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ORIGINAL ARTICLE

Online and In-Person Instruction in Laboratory Diagnostics: a Four-Year Student Cohort Study

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ABSTRACT

Background: **The rapid shift to online medical education in practical disciplines like Laboratory Diagnostics during the COVID-19 pandemic raised widespread concerns about its effectiveness. This retrospective study aimed to compare the effectiveness of online and in-person instruction and to evaluate the impact of this pedagogical change on student academic performance.**
Methods: **A retrospective mixed-methods study was conducted. Final exam scores from four consecutive cohorts of clinical medicine students for Laboratory Diagnostics (Classes of 2018 - 2021, 2021 - 2024 academic years) were analyzed, and 91 students with direct online learning experience were surveyed.**
Results: **Quantitative results showed a significant academic performance decline during the online teaching period. Median scores (100-point scale) dropped from 83 (Class 2018) to 72 (Class 2019) and 79 (Class 2020), before recovering to 84 (Class 2021) ($p < 0.001$). The failure rate surged from 2.2% in Class 2018 to 18.3% in Class 2019, returning to 0% in Class 2021 ($p < 0.001$). The questionnaire revealed mixed experiences of students with online learning. A notable 18.7% of students felt online learning "worse than in-person", while 17.6% reported "decreased learning efficiency" and 42.9% had "extended study time". Although most students provided positive feedback on instructional support and teacher performance, a minority identified shortcomings including insufficient course materials (6.6%), platform instability (4.4%), and limited instructor-student interaction (8.8%).**
Conclusions: **The findings firmly revealed that online instruction was associated with a significant performance decline in a practical discipline. The robust recovery upon returning to in-person instruction underscores its irreplaceable role. The four-year student cohort study recommends a strategic hybrid pedagogical model for Laboratory Diagnostics, combining online theory with dedicated in-person practical training.**
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KEYWORDS

Laboratory Diagnostics, online and in-person instruction, retrospective study, questionnaire, pedagogical shift, academic performance

LIST OF ABBREVIATIONS

AI - Artificial Intelligence
COVID-19 - Coronavirus Disease 2019
IBM - International Business Machines Corporation
IQR - Interquartile Range
IT - Information Technology

PMID - PubMed Identi
Q&A - Questions and Answers
SPSS - Statistical Package for the Social Sciences
WJX - Wen Juan Xing (an online questionnaire platform, provider: Changsha Ranxing IT Ltd.)

INTRODUCTION

The COVID-19 pandemic significantly transformed medical education, driving a rapid and widespread shift in teaching methods. In response to the global imperative for social distancing, institutions worldwide were forced to transition from traditional in-person instruction to online learning platforms [1,2]. While this shift was a vital public health measure, it introduced unprecedented challenges for clinical medicine, a field fundamentally reliant on hands-on practice, direct patient interaction, and collaborative physical environments. The abrupt move to an exclusively online format created a critical tension between the established strengths of in-person teaching and the new realities of digital delivery, especially in developing countries [3-6].

Traditional in-person teaching excels at providing direct, immediate feedback and facilitating dynamic, collaborative problem-solving. In contrast, online education offers flexibility, accessibility, and the ability to scale up content delivery [6], providing a valuable repository of resources that students can revisit at their convenience. The abrupt transition to an online-only format, however, raised critical questions among educators and students about its potential impact on student engagement, the acquisition of practical skills, and ultimately academic performance in complex clinical subjects [6-8]. The return to a post-pandemic reality now necessitates a retrospective evaluation of the consequences of this temporary, but dramatic, shift in teaching methods.

Within this context, the discipline of Laboratory Diagnostics occupies a fundamental and pivotal position in medical training. As a field focused on the analysis of biological samples to aid in the diagnosis, prognosis, and management of diseases, it forms the scientific bedrock of modern medical practice [9,10]. Laboratory Diagnostics is a crucial bridge between theoretical knowledge and practical application, equipping future physicians with the indispensable skills to interpret laboratory findings and comprehend complex disease processes. Given this critical role, a retrospective analysis of any disruption to its effective teaching is crucial for guiding the development of future pedagogical strategies.

