Diagnostic Pathology

RESEARCH

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Mobile device smartphones for intraoperative diagnosis at the University Hospital Trust of Modena/UNIMORE: from validation process to costs analysis

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Abstract

Background Telepathology enables remote diagnostic consultation through digital image transmission and is particularly valuable in settings where subspecialty expertise is not immediately available. This study evaluated the diagnostic accuracy of PathoZoom®, a web-based platform that allows real-time remote review of microscope images via mobile devices during intraoperative frozen section examination in a high-complexity academic hospital.

Methods Seventy-five consecutive frozen section cases, processed between January and April 2024 at the University Hospital Trust of Modena/UNIMORE, were included. All cases were first diagnosed using conventional light microscopy (LM) and then, after a washout period, the same slides were reviewed remotely using the PathoZoom® system and mobile smartphones. Diagnostic concordance between LM and telepathology was assessed, classifying discrepancies as major or minor, depending on their clinical impact in accordance with the current guidelines of the College of American Pathologists guidelines.

Results Overall concordance was 96% (72/75 cases). One major discordance occurred in a basal cell carcinoma margin assessment, interpreted as negative by telepathology and positive by LM. Two minor discrepancies involved polymorphonuclear cell counts in orthopedic specimens. No differences in performance were observed between mobile devices.

Conclusions Thanks to the technological setting and results, PathoZoom® and Smartphones are proposed as a diagnostic option for intraoperative consultation. Results support safety, feasibility and cost effectiveness of mobile-based telepathology in complex surgical settings and geographically extended healthcare networks.

Keywords Telepathology, Digital pathology, Intraoperative consultation, Frozen section, Mobile devices

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Introduction

Digital Pathology, particularly through whole slide imaging (WSI), has gained significant traction in recent years, enabling pathologists to digitize glass slides and analyze them on digital platforms that replicate traditional light microscopy (LM). This technology facilitates efficient slide navigation and virtual examination of tissue samples, with telepathology emerging as a key application. In telepathology, pathologists can consult remotely, thereby enhancing the accessibility of expert opinions. However, the high costs associated with medical-grade WSI equipment have limited its adoption, particularly in smaller, resource-constrained hospitals. A promising alternative is the use of digital cameras attached to microscopes to capture images of glass slides, which can then be shared in real-time via QR codes with mobile devices such as smartphones, effectively eliminating the need for expensive scanning equipment. One of such solutions, PathoZoom®, offers a practical and cost-effective method for intraoperative consultations, enhancing telepathology without necessitating large-scale infrastructure.

Previous experiences with digital pathology networks [1–3] and telepathology [4, 5] have demonstrated the potential of these technologies to enhance diagnostic workflows and improve patient outcomes. The goal of this study is to validate the feasibility and accuracy of PathoZoom® for mobile-based intraoperative consultations at University Hospital Trust of Modena/UNIMORE, conducted in accordance with the current guidelines of the College of American Pathologists guidelines (CAP) [6]. Through its implementation in routine surgical consultations, PathoZoom® could significantly enhance the efficiency of pathological diagnostics in complex surgical settings, enabling pathologists to provide expert consultations more effectively, irrespective of geographical barriers.

Materials and methods

A total of 75 consecutive cases were collected between January and April 2024 at University Hospital Trust of Modena/UNIMORE, the only laboratory designed for anatomical pathology in the Modena province. These intraoperative cases were processed at the hospital, where pathologists were tasked with providing diagnoses during surgeries. Each case was examined by the same pathologists involved in the study to ensure consistency in diagnostic interpretation.

The series included both oncological and non-oncological cases, distributed as follows:

- Oncological Cases (68 total): breast cancer surgery (16 cases), thoracic surgery (14 cases), head and neck surgery (ENT) (10 cases), oncologic surgery including transplants (9 cases), neurosurgery (5 cases), plastic surgery (4 cases), maxillofacial surgery (4 cases), urology (3 cases), general surgery (2 cases), and dermatologic surgery (1 case).
- Non-Oncological Cases (7 total): orthopedic surgery cases, evaluated for polymorphonuclear cells (PMNs) count.

