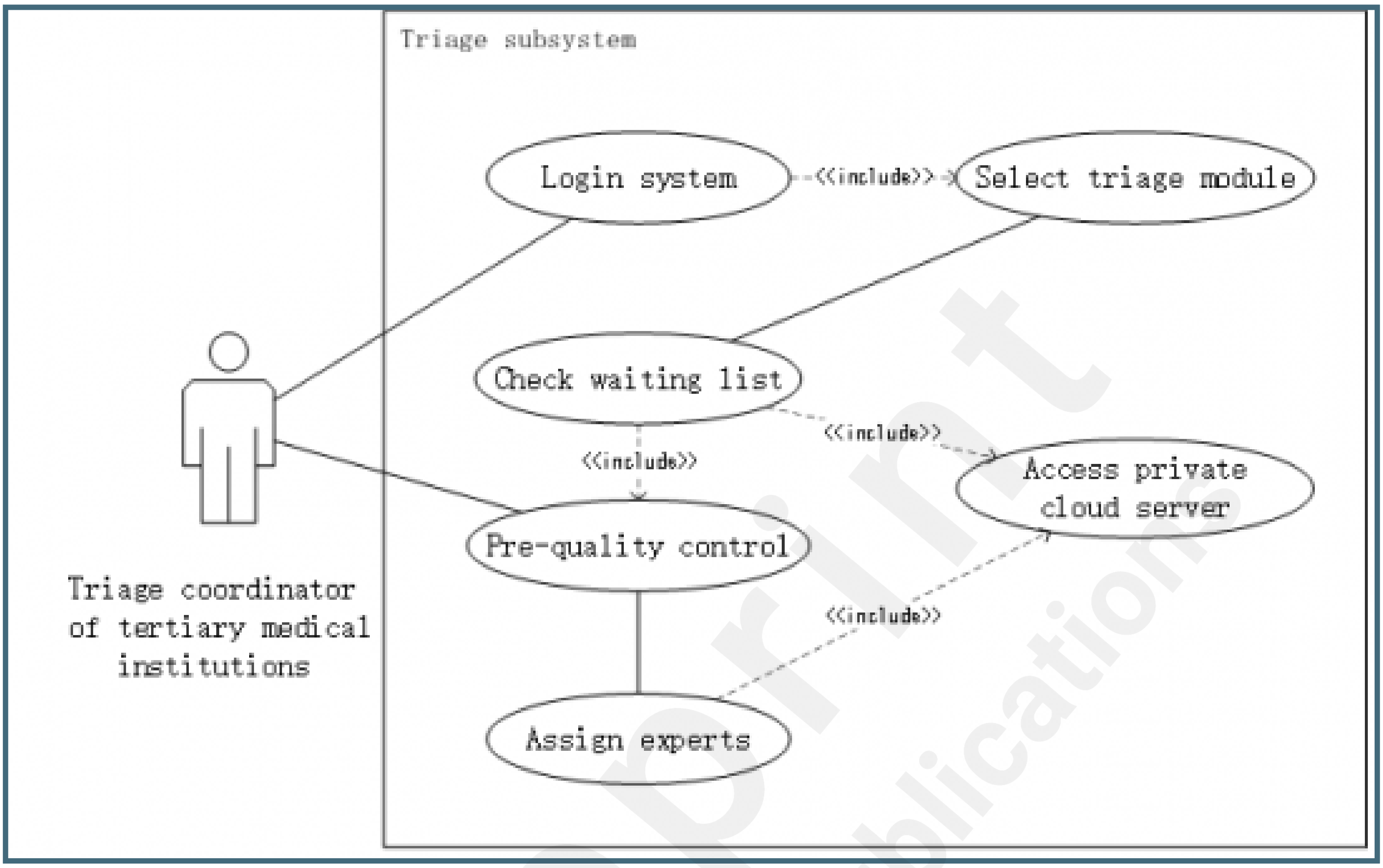
Use case diagram for overall system process design.