Despite numerous reports and a growing body of research suggesting a decline in student performance during periods of online learning [11,12], a specific and longitudinal analysis of this phenomenon within clinical medicine programs has been scarce. Few empirical studies have integrated quantitative academic data from distinct teaching periods with qualitative student feedback to fully understand this trend. This study, therefore, aimed to offer a retrospective analysis by systematically comparing the academic performance of four consecutive cohorts of clinical medicine students in Laboratory Diagnostics. We would quantitatively assess the changes in exam results and pass/fail rates across distinct teaching phases (pre-pandemic, pandemic, and post-pandemic recovery) to measure the lasting impact of this educational disruption. This quantitative analysis was then to be complemented by a detailed questionnaire to qualitatively explore student perceptions and experiences, identifying key factors that might have influenced these academic fluctuations and offering valuable insights for future pedagogical design.

MATERIALS AND METHODS

Research design

This study utilized a retrospective mixed-methods design to comprehensively evaluate the impact of online versus offline teaching on student academic performance. The quantitative component objectively assessed changes in student grades across different teaching modalities by analyzing documented data from four consecutive and comparable cohorts. Despite these cohorts originating from different academic years, the stable admission standards for our clinical medicine program ensured a high degree of student ability similarity. Furthermore, the uniform use of the university's designated online platform and teaching resources during the pandemic helped to control for potential confounding factors related to technological variations. To maximize evaluation consistency across the four years, all final examinations were constructed based on the identical curricular blueprint, drawn from a standardized departmental question bank, and evaluated using uniform scoring rubrics. Nevertheless, because the specific examination items varied annually, absolute statistical equivalence in exam difficulty cannot be definitively established. We acknowledge this potential non-equivalence in assessments as an inherent limitation of our observational design, which should be taken into consideration when interpreting the score comparisons. A qualitative component, employing a cross-sectional questionnaire, complemented this analysis by exploring students' perceptions and experiences to provide deeper insights into the observed academic trends.

Participants

Participants in this study were divided into two groups. The quantitative analysis involved four consecutive cohorts of undergraduate clinical medicine students (Classes of 2018, 2019, 2020 and 2021; 2021 - 2024 academic years) who completed the Laboratory Diagnostics course at our school. Given the retrospective observational nature of this study, no a priori statistical power calculation was conducted to determine the cohort size. Instead, the study size was established by including all eligible students who were formally enrolled in the pro-

gram and had complete final examination records for the Laboratory Diagnostics course during these four academic years. These cohorts were categorized into three distinct teaching periods: pre-pandemic in-person instruction (Class 2018), pandemic-affected online instruction (Classes of 2019 and 2020), and post-pandemic in-person recovery (Class 2021). The cohorts were considered comparable in terms of baseline academic ability due to stable school admission criteria over the years. Historical academic data were retrieved directly from the university's academic information system, without the need for active recruitment.

For the qualitative and survey-based analysis, an anonymous online questionnaire was administered to students, primarily from the Classes of 2019 and 2020, who had extensive direct experience with online learning during the pandemic. The questionnaire was systematically developed based on a thorough literature review and underwent content validation by a panel of three experts in medical education to ensure clinical and pedagogical relevance. Prior to formal distribution, a pilot test was conducted with a small subset of students (n = 15) to verify the clarity and face validity of the questions. Internal consistency for the Likert-scale items was evaluated, yielding a satisfactory Cronbach's alpha coefficient of 0.985.

The finalized survey was distributed to approximately 240 eligible students, yielding 91 valid voluntary responses, which corresponds to a response rate of 37.9%. The final survey size (n = 91) was not predetermined but was based entirely on voluntary participation. Although this constitutes a convenience sample, acquiring n = 91 valid responses from this specific target group was deemed sufficient to provide meaningful descriptive insights into students' subjective learning experiences and to triangulate our quantitative findings. We acknowledge the potential for non-response bias inherent in this response rate; students who chose to participate might possess stronger opinions or differing academic engagement levels regarding online learning compared to non-respondents. This factor should be considered when generalizing the survey findings. Strict anonymity was maintained to ensure the confidentiality of all responses.

Data collection

Academic performance data were collected retrospectively from the university's official academic information system. For each student in the Laboratory Diagnostics course, we obtained the final exam raw scores (on a 100-point scale) and the pass/fail status. Student ID numbers were anonymized upon data export to ensure privacy. Each student’s teaching modality (pre-pandemic in-person, pandemic online, or post-pandemic recovery) was categorized based on their academic year.

A self-developed questionnaire was used to collect qualitative data. The survey instrument collected students' demographic data and incorporated closed-ended questions utilizing a 5-point Likert scale, designed to assess key dimensions of their learning experience. These included student demographics (e.g., age, gender, but not the name or ID), self-evaluation of online learning (e.g., perceived learning efficiency and effectiveness), evaluation of institutional and platform support (e.g., adequacy of technical support), and evaluation of instructor performance (e.g., teaching dedication and familiarity with online tools). The questionnaire was administered via a secure online platform (WJX, Changsha Ranxing IT Ltd.), and all data were encrypted and kept anonymous. The first page of the questionnaire contained a consent form that all participants were required to complete before proceeding further.

