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Original Article

Medical Students' Perceptions of Online Practical Histology Teaching During the COVID-19 Pandemic

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Abstract : The Coronavirus Disease 2019 (COVID-19) pandemic forced an abrupt transition from face-to-face to online teaching in medical schools worldwide, raising important questions regarding the effectiveness and acceptability of online practical histology education. This study aimed to investigate medical students' perceptions of online histology practical sessions during the COVID-19 pandemic at Pusan National University School of Medicine (PNUSM), Korea. A structured, anonymous, offline questionnaire was administered to second-year medical students who had experienced both face-to-face and online practical histology courses. Ninety-one of 114 eligible students (79.8%) participated. The survey assessed overall satisfaction, perceived effectiveness in enhancing histology comprehension, attitudes toward replacing face-to-face sessions in emergencies, preferences for different online platforms [virtual microscopy at PNUSM, e-Histology, and open-access internet resources], and the perceived helpfulness of individual session components. Students reported significantly higher satisfaction and perceived effectiveness for online compared with face-to-face practical sessions (satisfaction: 3.79 ± 0.76 vs. 3.27 ± 0.97, $P < 0.001$; effectiveness: 3.87 ± 0.70 vs. 3.62 ± 0.89, $P = 0.003$). Most respondents (93.4%) agreed that online histology practicals could fully replace face-to-face sessions during public health emergencies. The preferred format for emergency and post-pandemic use was a multimodal combination of virtual microscopy, e-Histology, and open-access resources. Among face-to-face and online components, the theoretical histology classes and the use of practical images in the end-of-course examination were rated as particularly helpful for understanding histology. These findings suggest that well-designed multimodal online histology practicals can effectively support learning, are highly acceptable to students, and may complement traditional face-to-face instruction beyond the pandemic.

Keywords : Online histology education, Virtual microscopy, COVID-19 pandemic, Medical student perceptions, Practical histology teaching, e-Histology

INTRODUCTION

The outbreak of Coronavirus Disease 2019 (COVID-19), a highly contagious viral infection caused by severe acute respiratory syndrome coronavirus 2 (SARS-CoV-2), created a global crisis and profoundly altered the way

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people live, work, communicate, and learn. The pandemic affected an estimated 1.6 billion students worldwide [1,2]. By April 2020, UNESCO reported that 192 countries had closed schools, disrupting the education of nearly 90% of the world's students [3,4]. These disruptions placed immense pressure on public health systems and posed substantial challenges to medical education.

Consequently, universities worldwide suspended traditional face-to-face academic activities and rapidly transitioned to online learning modalities [5,6]. In Korea, medical schools adopted online instruction beginning in mid-February 2020 to ensure continuity of medical education. During this period, our institution also rapidly transitioned conventional face-to-face classes into fully online courses.

Histology, or microscopic anatomy, is a core component of the medical curriculum. Traditionally, undergraduate and postgraduate histology instruction has relied heavily on practical sessions involving direct microscopic examination of tissue sections. Alongside theoretical lectures, laboratory-based observation using light microscopes has been an essential component of histology education. Although the educational value of these practical sessions is well established, the most effective pedagogical approach remains a subject of ongoing discussion.

Recent technological advances have facilitated the widespread adoption of virtual microscopy in histology education [7,8]. With the advent of high-resolution digital slide scanners, conventional glass slides can be digitized and viewed as virtual slides, allowing students to examine identical material on personal computers [9-12]. Digital microscopy and whole-slide imaging technologies now enable the conversion of entire glass slides into high-fidelity digital formats, ensuring consistent image quality and accessibility [13-15]. As a result, many universities have increasingly incorporated virtual slides and digital learning resources into their practical histology curricula [16]. In line with these developments, our university has established a computer-equipped and networked classroom dedicated to histology practical sessions.

In our institution, online practical histology teaching relies primarily on the virtual microscopy platform at Pusan National University School of Medicine (PNUSM). Additionally, instructional support is provided by e-Histology, a digital histology education platform developed by the Korean Anatomists Association in collaboration with Panmun Education. e-Histology offers web-based access to high-resolution, zoomable virtual slides and supplemental learning materials, enabling students to conduct practical histology sessions remotely without requiring conventional light microscopy. Furthermore, various open-access online histology resources are used to supplement practical training.

Virtual microscopy systems in Korea are institution-specific and maintained by individual medical schools. The transition from light microscopy to virtual microscopy has supported the continuity of histology education during pandemic-related disruptions. However, the extent to which these digital modalities meet the essential learning needs of students during emergency remote instruction—such as that imposed by pandemic-related school closures—remains underexplored.

To address this gap, we conducted a survey in 2022 among medical students at PNUSM who had completed online practical histology sessions during the pandemic. The questionnaire focused on evaluating students' experiences with online histology practical programs and identifying strengths, limitations, and preferences related to digital histology instruction during COVID-19–related school closures.

MATERIALS AND METHODS

1. Survey implementation

The survey instrument was newly developed by the authors to evaluate medical students' perceptions of online and face-to-face practical histology teaching during the COVID-19 pandemic in Korea. The questionnaire was designed to address the specific educational context of emergency remote instruction, including instructional modalities, assessment formats, and perceived learning experiences. The initial draft of the questionnaire was reviewed and piloted with faculty members from the Office of Medical Education at PNUSM, including the seventh author, to assess clarity, relevance, and face validity. Minor revisions were made based on the feedback received prior to data collection. Data collection was conducted from July 4 to July 15, 2022.

Participation in the survey was voluntary. Informed consent was obtained from each participant after an explanation of the study objectives. Participants were assured

of confidentiality and informed that they could withdraw at any time. The questionnaire was self-administered and contained no identifying information. Only fully completed questionnaires were included in the analysis. The inclusion criteria were: (1) being a second-year medical student who had experienced both face-to-face and online practical histology courses, and (2) willingness to participate anonymously.

2. Data collection instrument

Medical students at PNUSM were invited to complete a structured and anonymous offline questionnaire. Only second-year students were approached because they had already completed histology coursework, including both face-to-face and online practical histology classes, during their first and second years. The questionnaire comprised seven items designed to assess commonly evaluated domains in medical education research, including overall satisfaction, perceived effectiveness in enhancing histology comprehension, learning motivation, instructional preferences, and perceived helpfulness of individual instructional components (Supplementary File 1). Five items were rated using a 5-point Likert scale, while two items required participants to select a single response from predefined options.