Context

In the Modena province, which spans an area of 2.690 km² and has a population of approximately 700.000, healthcare facilities are distributed across several hospitals, with University Hospital Trust of Modena/UNIMORE serving as the central hub for pathological services. The hospital is the reference point for various surgical specialties, including neurosurgery, otorhinolaryngology, biliary tract surgery, maxillofacial surgery, and transplantation. It also plays a vital role in complex surgeries that require intraoperative pathological assessments, such as sentinel lymph node biopsies, margin evaluations, and tumor assessments. Given the increasing workload and due to a shortage of pathologists [7, 8] and a rising case volume [9], innovative solutions are essential to meet the demands of modern pathology. At University Hospital Trust of Modena/UNIMORE, approximately 100.000 cases are examined annually by a team of 15 pathologists, including around 950 intraoperative consultations. In these high-pressure situations, pathologists may encounter cases that they are unfamiliar with or outside their area of expertise, particularly when handling frozen-section diagnoses. Digital Pathology becomes a crucial tool in these instances, allowing pathologists to share real-time images with expert colleagues remotely, ensuring immediate support and access to specialized input.

Pathologists' involvement

Three pathologists participated in the study, ensuring a comprehensive review of the cases. These included an Expert Pathologist in digital pathology (highly experienced in digital pathology and telepathology systems), a Senior Pathologist (with relevant experience in general pathology) a Resident in Pathology (who contributed to the case reviews under the guidance of the expert and senior pathologists). The experience of the pathologists in digital pathology was a key factor in the validation procedure. Digital Pathology experience is typically categorized by exposure to telepathology systems, familiarity with WSI, and proficiency in interpreting digital images on mobile platforms [6].

PathoZoom® camera system

The PathoZoom® Scan & LiveView system is a microscope-mounted digital camera solution designed to enable telepathology and digital slide visualization without the need for dedicated WSI scanners. The system converts a conventional light microscope into a Digital Pathology workstation, allowing both real-time live images sharing and manual generation of virtual slides. The PathoZoom® camera is designed to be plug-and-play compatible with standard optical microscopes through a C-mount interface, ensuring broad compatibility with commonly used laboratory microscope models. This feature allows the system to be easily integrated into existing pathology workflows without requiring modifications to the microscope or additional optical components. Images are captured directly from the microscope optical path, preserving the native optical resolution and color fidelity provided by the microscope objectives. The field of view and magnification are therefore determined by the objective lens in use (e.g., 4×, 10×, 20×, or 40×), rather than by the camera itself, allowing pathologists to maintain diagnostic practices consistent with conventional LM. The camera is connected to a workstation via high-speed USB (USB 3.0), enabling rapid image acquisition and real-time transmission. As the transmission of images occurs in real time, no additional time is required for either image transfer or remote evaluation of the specimen compared to conventional workflows. Using the PathoZoom® Scan & LiveView software, the system supports live streaming of the microscope view in high resolution to multiple remote devices, including smartphones, tablets, and personal computers. Remote users can access the live view through a secure web interface or QR code, without the need for dedicated client software. In addition to live viewing, PathoZoom® allows the creation of digital, zoomable virtual slides by manually moving the microscope stage during image acquisition. This approach provides a cost-effective alternative to automated WSI scanners while still enabling detailed digital examination and remote consultation. The accompanying CE-certified software includes tools for image navigation, zooming, measurements, and annotations, supporting diagnostic evaluation and collaborative review. Captured images and virtual slides can be stored locally or shared through cloud-based platforms, facilitating teleconsultation and interdisciplinary collaboration.

Mobile devices

In the context of telepathology, the use of advanced mobile devices is crucial to ensure fast and accurate communication during the review of pathology samples [10]. With the growing demand for telemedicine solutions, smartphones are excellent choices for supporting pathology image analysis, improving efficiency and accuracy in remote diagnoses. iPhone 13 and Honor 50 are equipped with advanced displays, powerful processors, and 5G connectivity—ideal for applications like PathoZoom®, which require both high visual quality and top-tier performance.

The iPhone 13 boasts a 6.1-inch Super Retina XDR display with a 2.532 × 1.170-pixel resolution, ensuring crisp, clear images with accurate color reproduction. Its OLED display is ideal for rendering fine details with precision, essential for pathology image review. The A15 Bionic chip ensures seamless operation, even when handling large, high-resolution images. Its 5G capabilities ensure fast and stable transmission of images, supporting smooth collaboration.