Statistical analysis

All statistical analyses were performed using SPSS software (version 27.0; IBM Corp., Armonk, NY, USA), and effect size calculations with their 95% confidence intervals (CIs) were performed using R software (version 4.4.3) with the effect size package. Since the continuous exam score data did not meet the assumption of a normal distribution, descriptive statistics were expressed as medians with interquartile ranges (IQR). A Kruskal-Wallis H test was used to compare the median scores across the four academic cohorts. To assess the practical magnitude of differences among multiple groups, the rank-based Eta-squared (η^2_H) was calculated as the effect size (0.04 - 0.13 indicating a medium effect, ≥ 0.14 indicating a large effect). Additionally, a Mann-Whitney U test was employed to compare the continuous scores between the two combined teaching modalities (in-person vs. online cohorts), using the rank-biserial correlation (r) to evaluate the effect size (0.10 - 0.29 small, 0.30 - 0.49 medium, ≥ 0.50 large). Categorical data, such as the distribution of students across different score categories (< 60, 60 - 75, 76 - 85, > 85), were presented as frequencies and percentages. Pearson's chi-squared (χ^2) test was utilized to assess the differences in these categorical distributions both among the four distinct academic years and between the combined in-person and online groups. To correct for potential positive bias in small samples or varying table dimensions, the adjusted Cramér's V (V_{adj}) was calculated to measure the effect sizes for these categorical comparisons (0.10 - 0.29 small, 0.30 - 0.49 medium, ≥ 0.50 large). Descriptive statistics were also used to analyze the Likert scale responses from the questionnaire. The statistical significance level was set at a two-sided $p < 0.05$.

RESULTS

Baseline characteristics and missing data

For the quantitative analysis, the four academic cohorts (Classes of 2018 - 2021) were comparable in baseline demographic characteristics. The overall cohort consisted of 421 students, with a relatively stable gender distribution (approximately 45% male and 55% female

Table 1. Comparison of scores across cohorts by online or in-person teaching modalities.

Class/Group	Median Score (p25, p75)	*H/U*	p	η^2_H or *r* [95% CI]
2018	83 (74.5, 89.5)	61.409	< 0.001	0.140 [0.09, 0.21]
2019	72 (63, 79)			
2020	79 (69.5, 86)			
2021	84 (77, 89)			
In-person (2018, 2021)	84 (77, 89)	13,448	< 0.001	0.326 [0.23, 0.42]
Online (2019, 2020)	76 (67, 84)			

Table 2. Analysis of the final exam score distribution across the four academic cohorts.

Class/Group	< 60 [n (%)]	60 - 75 [n (%)]	76 - 85 [n (%)]	> 85 [n (%)]	χ^2	p	V_{adj} [95% CI]
2018	2 (2.2%)	22 (24.2%)	32 (35.1%)	35 (38.5%)	57.892	< 0.001	0.2 [0.11, 0.24]
2019	17 (18.3%)	39 (41.9%)	28 (30.1%)	9 (9.7%)			
2020	14 (9.5%)	45 (30.6%)	48 (32.7%)	40 (27.2%)			
2021	0 (0.0%)	16 (17.8%)	33 (36.7%)	41 (45.6%)			
In-person (2018, 2021)	2 (1.1%)	38 (21.0%)	65 (35.9%)	76 (42.0%)	42.077	< 0.001	0.3 [0.19, 0.40]
Online (2019, 2020)	31 (12.9%)	84 (35.0%)	76 (31.7%)	49 (20.4%)			

Table 3. Demographic data of survey participants.

Item	Response	Percentage (%)
Gender		
	Male	45.0%
	Female	55.0%
Age/Year		
	18 - 20	30.8%
	21	30.8%
	22	25.2%
	23	13.2%
Prior Online Course Experience		
	None	31.9%
	Little	45.0%
	Frequent	23.1%
Ethnicity		
	Han	96.7%
	Ethnic Minority	3.3%
Geographical Origin		
	Major City	8.8%
	Small/Medium City	18.7%
	Town	22.0%
	Rural	50.5%

Table 4. Student self-evaluation about online learning effectiveness.