A 5-point Likert scale was chosen to balance respondent usability with sufficient sensitivity to detect differences in students' perceptions across instructional formats. The scale anchors were clearly defined for each item to ensure consistent interpretation.

3. Data analysis

After data collection, responses were organized in Microsoft Excel (version 16). Statistical analyses were performed using the IBM Statistical Package for the Social Sciences (SPSS) version 29, and graphical analyses were generated using Microsoft Excel. Survey results were summarized using descriptive statistics. Because Likert scale responses are ordinal and were obtained from the same students across different instructional modes, non-parametric tests were applied. Comparisons between two related groups were performed using the Wilcoxon signed-rank test, while comparisons among more than three related groups were conducted using the Friedman test. When the Friedman test indicated statistical significance, post-hoc pairwise comparisons were performed using the Wilcoxon signed-rank test. To control the family-wise error rate arising from multiple post-hoc comparisons, Holm correction was applied to the resulting P values using Microsoft Excel. Results are presented as mean ± standard deviation (SD), and statistical significance was defined as $P < 0.05$.

RESULTS

1. Participant demographics

Of the 114 second-grade students enrolled in the 2022 academic year at PNUSM, 91 students (79.8%; 59 males and 32 females) voluntarily participated in this study after providing consent forms. The proportion of male to female students among respondents was 64.8% and 35.2%, respectively.

2. General satisfaction with the four modes of histology practical sessions

As shown in Fig. 1, students reported a moderately high level of overall satisfaction with the histology practical sessions. Notably, satisfaction was significantly higher for the online mode compared with the face-to-face mode, with mean Likert scores of 3.79 ± 0.76 and 3.27 ± 0.97, respectively (Wilcoxon signed-rank test, $Z = -4.434$, $P < 0.001$), where 1 indicates "utmost dissatisfaction" and 5 indicates "utmost satisfaction".

The mean satisfaction scores for the three online histology lab session (OHLS) formats—"virtual microscopy at PNUSM", "e-Histology", and "open-access online histology resources"—were 3.78 ± 0.90, 3.81 ± 0.87, and 3.79 ± 0.88 on a Likert scale, respectively (Fig. 1). A Friedman test indicated no significant differences in satisfaction among the three OHLS formats ($\chi^2(2) = 0.56$, $P = 0.973$).

Furthermore, most students indicated that the online mode provided a better learning experience than the offline mode. Regarding satisfaction with the face-to-face module as a motivator for learning, fewer than half of the respondents (38.46%) reported being completely satisfied (12.09%) or satisfied (26.37%), while 39.56% were neutral (Fig. 2A). Meanwhile, 21.98% felt dissatisfied (20.88%) or completely dissatisfied (1.10%) with the face-to-face module's ability to motivate them (Fig. 2A).

In contrast, a majority of students (65.20%) favored the

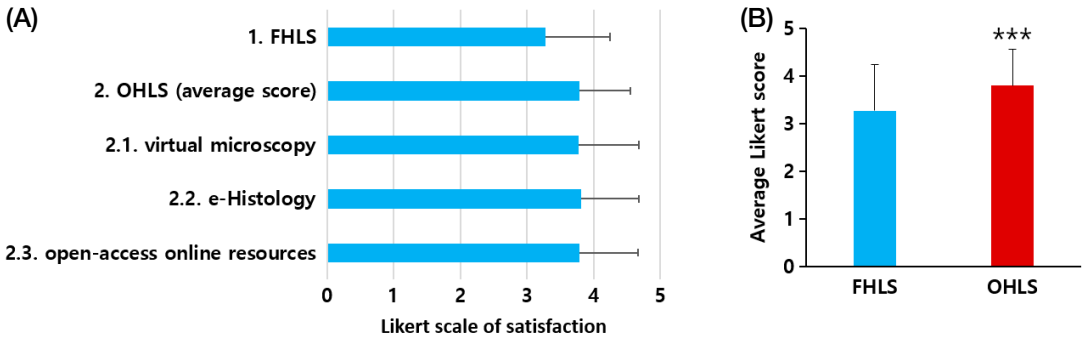

Fig. 1. Student satisfaction with different modes of histology practical sessions (n = 91). (A) Mean satisfaction scores for face-to-face histology lab sessions (FHLS) and individual online histology lab session (OHLS) modalities. (B) Comparison of overall satisfaction between FHLS and OHLS. Satisfaction was rated on a 5-point Likert scale (1 = "utmost dissatisfaction"; 5 = "utmost satisfaction"). Error bars represent standard deviations. Statistical significance was assessed using the Wilcoxon signed-rank test; ***$P < 0.001$ compared with FHLS.

online learning mode as a motivational driver, with 21.98% reporting being completely satisfied and 43.22% satisfied (Fig. 2B). Another 27.84% expressed a neutral stance, and only 6.96% were dissatisfied (6.23%) or completely dissatisfied (0.73%) (Fig. 2B). This trend was observed in both male and female students, indicating a broader preference for online learning as a more motivating modality.

To gain deeper insight into students' perceptions of online learning satisfaction, all participants were asked to evaluate their level of satisfaction with different online platforms used for practical histology. The results indicated generally positive attitudes toward all three modes of online histology instruction.

For OHLS delivered through "virtual microscopy at PNUSM", most students (64.84%) reported being completely satisfied (21.98%) or satisfied (42.86%) with its ability to motivate them to learn, while 27.47% were neutral (Fig. 2C). Only 7.69% expressed dissatisfaction (6.59%) or complete dissatisfaction (1.10%) (Fig. 2C).

Similarly, regarding OHLS using "e-Histology", a majority of respondents (68.13%) reported being completely satisfied (20.88%) or satisfied (47.25%) with its motivational impact (Fig. 2D). Another 25.27% were neutral, and only 6.59% felt dissatisfied (5.49%) or completely dissatisfied (1.10%) (Fig. 2D).