The Honor 50 features a 6.57-inch OLED screen with a resolution of 2.340 × 1.080 pixels. Although the resolution is slightly lower than the iPhone 13's, its OLED technology still provides clear and vibrant visuals. The Snapdragon 778G chipset ensures smooth processing of high-resolution images, making it suitable for telepathology. Its 5G connectivity allows for rapid image transmission during live consultations.

Both devices run stable and secure operating systems—iOS 15 on the iPhone 13 and Android 11 with Magic UI 4.2 on the Honor 50—ensuring optimal performance for telemedicine applications.

Telepathology workflow

For the digital assessment, glass slides were digitized and made available for remote consultation through secure access enabled by QR code sharing. During the remote evaluation, microscope manipulation and slide navigation were performed on-site by a trained pathologist within the institution, while the reviewing pathologist assessed the streamed digital images in real time from a remote location. Slide exploration along the x–y axes and changes in magnification were carried out by the on-site colleague operating the microscope, upon request of the remotely connected pathologist (Fig. 1). Diagnoses obtained through digital evaluation were subsequently compared with those rendered by conventional microscopy.

Validation procedure

The primary objective of this study was to validate PathoZoom®'s diagnostic accuracy by comparing its results with those obtained with LM. This comparison was carried out according to the CAP guidelines, which recommend that Digital Pathology systems undergo rigorous validation through comparison with conventional methods, preferably using the same observer to minimize interobserver variability [6]. Each case was initially examined under a traditional light microscope by the participating pathologists, and the original diagnosis was recorded as the reference standard. In accordance with CAP recommendations, the same pathologist who rendered the initial diagnosis subsequently reviewed

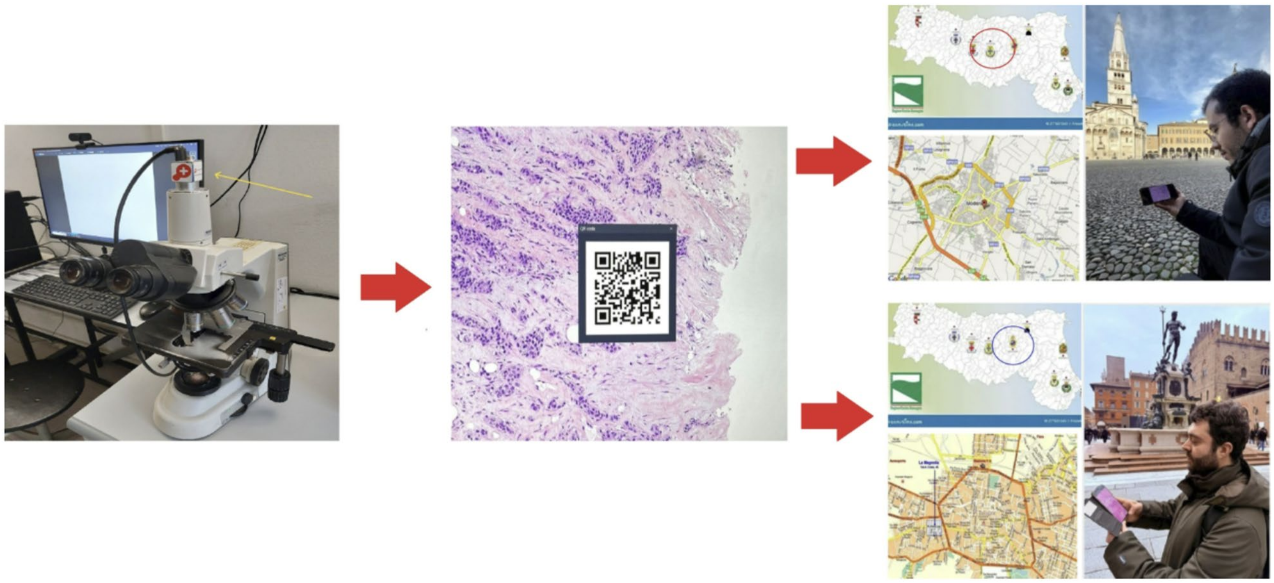

Fig. 1 Telepathology workflow: from the digital workstation at the Policlinico di Modena, images are shared in real time via QR code generation. The QR code allows remote visualization of the digital slides on smartphones. Representative remote viewing locations are shown: Piazza Grande, Modena (top) and Piazza del Nettuno, Bologna (bottom)

the corresponding digital images. After a one-month washout period the same slides were re-evaluated using PathoZoom®. The diagnoses obtained through digital review were then compared with those from conventional microscopy and defined in terms of concordance: the degree of agreement between diagnoses made using traditional LM and those obtained through Digital Pathology systems. Namely, major discordance: difference in diagnosis that would influence clinical management, such as altering the surgical approach or treatment plan, minor discordance: a difference that does not affect patient management or alter surgical decisions.