Item	Response	Percentage (%)
Q1. Improvement in Learning Effectiveness		
	Far Worse than In-person	**5.5%**
	Worse than In-person	**13.2%**
	No Significant Difference	**47.2%**
	Better than In-person	**18.7%**
	Far Better than In-person	**15.4%**
Q2. Improvement in Learning Efficiency		
	Drastic Decrease	**2.2%**
	Decrease	**15.4%**
	No Change	**39.5%**
	Increase	**25.3%**
	Drastic Increase	**17.6%**
Q3. Extension of Study Time		
	Drastic Shortening	**1.1%**
	Shortening	**12.1%**
	No Change	**44.0%**
	Extension	**28.5%**
	Drastic Extension	**14.3%**
Q4. Self-regulated Learning Ability		
	Very Weak	**1.1%**
	Weak	**7.7%**
	Average	**42.8%**
	Strong	**29.7%**
	Very Strong	**18.7%**
Q5. Adequacy of Participation		
	Very Insufficient	**2.2%**
	Insufficient	**2.2%**
	Average	**35.1%**
	Sufficient	**31.9%**
	Very Sufficient	**28.6%**
Q6. Study Habits		
	Very Weak	**1.1%**
	Weak	**7.7%**
	Average	**31.8%**
	Strong	**37.4%**
	Very Strong	**22.0%**
Q7. Familiarity with Tools and Platforms		
	Not at all Familiar	**0.0%**
	Not Familiar	**2.2%**
	Average	**28.6%**
	Familiar	**44.0%**
	Very Familiar	**25.2%**

Table 5. Student evaluations of instructor performance.

Item	Response	Percentage (%)
Q1. Satisfaction with Instructor's Dedication and Earnestness		
	Very Dissatisfied	**0.0%**
	Dissatisfied	**2.2%**
	Neutral	**22.0%**
	Satisfied	**47.2%**
	Very Satisfied	**28.6%**
Q2. Familiarity with Online Teaching Tools		
	Not at all Familiar	**0.0%**
	Not Familiar	**2.2%**
	Neutral	**28.5%**
	Familiar	**44.0%**
	Very Familiar	**25.3%**
Q3. Satisfaction with Classroom Discipline Maintenance		
	Very Dissatisfied	**0.0%**
	Dissatisfied	**2.2%**
	Neutral	**29.6%**
	Satisfied	**39.6%**
	Very Satisfied	**28.6%**
Q4. Frequency of Questions and Discussions		
	Almost Never	**1.1%**
	Rarely	**6.6%**
	Average	**34.1%**
	Quite Frequently	**35.1%**
	Very Frequently	**23.1%**
Q5. Frequency of Assigning Homework		
	Almost Never	**1.1%**
	Rarely	**4.4%**
	Average	**26.4%**
	Quite Frequently	**42.8%**
	Very Frequently	**25.3%**
Q6. Frequency of Q&A Sessions and Tutoring		
	Almost Never	**1.1%**
	Rarely	**5.5%**
	Average	**28.6%**
	Quite Frequently	**40.6%**
	Very Frequently	**24.2%**
Q7. Timeliness in Understanding Students' Situations		
	Not at all	**1.1%**
	Very Little	**7.7%**
	Average	**34.1%**
	Quite a bit	**35.1%**
	A Great Deal	**22.0%**

Table 5. Student evaluations of instructor performance (continued).

Item	Response	Percentage (%)
Q8. Timeliness in Grasping Students' Classroom Performance		
	Almost Never	**1.1%**
	Rarely	**7.7%**
	Average	**34.1%**
	Quite a bit	**35.1%**
	A Great Deal	**22.0%**
Q9. Timeliness and Effectiveness of Communication		
	Not at all	**1.1%**
	Very Little	**7.7%**
	Average	**34.1%**
	Quite a bit	**36.2%**
	A Great Deal	**20.9%**