For OHLS based on "open-access online histology resources", 62.64% of students reported being completely satisfied (23.08%) or satisfied (39.56%), while 30.77% remained neutral (Fig. 2E). Only 6.59% expressed dissatisfaction (6.59%), and none reported being completely dissatisfied (0.00%) with this modality as a learning motivator (Fig. 2E).

3. Perceived effectiveness of face-to-face versus online histology practicals in enhancing comprehension

Additionally, we sought to assess the effectiveness of face-to-face and online histology practical learning modules in enhancing students' comprehension of histology. Participants were asked to rate the perceived effectiveness of both formats based on their learning experiences during the pandemic. As shown in Fig. 3A, students generally reported moderately high levels of perceived effectiveness for both formats, with significantly higher ratings for the online mode compared with the face-to-face mode (3.87 ± 0.70 vs. 3.62 ± 0.89 on a Likert scale; Wilcoxon signed-rank test, $Z = -3.003$, $P = 0.003$), where 1 represents "utmost ineffectiveness" and 5 represents "utmost effectiveness".

Regarding the perceived effectiveness of face-to-face histology practical classes in motivating students to learn, the majority of respondents (63.74%) rated them as effective (52.75%) or extremely effective (10.99%), while 26.37% were neutral (Fig. 3B). Only 9.89% rated face-to-face sessions as slightly effective (6.59%) or least effective (3.30%) in motivating learning (Fig. 3B).

In contrast, a larger proportion of students (70.33%) perceived online histology practical learning as effective (52.75%) or extremely effective (17.58%) in motivating them to learn, while 28.57% were neutral (Fig. 3C). Only a very small fraction (1.10%) rated online sessions as slightly effective (1.10%) or least effective (0.00%) for motivation (Fig. 3C).

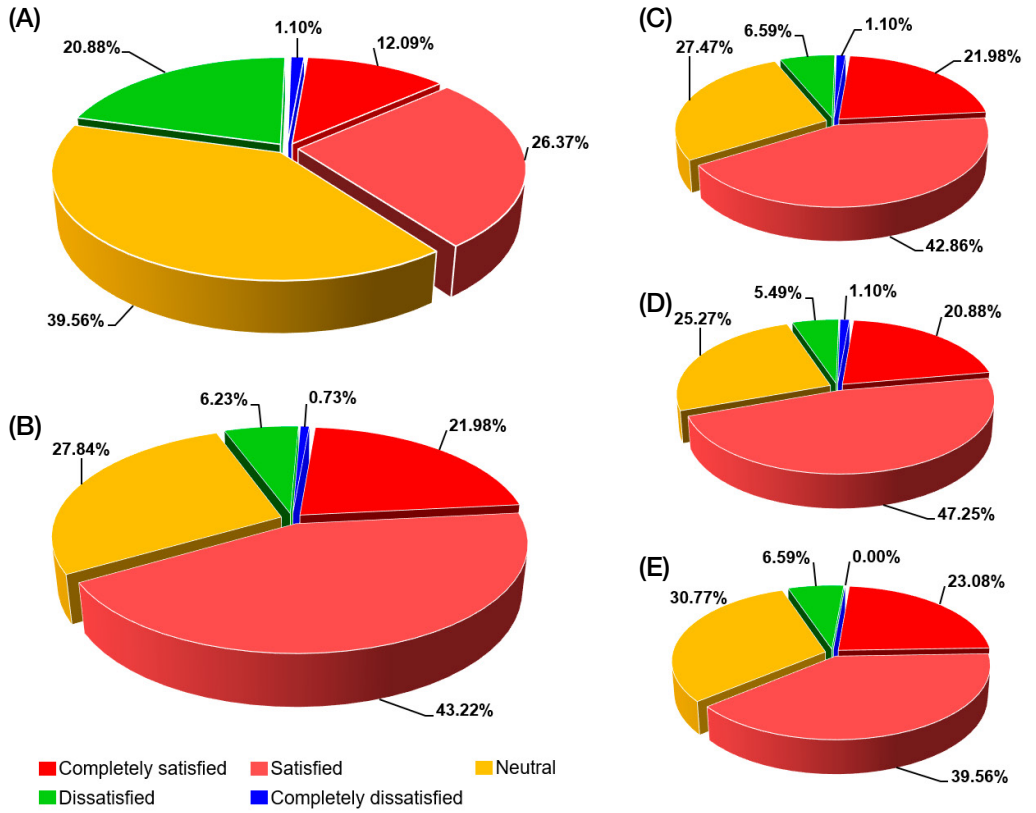

Fig. 2. Distribution of students' satisfaction with different modes of histology practical sessions (n = 91). (A) Percentage distribution of satisfaction levels for face-to-face histology lab sessions. (B) Percentage distribution of satisfaction levels for online histology lab sessions (OHLS). (C) Percentage distribution of satisfaction levels for OHLS using virtual microscopy at PNUSM. (D) Percentage distribution of satisfaction levels for OHLS using e-Histology. (E) Percentage distribution of satisfaction levels for OHLS using open-access online histology resources.

4. Perceptions of online histology practicals as a full alternative to face-to-face sessions in emergencies

When students were asked whether the online histology practical education system could fully replace face-to-face sessions in the event of another emergency that disrupts in-person classes, such as the COVID-19 pandemic, the mean Likert score reflecting their agreement was 4.03 ± 0.41 (Fig. 4A), where 1 represents "utmost disagreement" and 5 represents "utmost agreement."

Furthermore, more than nine out of ten respondents (93.41%) agreed (83.52%) or strongly agreed (9.89%) that online histology practical sessions could replace face-to-face formats during such circumstances (Fig. 4B). Only 6.59% expressed a neutral opinion, and none of the students (0.00%) disagreed or strongly disagreed, indicating no negative attitudes toward fully substituting face-to-face sessions with online modalities during public health emergencies (Fig. 4B).