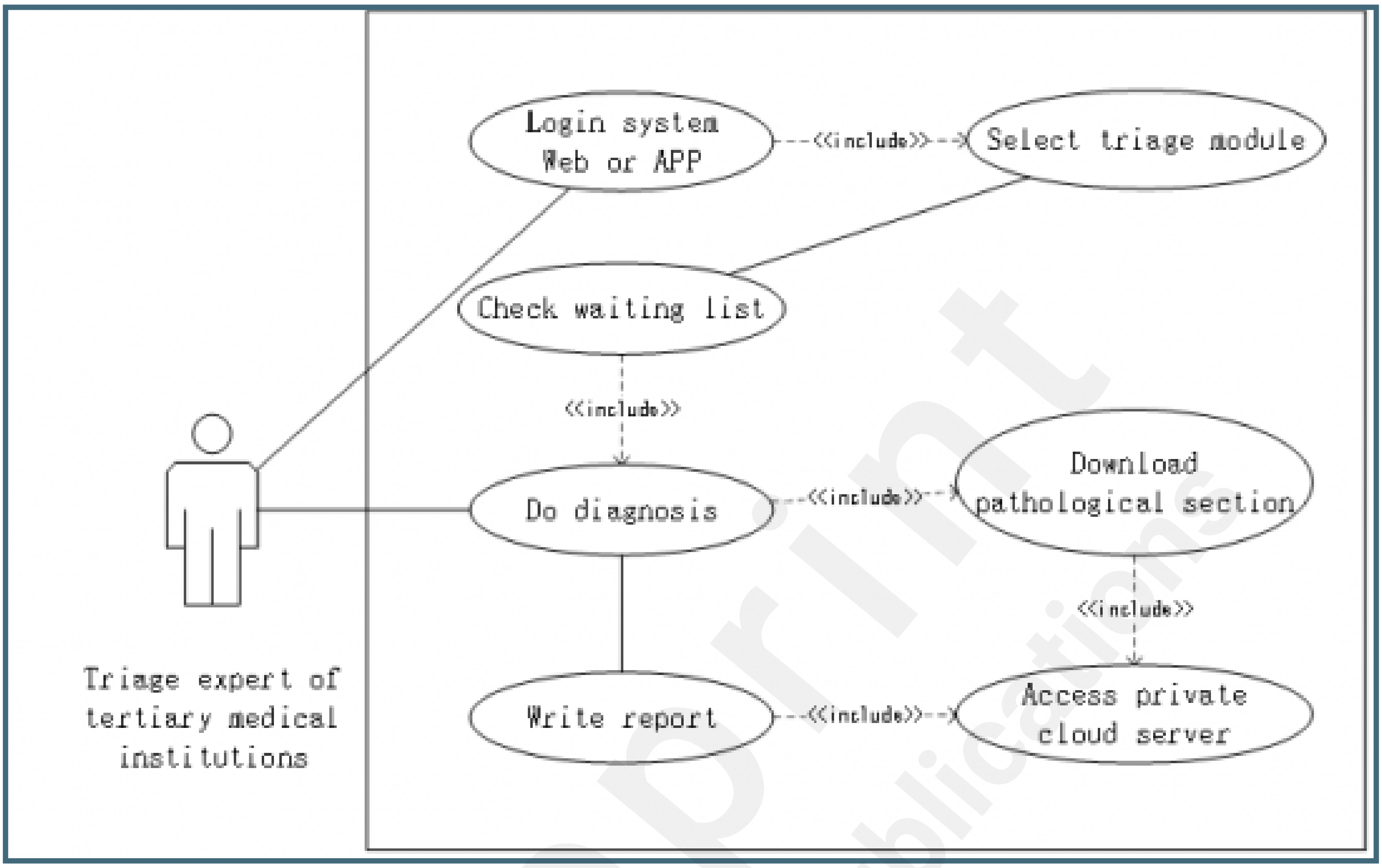
Workflow diagram for telepathology consultation request submission.



Workflow diagram for case triage and quality control in telepathology.



Workflow diagram for remote pathology diagnosis and reporting.



System user interface design for web and WeChat mini-program.