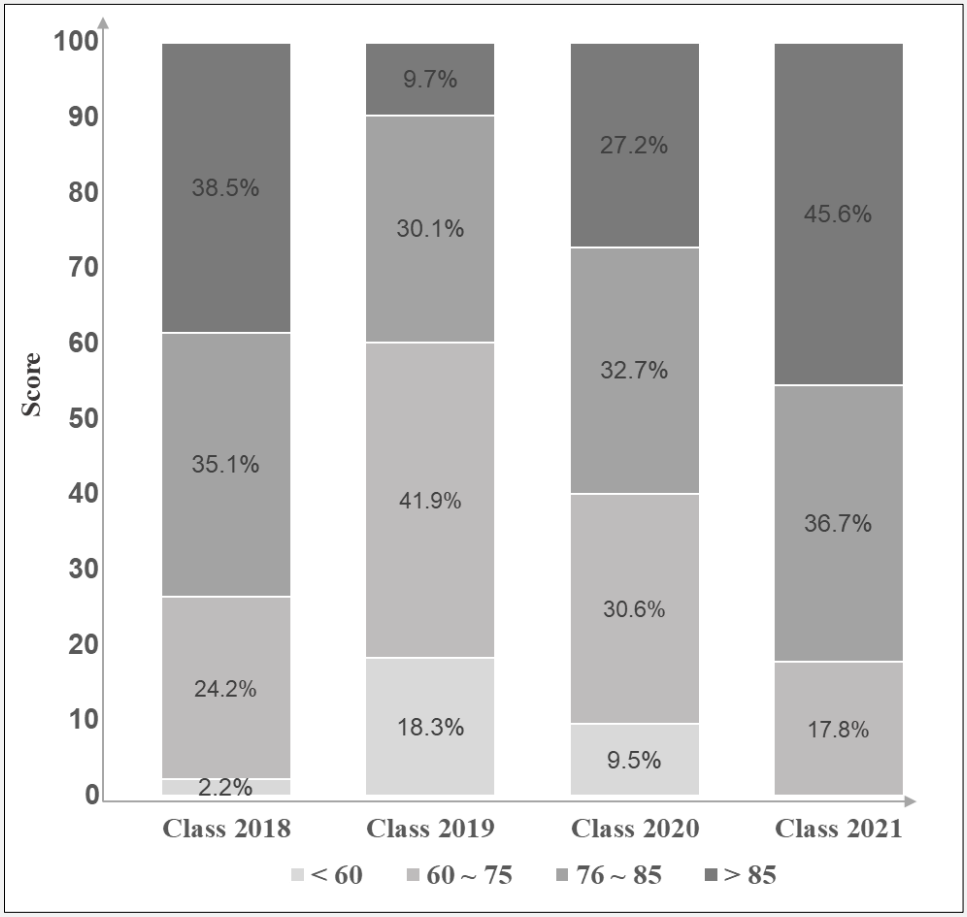

Figure 1. Final exam score distribution across four academic cohorts. It displays the percentage of students in each score category (< 60, 60 - 75, 76 - 85, > 85) for the four academic cohorts.

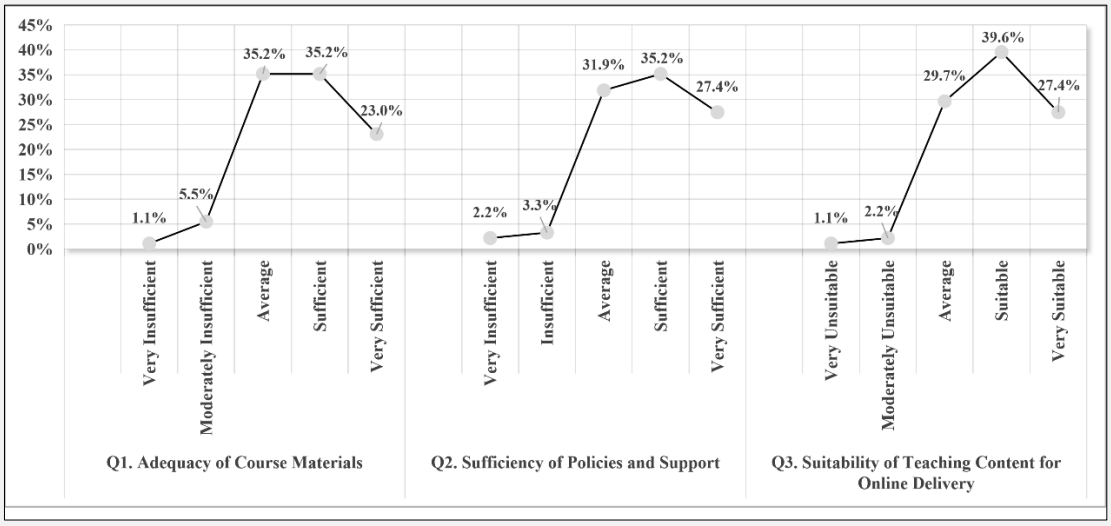

Figure 2. Student evaluations of the institution's academic supports.