5. Student perceptions of the ideal online format for COVID-19-like emergencies

When students were asked to select their preferred type of online histology practical class as the ideal substitute for conventional face-to-face histology lab sessions (FHLS) during emergencies such as the COVID-19 pandemic, 26.37%, 10.99%, and 7.69% chose OHLS using (1) "virtual microscopy at PNUSM", (2) "e-Histology", and (3) "open-access online histology resources", respectively (Fig. 5). Additionally, 12.09%, 4.40%, and 5.49% selected combinations of (1) + (2), (1) + (3), and (2) + (3), respectively (Fig. 5). Notably, the largest proportion of students (32.97%) preferred the combined use of all three formats—(1), (2), and (3)—as the ideal approach for online histology practi-

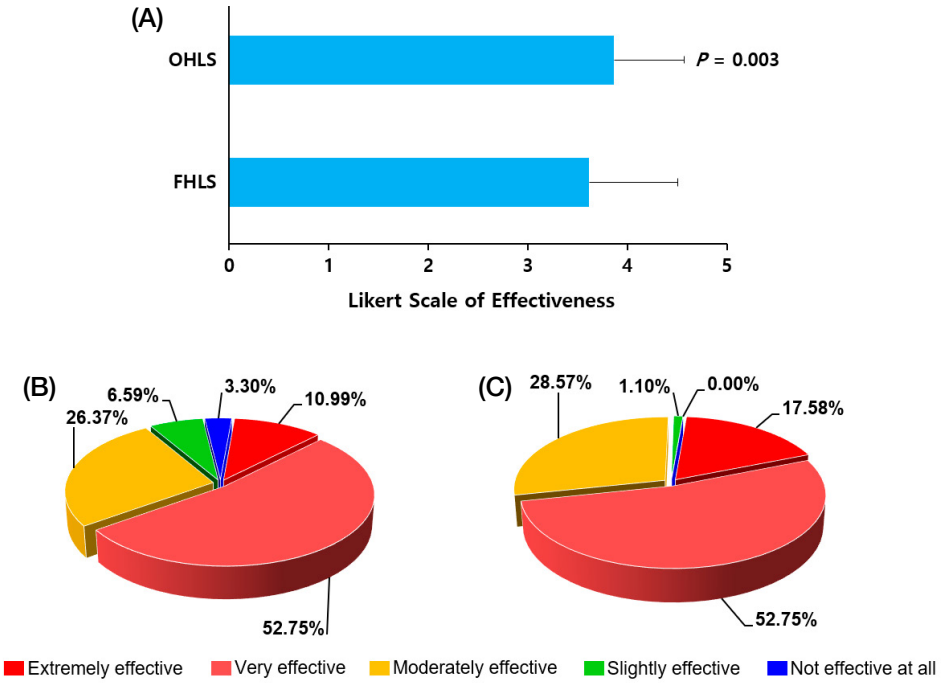

Fig. 3. Level and distribution of students' perceptions regarding the effectiveness of histology practical sessions in enhancing histology comprehension (n = 91). (A) Bar chart showing the mean perceived effectiveness of different modes of histology practical sessions. Scores were rated on a 5-point Likert scale (1 = "utmost ineffective"; 5 = "extremely effective"). Error bars represent standard deviations. Statistical significance was assessed using the Wilcoxon signed-rank test; $P = 0.003$ compared with FHLS. (B, C) Pie charts depicting the distribution of students' perceived effectiveness for Pusan National University School of Medicine (PNUSM) (B) and online histology lab sessions (C). Abbreviations: FHLS, face-to-face histology lab sessions; OHLS, online histology lab sessions.

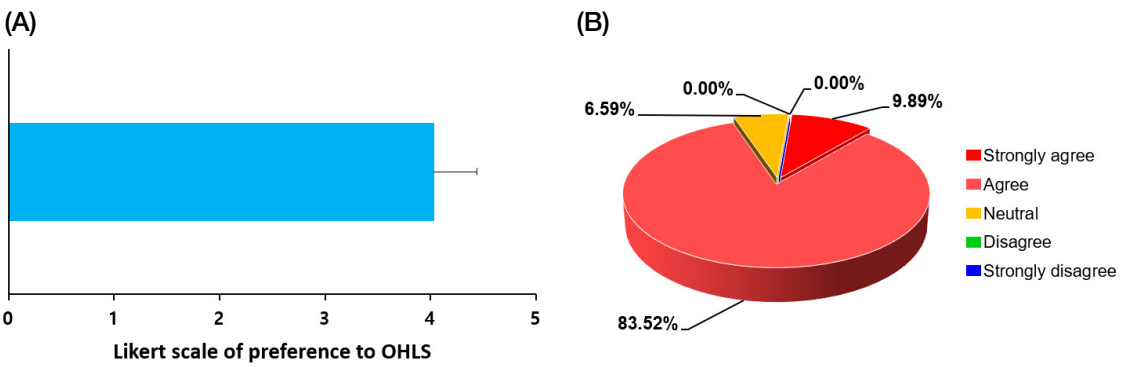

Fig. 4. Level and distribution of students' preferences for online histology lab sessions (OHLS) during public health emergencies (n = 91). (A) Bar chart showing the mean level of student agreement regarding the use of OHLS as a replacement for face-to-face sessions during public health emergencies. Ratings were based on a 5-point Likert scale (1 = "strongly disagree"; 5 = "strongly agree"). Error bars indicate standard deviations. (B) Pie chart illustrating the frequency distribution of students' preferences for OHLS under emergency conditions.

cal learning during emergency situations (Fig. 5).

6. Perceived ideal components of histology practical formats in the post-COVID era

When students were asked which type of histology practical learning they wished to maintain after the end of the COVID-19 pandemic, a large majority preferred OHLS (79.12%) over FHLS (20.88%) (Fig. 6A).

Of the 91 respondents, 72 students who selected OHLS as their preferred post-pandemic method were further asked to identify their favored type of OHLS (Fig. 6B). Among

them, 26.39%, 19.44%, and 4.17% preferred OHLS using (1) "virtual microscopy at PNUSM", (2) "e-Histology", and (3) "open-access online histology resources", respectively (Fig. 6B). Additionally, 12.50%, 4.17%, and 4.17% expressed preference for combined formats of (1)+(2), (1)+(3), and (2)+(3), respectively. Notably, the largest proportion (29.17%) favored the combined use of all three formats—(1), (2), and (3)—as the most desirable approach for future histology practical learning (Fig. 6B).