Table 1 Distribution of cases across surgical specialties

Surgical Specialty	Percentage of Cases (%)
Breast Surgery	21.4
Thoracic Surgery	18.7
Hepatobiliary and Pancreatic Surgery	12
Orthopedic Surgery	9.3
Otorhinolaryngology	13.3
Maxillofacial Surgery	5.3
Neurosurgery	6.7
Urological Surgery	4
General Surgery	2.7
Plastic Surgery	5.3
Dermatological Surgery	1.3

Results

A total of 75 intraoperative specimens were analyzed. The cohort included 45 females (60%) and 30 males (40%) patients, ranging in age from 14 to 92 years old (median age: 65 years).

Surgical specialties and specimen types

Most cases were oncologic surgical procedures spanning multiple specialties. Breast surgery accounted for the largest proportion (21.4%), mainly involving sentinel lymph node evaluation for metastases and assessment of retroareolar tissue for invasive or in situ carcinoma. Thoracic surgery represented 18.7% of cases and included atypical lung resections, lobectomies for PET-positive nodules, and transthoracic biopsies. Otorhinolaryngology comprised 13.3%, primarily tumor resections of the upper aerodigestive tract and laryngectomies. Hepatobiliary and pancreatic surgery accounted for 12%, including hepatic wedge resections, bile duct margin evaluations, pancreatic lesions, and transplant-related procedures. Orthopedic surgery represented 9.3% of specimens, all involving PMNs counts to exclude periprosthetic infection. Neurosurgery comprised 6.7%, mainly cerebellar and intramedullary lesion resections. Maxillofacial surgery accounted for 5.3%, including tongue tumor resections and lacrimal gland biopsies. Urological surgery represented 4%, including testicular nodules, ureteral margin assessments, and peritoneal adhesion evaluations, while plastic surgery also accounted for 5.3%, primarily excisions of eyelid basal cell carcinomas. General surgery comprised 2.7%, mainly lymph node evaluations, and dermatological surgery represented 1.3% of the series. Table 1 summarizes the distribution of cases across surgical specialties.

Concordance analysis between light microscopy and mobile phone–based Pathozoom® system

Concordance between intraoperative frozen-section evaluation using conventional LM and assessment with the mobile phone–based PathoZoom® system was observed in 72 of 75 cases (96%) (Fig. 2A and B-Fig. 2C and D). There was one major discordance in a plastic surgery case involving a basal cell carcinoma, in which the surgical margin was interpreted as negative on telepathology, as the suspicious structure was considered a cutaneous appendage, whereas it was reported as positive on conventional frozen-section evaluation (Fig. 3C and D). Additionally, two cases of PMNs counts in orthopedic specimens showed discordant findings categorized as minor discrepancies (Fig. 3A and B). No differences in diagnostic agreement were detected between iPhone- and Honor-based PathoZoom® devices. The evaluation time for each case with PathoZoom® ranged from 2 to 18 min.

Discussion

In this study, we validated the mobile-based PathoZoom® platform according to the CAP guidelines. Our system enables reliable intraoperative frozen-section consultation with a high diagnostic concordance compared with LM. Overall concordance reached 96%, with only three discordant cases, including one major and two minor discrepancies. The major discrepancy observed in this study can be attributed to the morphological similarity between basal cell carcinoma and cutaneous adnexal structures, a well-recognized diagnostic pitfall in the context of intraoperative margin assessment [11]; therefore, it should be