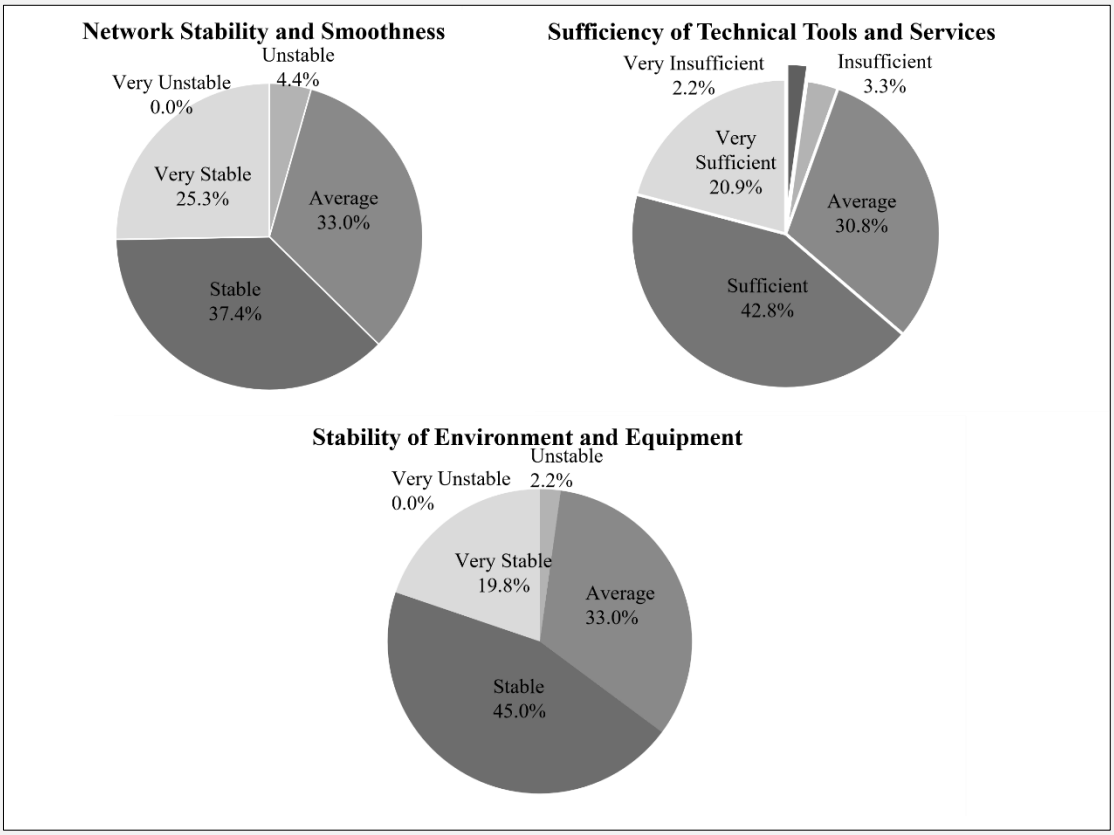

Figure 3. Student evaluations of the platform's technical supports.

across the years) and a mean age of 21.6 years at the time of examination. Because the study design included only students with complete academic records from the university system, there were no missing data points (n = 0 missing) for the primary variable of final examination scores.

Regarding the qualitative survey component, detailed demographic characteristics of the 91 respondents are presented in following tables. All 91 voluntary participants completed the mandatory fields of the online questionnaire; therefore, no missing data (n = 0 missing) were present in the final survey dataset used for analysis.

Quantitative component assessment across different teaching modalities

A descriptive analysis of the median final exam scores was performed for the four academic cohorts. A Kruskal-Wallis H test showed a significant difference in median scores among the four cohorts (H = 61.409, p < 0.001, η^2_H = 0.140, 95% CI: 0.09 - 0.21, indicating a large effect), with a notable performance dip observed during the online teaching years. Further rank-sum test analysis demonstrated that the median score for the combined in-person cohorts (Classes of 2018 and 2021) was significantly higher than that of the combined online cohorts (Classes of 2019 and 2020) (U = 13,448, p < 0.001, r = 0.326, 95% CI: 0.23 - 0.42, representing a medium effect) (Table 1).