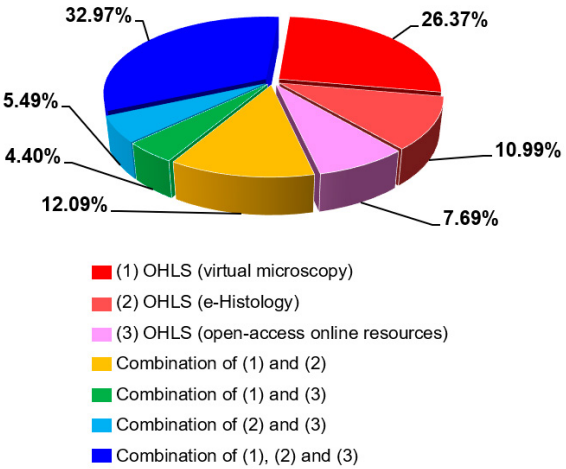

Fig. 5. Pie charts showing the frequency distribution of students' preferences for the ideal mode of online histology lab sessions (OHLS) in the event of a public health emergency (n=91) during the COVID-19 pandemic.

7. Effectiveness of face-to-face practical session components in supporting histology understanding

When students were asked to rate the helpfulness of individual components of the face-to-face histology practical sessions in enhancing their understanding of histology, mean Likert scores were as follows: 3.97±0.74 for the theoretical histology class, 3.44±0.93 for the histology practical protocol, 3.26±0.94 for the online histology practice resources, 3.71±0.96 for the preparation of histology practical reports, 2.97±1.09 for the formative practical histology assessment, 3.26±0.98 for the histology slide identification quiz, 4.03±0.85 for the use of histology practical images in the end-of-course examination, 3.32±0.94 for the peer discussion, and 3.79±0.73 for the student-instructor interaction (Fig. 7A). These scores were based on a Likert scale ranging from 1 ("not at all helpful") to 5 ("extremely helpful"). The highest ratings were observed for the use of histology practical images in the end-of-course examination and the theoretical histology class, whereas the lowest rating was reported for formative practical histology assessment (Fig. 7A). A Friedman test demonstrated significant differences in perceived effectiveness among the nine face-to-face histology practical session components ($\chi^2(8)=107.74$, $P<0.001$). Post-hoc pairwise comparisons using the Wilcoxon signed-rank test with Holm correction showed that the theoretical histology class was rated

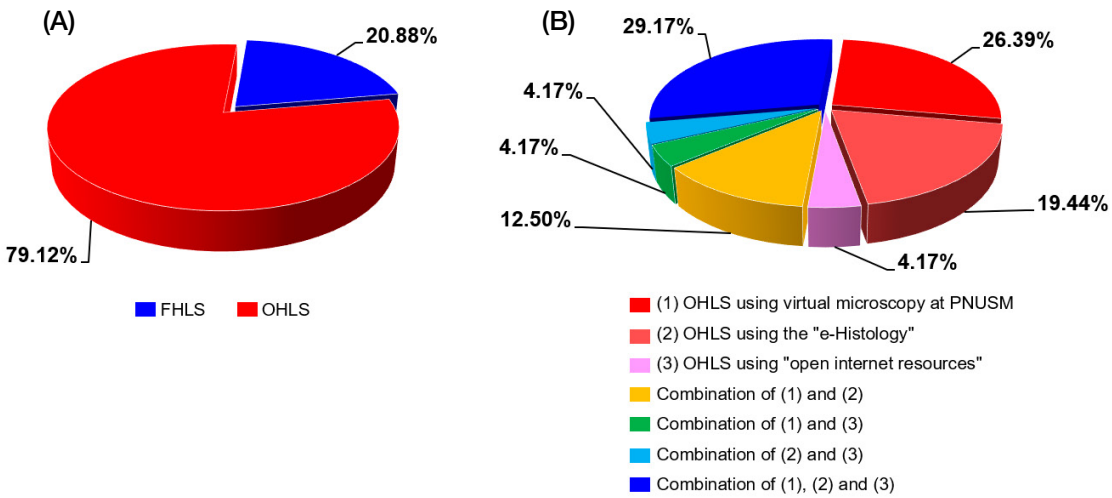

Fig. 6. (A) Pie chart showing the frequency distribution of students' preferences for the type of histology practical learning they wish to maintain after the end of the COVID-19 pandemic (n=91). (B) Pie chart showing the frequency distribution of students' preferences for different modes of online histology lab sessions (OHLS) they wish to maintain post-pandemic (n=91) at PNUSM. Abbreviations: FHLS, face-to-face histology lab sessions.