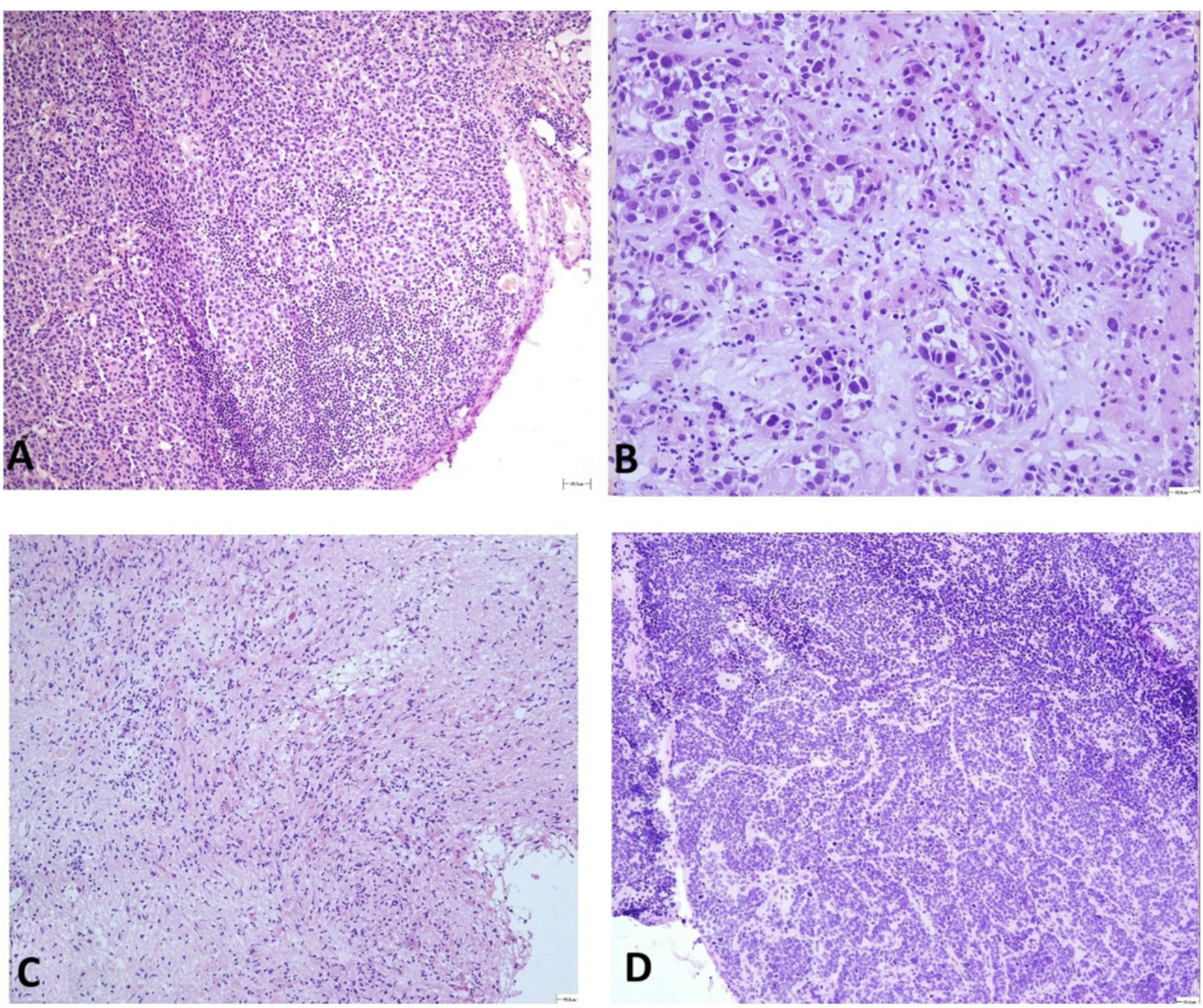

Fig. 2 Representative examples of digitized slides viewed on a smartphone screen, all showing concordant findings between conventional light microscopy and digital pathology: (**A**) Sentinel lymph node from breast carcinoma showing metastatic involvement (Case 9, H&E, 10×). **B** Liver localization of adenocarcinoma (Case 31, H&E, 20×). **C** Brain neoplasm consistent with pilocytic astrocytoma (Case 39, H&E, 10×). **D** Small cell lung carcinoma (Case 5, H&E, 10×)