Analysis of the final exam score distribution across the four academic cohorts revealed a significant association between the academic year and score distribution (χ^2 = 57.892, p < 0.001, V_{adj} = 0.2, 95% CI: 0.11 - 0.24, suggesting a small effect). A subsequent chi-squared test on the combined cohorts also showed a significant difference in score distribution between the combined in-person groups (Classes of 2018 and 2021) and the combined online groups (Classes of 2019 and 2020) (χ^2 = 42.077, p < 0.001, V_{adj} = 0.3, 95% CI: 0.19 - 0.40, suggesting a medium effect). Specifically, the combined in-person groups exhibited a substantially lower failure rate and a higher proportion of top-tier scores (> 85) compared to the online groups (Table 2). This academic fluctuation was evident across individual years: failure rates peaked and high-score rates plummeted during the initial shift to online instruction (Class 2019), followed by a robust recovery in performance upon returning to in-person learning (Class 2021) (Figure 1).

Questionnaire survey findings

A total of 91 students participated in the survey, with 55.0% females and 45.0% males. Ages were concentrated between 18 and 23 years. The sample ethnicity was predominantly Han (96.7%), and over half (50.6%) were from rural areas. A total of 76.9% of students had limited to no prior experience with online courses before the pandemic (combining 31.9% “None” and 45.0% “Little”) (Table 3).

Student self-evaluation

The survey results indicate that a portion of students held reservations about online learning effectiveness. A combined total of 18.7% of students rated online learning as "worse than in-person" (comprising 5.5% “Far Worse” and 13.2% “Worse”), while a combined 34.1% rated it as "better than in-person" (comprising 18.7% “Better” and 15.4% “Far Better”). In terms of efficiency, a combined total of 17.6% of students reported a decline, consisting of 15.4% who noted a “Decrease” and 2.2% who noted a “Drastic Decrease”. Additionally, 42.8% of students reported an extension of their study time (combining 28.5% “Extension” and 14.3% “Drastic Extension”), in contrast to the combined 13.2% who reported a reduction (12.1% “Shortening” and 1.1% “Drastic Shortening”). A total of 8.8% of students rated their self-regulated learning ability (1.1% “Very Weak” and 7.7% “Weak”) and a matching 8.8% rated their study habits (1.1% “Very Weak” and 7.7% “Weak”) as weak. In addition to these primary findings, other minor parameters were also comprehensively evaluated as part of this study (Table 4).

Evaluation of institutional support and platforms

While student evaluations of institutional and platform support were generally positive, the data also reflected certain shortcomings. A combined total of 6.6% of students rated course materials as “very insufficient” or “moderately insufficient” (1.1% and 5.5%, respectively) and 5.5% reported that institutional support was insufficient (combining 2.2% “Very Insufficient” and 3.3% “Insufficient”). The data on suitability of teaching content for online delivery were presented as well (Figure 2). Regarding the technical platform, 4.4% of students reported platform instability (4.4% “Unstable” and 0.0% “Very Unstable”), and 5.5% reported insufficient technical tool support (combining 2.2% “Very Insufficient” and 3.3% “Insufficient”). Assessment on stability of environment and equipment was also documented (Figure 3).

Instructor evaluation

Student evaluations of instructor performance showed that a combined 75.8% were “satisfied” or “very satisfied” with their dedication and earnestness (47.2% and 28.6%, respectively). Furthermore, 69.3% of students rated instructor's familiarity with online teaching tools as “familiar” or “very familiar” (44.0% and 25.3%, respectively). Regarding teaching activities, 68.2% were satisfied with discipline maintenance (combining 39.6% “Satisfied” and 28.6% “Very Satisfied”), and the majority rated the frequency of questions/discussions at 58.2% (35.1% “Quite Frequently” and 23.1% “Very Frequently”). Similarly, high frequencies were reported for homework at 68.2% (42.8% and 25.3%), and Q&A sessions at 64.8% (40.6% and 24.2%) as high (Table 5).

However, some findings pointed to limitations in student-instructor interaction. A total of 8.8% of students reported that instructors had “very little” to “almost no”

understanding of their situations (7.7% and 1.1%, respectively) or classroom performance (7.7% "Rarely" and 1.1% "Almost Never"). This corresponded with the 8.8% of students who found communication timeliness and effectiveness to be "not at all" (1.1%) or "very little" (7.7%). In addition to the primary findings, Table 5 also comprehensively summarized other relevant factors that were evaluated as part of this study.