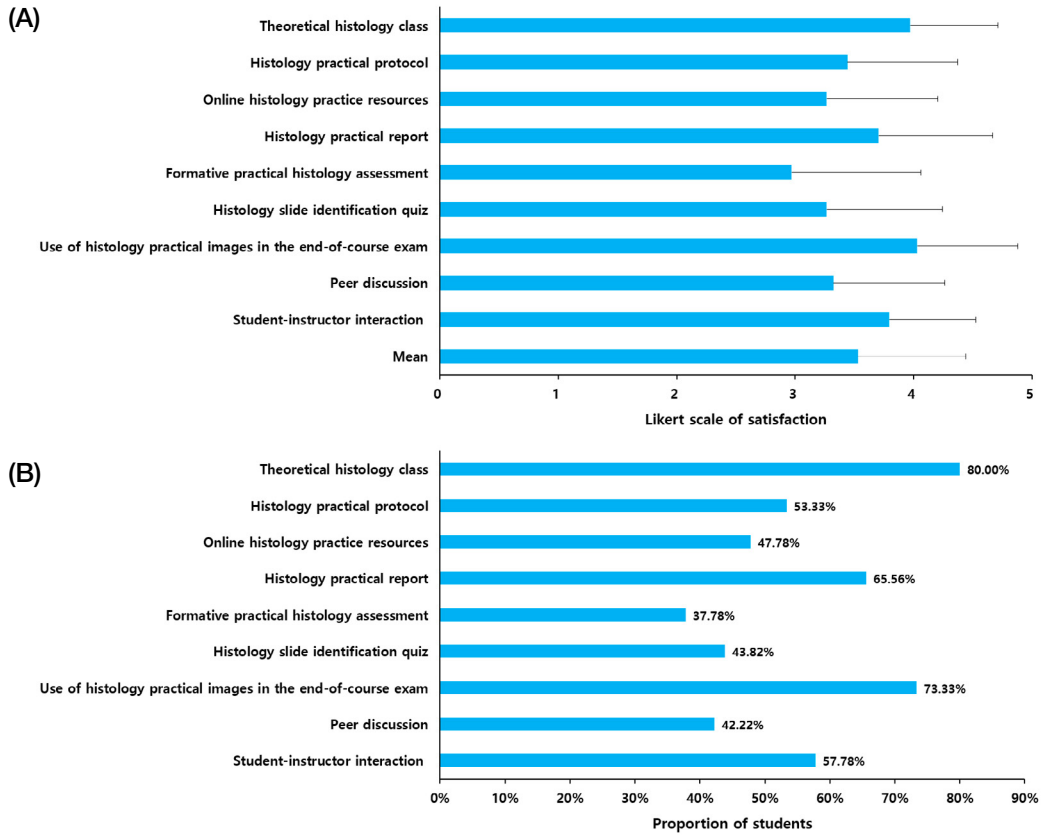

Fig. 7. Level and frequency distribution of students' perceptions of the helpfulness of resources used in face-to-face histology practical sessions for enhancing their comprehension of histology (n=91). (A) Bar chart showing the mean ratings of the helpfulness of various components of face-to-face histology practical sessions. Ratings were based on a 5-point Likert scale (1="not helpful at all"; 5="extremely helpful"). Error bars indicate standard deviations. (B) Bar chart showing the frequency distribution of students' ratings of the helpfulness of each component of face-to-face histology practical sessions.

significantly higher than all other components (Holm-adjusted $P<0.05$), except for the use of histology practical images in the end-of-course examination (Holm-adjusted $P=0.256$). Similarly, the use of histology practical images in the end-of-course examination was rated significantly higher than most other components (Holm-adjusted $P<0.05$), but not higher than the theoretical histology class or the preparation of histology practical reports.

Furthermore, the proportion of students who rated each component as helpful (i.e., "very helpful" or "extremely helpful") was as follows: 80.00% for the theoretical histology class, 53.33% for the histology practical protocol, 47.78% for the online histology practice resources, 65.56% for the preparation of histology practical reports, 37.78% for the formative practical histology assessment, 43.82% for the histology slide identification quiz, 73.33% for the use of histology practical images in the end-of-course examination, 42.22% for the peer discussion, and 57.78% for the student-instructor interaction (Fig. 7B).

8. Effectiveness of online histology practical session components in supporting histology understanding

When students were asked to rate the helpfulness of various components of the online histology practical sessions in enhancing their comprehension of histology, the mean Likert scores were as follows: 4.09±0.75 for the theoretical histology class, 3.64±0.95 for the histology practical protocol, 3.67±0.90 for the online histology practice resources, 3.81±0.97 for the preparation of histology practical reports, 3.22±1.11 for the formative practical histology assessment, 3.24±0.96 for the histology slide identification quiz, and 3.91±0.74 for the use of histology practical

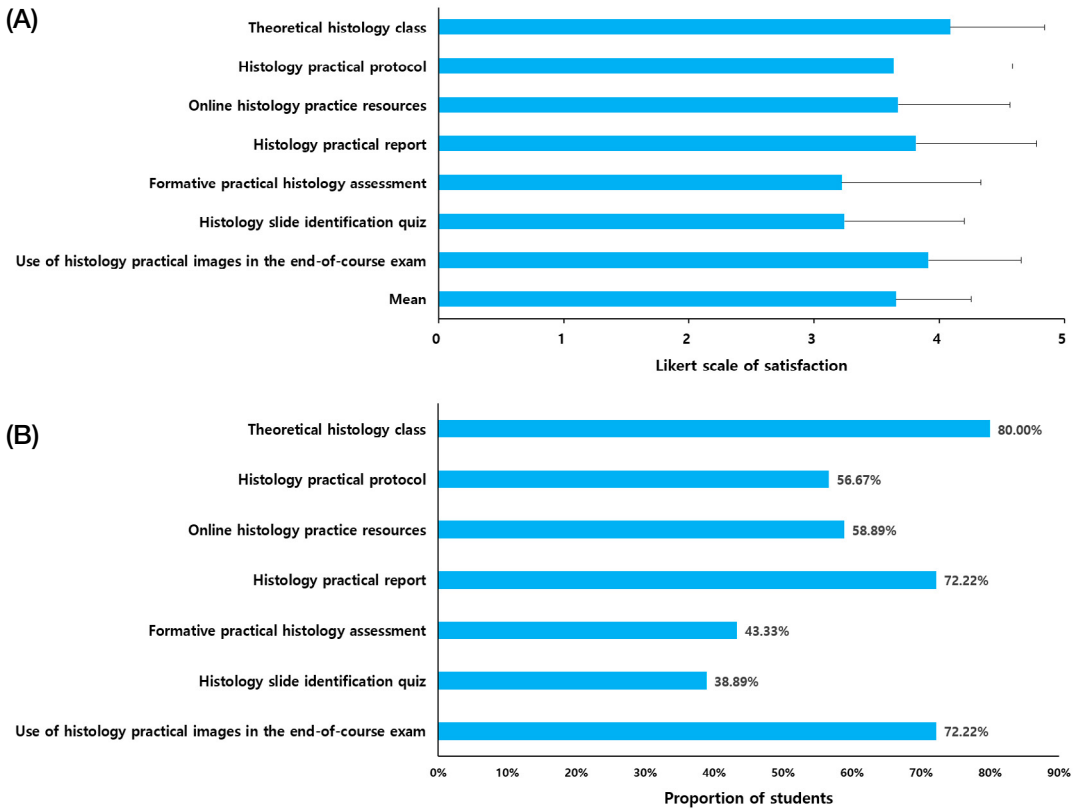

Fig. 8. Level and frequency distribution of students' perceptions of the helpfulness of resources used in online histology practical sessions for enhancing their comprehension of histology (n = 91). (A) Bar chart showing the mean ratings of the helpfulness of various components of online histology practical sessions. Ratings were based on a 5-point Likert scale (1 = "not helpful at all"; 5 = "extremely helpful"). Error bars indicate standard deviations. (B) Bar chart showing the frequency distribution of students' ratings of the helpfulness of each component of online histology practical sessions.