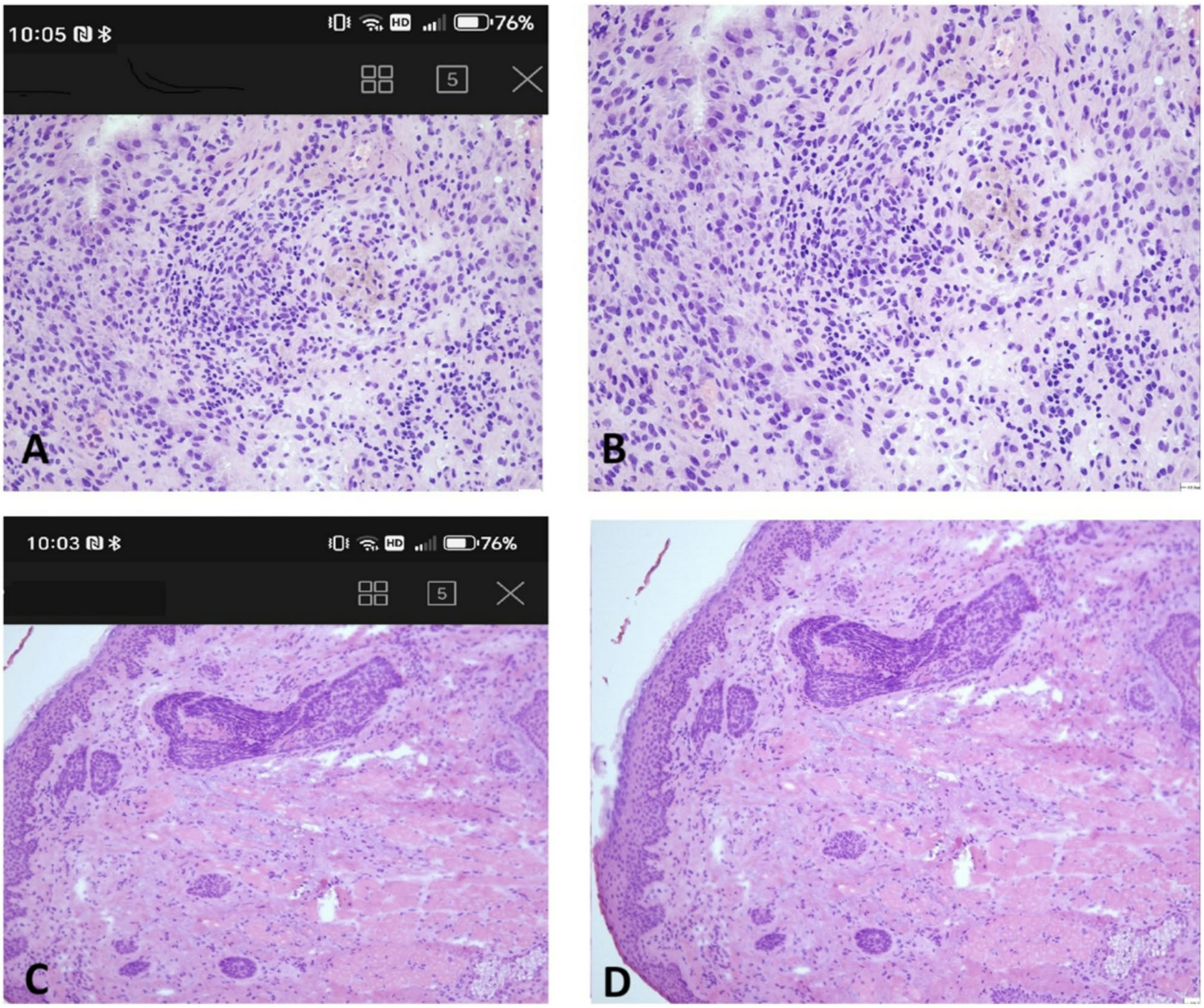

Fig. 3 Representative examples of digitized slides demonstrating discordance between digital pathology on a smartphone (left) and conventional light microscopy (right): (**A**-**B**) Synovial tissue evaluated for polymorphonuclear cell count, showing minor discordant findings (Case 34, H&E, 20×). (**C**-**D**) Positive skin surgical margin for basal cell carcinoma, showing major discordant findings (Case 42, H&E, 10×)

interpreted as an interpretative limitation that may occur independently of the diagnostic modality used. Minor discrepancies were observed in the assessment of PMNs in orthopedic specimens obtained during prosthetic revision surgery, where differences were related to counts around commonly adopted diagnostic thresholds; the literature indeed reports considerable variability in both cut-off values and methodological approaches for PMN evaluation in frozen sections, which may contribute to minor interpretative differences. This finding reflects the intrinsic variability of intraoperative PMN assessment and should be interpreted within the overall clinical and microbiological context rather than as an isolated diagnostic parameter [12]. Importantly, while these discrepancies were primarily interpreted as morphological pitfalls, we also underscore that in Digital Pathology a number of additional technical and workflow-related factors may contribute, including image quality, display resolution and color calibration, subtle delays during field navigation or transmission, and the pathologist's familiarity with digital interpretation; these variables are well-recognized in telepathology practice, may potentially exacerbate diagnostic challenges, and further highlight the importance of rigorous validation prior to clinical implementation.