DISCUSSION

This study retrospectively analyzed the impact of in-person/online teaching on clinical medicine students for Laboratory Diagnostics before and after the outbreak of COVID-19. Our results show a significant association between the teaching modality and student performance. Grades during online periods were markedly lower than in-person periods, with a strong rebound in academic performance upon the return to offline instruction. A student questionnaire provided further insight into the factors behind this academic fluctuation. The profound impact of the COVID-19 pandemic on global medical education, with pedagogical shifts, proved to be a double-edged sword [13-17]. While online learning offered flexibility and accessibility, it posed significant challenges for academic outcomes, particularly in procedural and clinical skills-based disciplines. For instance, studies report a general decline in medical student exam scores and an increase in failure rates following the shift to online teaching [12,17]. Our findings were in line with these negative trends. Our results showed that median scores were significantly lower and failure rates were significantly higher for the online cohorts (Classes of 2019 and 2020) compared to those of the in-person cohorts (Classes of 2018 and 2021). This academic fluctuation indicates a strong association between the teaching modality and student performance, although the observational nature of our study precludes definitively ruling out the potential influence of student's baseline abilities or other unmeasured confounders. The sharp decline in performance for Class 2019 cohort stood in stark contrast to the robust recovery observed in Class 2021 cohort upon returning to in-person instruction. This pattern of decline and recovery underscored the irreplaceable role of offline teaching in clinical medical education.

The impact of online teaching on academic outcomes is a multifaceted issue, with recent literature highlighting both benefits and significant challenges [18-22]. Several studies have suggested that online learning can lead to decreased student engagement, inadequate self-discipline, and reduced learning efficiency [19,21]. By integrating our quantitative findings with the questionnaire results, we gained a deeper understanding of the specific causes behind the decline in grades. First, a key finding was that 18.7% of students explicitly felt that online learning was "worse than in-person". For a practical discipline like Laboratory Diagnostics, this perception may stem from the lack of face-to-face discussions and hands-on practice opportunities during online sessions. Such limitations could be a primary reason for deficiencies in both depth of understanding and practical application skills. Second, the data indicate that online teaching would demand greater self-management from students. A notable 42.9% reported an extension of their study time, which may be an indicator of reduced efficiency, a point further supported by the 17.6% who directly reported a decrease in their learning efficiency. Furthermore, though instructors and platforms generally received positive ratings, some technical and communicative shortcomings were identified. For instance, 8.8% of students felt instructors had a limited understanding of their situation, and 4.4% experienced platform instability.

These factors, while reported by a minority, could disrupt learning continuity and contribute to a suboptimal experience.

Several limitations of this study should be acknowledged. First, the relatively small sample size, as well as a single-center study, may restrict the generalizability of our conclusions. Second, by focusing on exam scores as the primary outcome, our study did not fully assess the impact of online instruction on other critical competencies, such as clinical skills or critical thinking. This presents a clear avenue for future research using observational assessments and in-depth interviews to evaluate the impact on students' non-cognitive skills. Despite these limitations, our findings underscored the central role of in-person instruction in clinical medical education. While online learning was a vital tool during the crisis, its inherent deficiencies in learning effectiveness and efficiency cannot be ignored.

Despite these significant findings, our study has several limitations that should be acknowledged. First, due to the unadjusted, retrospective observational design across four academic years, we cannot completely rule out the influence of secular trends or unmeasured confounders, such as slight variations in student's baseline characteristics or broader pedagogical evolutions over time. Second, while we utilized standardized blueprints and departmental question banks to maximize consistency, absolute statistical equivalence of the final examinations across different years cannot be definitively established. Finally, the questionnaire component of our study had a response rate of 37.9%, which introduces the possibility of non-response bias; the perspectives of the respondents may not fully represent the entire cohort. Future multicenter, prospectively designed studies with multivariate adjustments are warranted to further validate our findings.

In conclusion, the present study offers a crucial lesson for future educational strategies: while online instruction is a valuable tool, it would not be a complete substitute for in-person teaching in practical fields. We recommend adopting a strategic hybrid pedagogical model for Laboratory Diagnostics and similar disciplines, which combines the strengths of online theory delivery

with mandatory in-person practical training to ensure comprehensive student development.

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Declaration of Generative AI in Scientific Writing:
The author(s) declared that generative AI was not used in the creation of this manuscript.

Ethics Approval and Consent to Participate:
This study was performed in line with the principles of the Declaration of Helsinki. Informed consent was obtained from all participants. Participation was voluntary and anonymous. Respondents were informed about the nature and purpose of the survey before providing consent, and they were given the option to withdraw at any time. The authors declare that this report does not contain any personal information that could lead to the identification of the students. Ethical approval was obtained from the Ethics Committee of the First Affiliated Hospital of Anhui Medical University. Clinical trial number: Not applicable.

Availability of Data and Materials:
The raw data supporting the conclusions of this article will be made available by the authors, without undue reservation.

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The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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