images in the end-of-course examination (Fig. 8A). These scores were based on a Likert scale ranging from 1 ("not at all helpful") to 5 ("extremely helpful"). The highest ratings were observed for the "theoretical histology class" and the "use of histology practical images in the end-of-course examination" (Fig. 8A). A Friedman test demonstrated significant differences in perceived effectiveness among the seven online histology practical session components ($\chi^2(6) = 82.65$, $P < 0.001$). Post-hoc pairwise comparisons using the Wilcoxon signed-rank tests with Holm correction indicated that the theoretical histology class was rated significantly higher than most other components (Holm-adjusted $P < 0.05$), except for the preparation of histology practical reports and the use of histology practical images in the end-of-course examination. The use of histology practical images in the end-of-course examination was rated significantly higher than formative practical assessment and the histology slide identification quiz (Holm-adjusted $P < 0.05$), but not higher than the remaining components.

Furthermore, the proportion of students who rated each component as helpful (i.e., "very helpful" or "extremely helpful") was as follows: 80.00% for the theoretical histology class, 56.67% for the histology practical protocol, 58.89% for the online histology practice resources, 72.22% for the preparation of histology practical reports, 43.33% for the formative practical histology assessment, 38.89% for the histology slide identification quiz, and 72.22% for the use of histology practical images in the end-of-course examination (Fig. 8B).

DISCUSSION

The COVID-19 pandemic necessitated the rapid transition of medical education in Korea to fully online platforms beginning in early 2020. This abrupt shift from traditional

face-to-face instruction to remote learning created a unique context for examining the immediate implementation of online medical education. In this study, 91 valid responses (79.8%) were obtained from 114 second-year medical students enrolled at PNUSM in 2022. Given the high response rate and representativeness of the cohort, the findings provide meaningful insight into online practical histology teaching during the pandemic.

Although online learning has long been debated in higher education under normal circumstances, its adoption became unavoidable during COVID-19-related disruptions [17-19]. For many educators, the initial challenge centered on how to transition effectively to online instruction, while evaluations of broader impacts—such as changes in learning experience, engagement, and perceived outcomes—have taken longer to emerge [19].

Learning outcomes are a key indicator of the success of online instruction. Interestingly, 93.0% of students in our study reported that online histology practical sessions helped them achieve the intended learning outcomes, compared with 78.8% who reported the same for face-to-face sessions. This difference may reflect the unique circumstances of mandatory remote instruction, during which students may have adapted their study habits or relied more heavily on digital materials. Consistent with our findings, several studies have also demonstrated that online histology teaching effectively supports individual learning [20], that students' perceptions of online histology courses during COVID-19 lockdown were generally positive [21], and that online practical histology increased students' engagement, enjoyment, and knowledge retention during distance learning [22].

Despite this, when focusing specifically on perceived effectiveness for enhancing understanding, students rated online practical sessions higher (70.3% very/extremely effective) than face-to-face sessions (63.7%). This finding suggests that, in the context of the COVID-19 pandemic, online histology practicals were perceived by a greater proportion of students as effective in supporting learning, despite the absence of in-person instruction. These results may reflect students' increased reliance on digital learning resources, repeated access to virtual slides, and flexible self-paced study during mandatory remote instruction.

In contrast, prior work has shown that in-person histology practicals offer unique advantages, particularly regarding real-time instructor interaction, immediate feedback, and collaborative peer learning. Multiple studies have reported that although students value the convenience of virtual slides, many still consider face-to-face sessions beneficial for mastering complex microscopic structures and receiving individualized guidance [23-25]. Taken together, our findings suggest that while online instruction can effectively support perceived learning improvement, face-to-face practicals may retain complementary strengths related to deeper conceptual engagement, underscoring the potential value of blended face-to-face and online learning approaches.

At the same time, a striking 93.4% of students agreed or strongly agreed that online histology practicals could fully replace face-to-face practicals during public health emergencies. This aligns with observations from other institutions where students viewed digital histology as a viable and effective alternative when on-campus access was restricted [19,26]. At the same time, several studies caution that relying exclusively on online modalities may reduce opportunities for face-to-face practical histology learning and benefiting from physical laboratory interactions, suggesting that blended or hybrid models may offer the greatest pedagogical value in the post-pandemic era [27-29].

Regarding online modality preferences during emergencies, the most favored format was a multimodal combination of (1) virtual microscopy at PNUSM, (2) e-Histology, and (3) open-access internet resources. A similar pattern was seen in student preferences for continuing online histology practicals after the pandemic, with 29.2% favoring the same combination. This preference likely reflects the complementary strengths of these platforms and reinforces the growing consensus that multimodal digital environments provide the most robust support for learning.

This preference is also consistent with recent findings that the most successful online histology programs combine structured digital slide sets with supplementary learning tools such as quizzes, digital histology education platforms, and interactive modules, all of which enhance engagement and address diverse learning styles [10,31,32]. Such integrated approaches have been associated with increased motivation, improved comprehension, and better long-term retention in histology courses.

Analysis of the perceived helpfulness of face-to-face session components revealed that theoretical histology classes were considered the most effective element, followed by the use of histology images in the end-of-course examina-

tion, the preparation of practical reports, student-instructor interaction, and the histology practical protocol. Components such as peer discussion, online resources, slide identification quizzes, and formative assessments were rated as less helpful. This suggests that structured instructor-led activities and well-designed assessments may contribute more directly to student comprehension than unstructured or peer-driven components.

In line with our findings, numerous studies reported high levels of student satisfaction with online or virtual microscopy-based histology instruction during COVID-19. Studies have shown that virtual microscopy improves accessibility, allows repeated viewing, and minimizes technical issues associated with traditional microscopes, leading to increased student confidence and satisfaction [10,23,29,30]. Similarly, several studies observed high satisfaction and perceived learning effectiveness in digital histology environments [23,33], supporting our conclusion that online practicals can reliably support intended learning outcomes.