Regarding sample size, the present study included 75 cases, which exceeds the minimum requirement recommended by the CAP for Digital Pathology validation studies (approximately 60 cases). However, despite meeting this threshold, the relatively limited sample size results in a 95% confidence interval for the observed 96% concordance borderline with the commonly accepted 95% diagnostic validation benchmark. We therefore acknowledge that, although our findings are consistent with high diagnostic accuracy, larger prospective and ideally multicenter validation studies are required to provide more robust statistical confidence and confirm diagnostic safety.

Several studies have shown that WSI provides image quality comparable to on-site microscopy, with diagnostic accuracy similar to conventional evaluation and turnaround times compatible with intraoperative workflows [13–15]. Multicenter validation studies have reported agreement rates approaching 97% in oncologic frozen sections, further reinforcing the reliability of digital systems in this setting [14]. Nevertheless, the literature has highlighted technical challenges intrinsic to frozen section material, including increased section thickness, tissue folds, freezing artifacts, and occasional focus loss during scanning [15]. Importantly, these limitations have rarely precluded correct diagnosis when digital systems were embedded in optimized workflows and operated by adequately trained personnel [15]. Additional studies have confirmed the feasibility and safety of remote digital frozen section interpretation for oncologic and transplant intraoperative services, showing high concordance with conventional microscopy [16]. Further analyses have explored the technical and diagnostic issues emerging from validation studies of WSI, emphasizing the importance of standardization, awareness of platform-specific limitations, and continuous training of personnel [15]. Concurrently, validation studies involving portable and tablet-based digital solutions have demonstrated diagnostic performance not inferior to optical microscopy, suggesting that simpler and more cost-effective technologies can effectively support remote pathology consultation [5].

Although PathoZoom® differs technically from fully automated WSI scanners, our experience indicates that comparable diagnostic performance can be achieved using a simplified microscope-mounted digital camera system combined with real-time mobile visualization. By preserving the optical quality of conventional microscopy and enabling immediate image sharing through smartphones or web-based interfaces, PathoZoom® circumvents many of the infrastructural and economic barriers associated with high-end WSI platforms, while remaining fully compatible with routine frozen section workflows. In our series, image quality proved adequate across a broad range of surgical subspecialties, including breast, thoracic, hepatobiliary, head and neck, neurosurgical, orthopedic, and dermatologic pathology.

The clinical relevance of this approach becomes particularly significant when considered within a real-world hub-and-spoke healthcare model, such as that adopted in the province of Modena. In this territorial system, the University Hospital Trust of Modena/UNIMORE serves as the central referral hub for complex surgical activity and subspecialty pathology expertise, while other hospitals, including Carpi, Sassuolo, Mirandola, Vignola, and Castelfranco, manage a substantial volume of routine and intermediate-complexity surgical procedures. Intraoperative pathology in such settings is frequently performed under significant time pressure and may require subspecialty expertise that is not consistently available on site, particularly during off-hours.

Within this organizational framework, PathoZoom® proved especially useful in scenarios in which a pathologist was working alone or facing diagnostically challenging cases outside their primary subspecialty. The ability to share real-time microscopic images with expert colleagues at the hub enhanced diagnostic confidence and supported timely and accurate intraoperative surgical decision-making. Importantly, the introduction of PathoZoom® did not require major changes to the established technical and information workflow: tissue processing, staining, and microscopic examination remained unchanged, while digital image sharing was seamlessly integrated into routine practice. These observations reinforce a key concept emphasized in the telepathology literature, namely that the success of Digital Pathology systems depends not only on image quality but also on effective workflow integration, communication, and adequate training of on-site personnel [17].