Taken together, our findings indicate that carefully designed, multimodal online histology practicals can serve as effective complements to traditional instruction, both during emergencies and within long-term curricular planning. Several implications emerge. First, although the emergency-driven transition to online teaching was abrupt, many online modalities demonstrated considerable educational value. Second, multimodal digital formats appear particularly promising and may merit continued use in post-pandemic medical education. Third, differences in perceived effectiveness between face-to-face and online formats suggest that pedagogical strategies should be tailored rather than directly transferred from one modality to the other. Finally, because our study relied on student self-reported perceptions, future research incorporating external evaluations and objective performance measures will be essential.

This study has several limitations that should be considered when interpreting the findings. Most importantly, the study relied solely on students' self-reported perceptions and did not include objective measures of academic performance, such as examination scores, practical test results, or long-term knowledge retention. As a result, the findings reflect perceived learning improvement rather than direct evidence of learning outcomes. Future studies incorporating objective performance assessments alongside subjective evaluations would be valuable in more comprehensively comparing the educational effectiveness of online and face-to-face histology practical sessions. Additionally, the findings may not be generalizable to medical schools with different levels of technological infrastructure for online histology teaching. Furthermore, because the transition to online learning occurred abruptly and the survey was conducted shortly after the acute pandemic phase, temporal biases may exist. Thus, the results provide a snapshot of a specific period and may not fully capture long-term trends or evolving educational practices.

Nevertheless, this study provides valuable insight into how medical schools in Korea adapted histology practical education during the COVID-19 pandemic. Taken together, our findings indicate that carefully designed, multimodal online histology practicals can effectively support learning in both emergency and post-pandemic contexts, help guide refinement of online histology curricula, inform infrastructure planning, and support international educators seeking effective strategies for emergency-driven transitions in medical education.

CONCLUSION

This study examined medical students' perceptions of online practical histology teaching during the COVID-19 pandemic at a Korean medical school, focusing on virtual microscopy, e-Histology, and open-access online resources. Students reported high levels of satisfaction and perceived effectiveness for online histology practical sessions, with many indicating that these modalities helped them achieve the intended learning outcomes and could fully replace face-to-face sessions during public health emergencies.

A multimodal approach—combining institutional virtual microscopy, e-Histology, and open-access resources—was consistently preferred both for emergency use and for continued implementation in the post-pandemic era. In addition to theoretical histology teaching, the use of practical images in end-of-course examinations were perceived as particularly helpful for enhancing histology understanding across both face-to-face and online formats.

These findings suggest that well-designed, multimodal online histology practicals can provide an effective and acceptable complement to traditional laboratory-based teaching. Future work should incorporate objective learning outcomes and multi-institutional data to further define best

practices for integrating digital and face-to-face histology education in a sustainable, post-pandemic curriculum.

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SUPPLEMENTARY

Questionnaire on Medical Students' Perceptions of Online Practical Histology Teaching

Q1. Please rate your general satisfaction with the 4 different modes of histology practical sessions that have been provided thus far:

Item		Completely dissatisfied	Dissatisfied	Neither satisfied nor dissatisfied	Satisfied	Completely satisfied
face-to-face histology practical class		1	2	3	4	5
Online histology practical class	e-learning by virtual microscopy	1	2	3	4	5
	e-Histology	1	2	3	4	5
	Open internet practical histology resources	1	2	3	4	5

Q2. How would you rate the effectiveness of the face-to-face/online histology practical learning modules you have had so far in enhancing your comprehension of histology:

Item	Not effective at all	Slightly effective	Moderately effective	Very effective	Extremely effective
face-to-face virtual microscopy	1	2	3	4	5
Online histology practical classes	1	2	3	4	5

Q3. If an emergency situation distracting face-to-face contact in physical classes such as the current COVID-19 crisis recurs, do you think the online histology practical education system can fully displace face-to-face histology practical sessions?

Strongly disagree	Disagree	Neutral	Agree	Strongly agree
1	2	3	4	5

Q4. Which of the following online histology practical forms do you think is ideal for an emergency situation, such as the COVID-19 pandemic (or any situation where face-to-face practical classes are unavailable)? Please select only one.

1) e-learning by virtual microscopy
2) e-learning by the e-Histology online module
3) Open internet practical histology resources
4) 1 + 2 hybrid
5) 1 + 3 hybrid
6) 2 + 3 hybrid
7) 1 + 2 + 3 hybrid

Q5. Which of the following 2 options do you hope to maintain for the histology practical class after the end of the COVID-19 pandemic situation?

1) face-to-face virtual microscopy
2) online histology practical classes

Q5-1. If you select 'online histology practical classes' in the previous question (Q5), which of the following options do you prefer the most?

1) e-learning by virtual microscopy
2) e-learning by the e-Histology online module
3) Open internet practical histology resources
4) 1 + 2 hybrid
5) 1 + 3 hybrid
6) 2 + 3 hybrid
7) 1 + 2 + 3 hybrid

Q6. How would you rate the helpfulness of the following items used in face-to-face histology practical sessions based on your experience and engagement (you have had so far) in enhancing your comprehension of histology:

	Not helpful at all	Slightly helpful	Moderately helpful	Very helpful	Absolutely helpful
Theoretical histology class	1	2	3	4	5
Histology practical protocol	1	2	3	4	5
Internet resources	1	2	3	4	5
Preparing histology practical report	1	2	3	4	5
Formative evaluation	1	2	3	4	5
Final histology practical quiz with images	1	2	3	4	5
Use of histology practical images in the theoretical histology exam	1	2	3	4	5
Interaction between students	1	2	3	4	5
Interaction between students and professor	1	2	3	4	5

Q7. How would you rate the helpfulness of the following items used in non-face-to-face histology practical sessions based on your experience and engagement (you have had so far) in enhancing your comprehension of histology:

	Not helpful at all	Slightly helpful	Moderately helpful	Very helpful	Absolutely helpful
Theoretical histology class (lecture)	1	2	3	4	5
Histology practical protocol	1	2	3	4	5
Internet resources	1	2	3	4	5
Preparing histology practical report	1	2	3	4	5
Formative evaluation	1	2	3	4	5
Final histology practical quiz with images	1	2	3	4	5
Use of histology practical images in the theoretical histology exam	1	2	3	4	5