From a technical standpoint, image transmission occurs in real time without upload delays or intermediate processing, allowing the remote pathologist to evaluate the specimen concurrently with image acquisition by the on-site operator. Although turnaround time (TAT) was not formally recorded, the overall intraoperative workflow—including slide preparation, field acquisition, image transmission, and remote diagnostic interpretation—remains within the conventional frozen section time frame of approximately 15–20 min and is comparable to standard on-site evaluation. We acknowledge that the absence of formal TAT assessment represents a limitation of this study, and that future investigations should include structured time–motion analyses to more accurately characterize workflow efficiency and temporal variability.

Beyond diagnostic performance, a major strength of the PathoZoom®-based approach lies in its ability to secure pathology coverage across a wide territory with limited investment. Fully automated WSI scanners require substantial capital expenditure, typically ranging from €60.000 to over €200.000 per unit [18], in addition to maintenance, software, and infrastructure costs. In contrast, the PathoZoom® approach relies on existing microscopy infrastructure combined with a digital camera system and commercially available mobile devices. In this study, compatible smartphones were not limited to specific models but included commonly available devices, with an indicative cost range of approximately €400–€800 per unit, depending on configuration and manufacturer. The use of high-quality mobile devices is recommended to ensure optimal image rendering performance, although the system remains compatible with a broad range of commercially available smartphones and tablets.

The implementation of telepathology also contributes to the reduction of indirect operational costs associated with inter-facility travel of pathology personnel between hub and spoke hospitals, improving allocation efficiency and reducing logistical burden. Although a formal cost-effectiveness analysis was not performed in the present study, previous reports suggest that such organizational models may result in substantial annual savings through reduced travel requirements and improved workforce utilization.

When considered as an integrated implementation package including equipment, personnel training, and basic IT infrastructure, the total investment required remains limited to a few tens of thousands of euros per site, representing a significantly lower financial burden compared with full WSI deployment and supporting scalable implementation within regional healthcare networks.

Conclusion

Our findings highlight that the validation of Digital Pathology systems requires standardized criteria, adequate operator training, and continuous quality assurance, which remain essential regardless of the technological platform used. Multicenter comparative studies between mobile-based telepathology systems and fully automated WSI platforms will be essential to define performance benchmarks and clinical implementation standards. Future integration with artificial intelligence-based decision support tools may further improve diagnostic accuracy, workflow efficiency, and robustness of mobile telepathology applications [19].

Abbreviations

CAP	College of American Pathologists
ENT	Ear, Nose and Throat
LM	Light Microscopy
PMNs	Polymorphonuclear Cells
QR	Quick Response
USB	Universal Serial Bus
WSI	Whole Slide Imaging
TAT	Turnaround time

Supplementary Information

The online version contains supplementary material available at https://doi.org/10.1186/s13000-026-01792-w.

Supplementary Material 1.

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Not applicable.

Authors' contributions

Viscardo Paolo Fabbri, Luca Reggiani Bonetti, Alessandro Mazzini, and Albino Eccher reviewed the cases and were integral to the conceptualization of the data. Viscardo Paolo Fabbri, Alrssandro Mazzini, Stefano Marletta and Albino Eccher prepared figures and tables.All authors contributed to the conceptualization of the study, manuscript drafting, and language revision, and approved the final version of the manuscript.

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Data availability

The data that support the findings of this study are available from the corresponding author upon reasonable request.

Declarations

Ethics approval and consent to participate

Ethics approval and informed consent to participate were deemed unnecessary for this study because the local Institutional Review Board (AVEN) determined the research was retrospective and observational, and did not interfere with standard diagnostic or therapeutic procedures (in accordance with Legislative Decree No. 211 of June 24, 2003, which transposes the European Directive 2001/20/EC); furthermore, all data were fully anonymized, and the study was conducted in accordance with the Declaration of Helsinki.

Consent for publication

Given the retrospective observational nature of the study, which did not deviate from standard diagnostic routines, the need for informed consent and consent for publication was waived as all data and images were fully anonymized, ensuring that no individual participant can be identified. Regarding Fig. 1, the individuals depicted are authors of this manuscript (Viscardo Paolo Fabbri and Alessandro Mazzini), both of whom have provided explicit consent for the publication of these images.

Competing interests

The authors declare no potential conflicts of interest. Specifically, the authors have no financial or commercial relationships with the manufacturers of the devices used in this study (PathoZoom®, iPhone®, and Honor®), and the companies had no role in the study design, data collection, analysis, or manuscript preparation.

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