

## TEACHING INNOVATION

# Development and implementation of a blended teaching model integrating an online flipped classroom with offline laboratory instruction in histology and embryology

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## Abstract

Histology laboratory time is often consumed by basic orientation that students could complete before class. We therefore evaluated a blended model that moved part of this preparation online and reserved the face-to-face session for observation, questioning, and inquiry. The study used a quasi-experimental design and included 252 undergraduates from six intact clinical medicine classes in the 2025–2026 academic year. Three classes ( $n=126$ ) used the blended model and three classes ( $n=126$ ) received conventional laboratory instruction. Before each laboratory session, students in the intervention group used Rain Classroom to review microlectures and related materials and to complete self-assessments. Laboratory time was then organized around targeted questions, tiered inquiry tasks, group discussion, and instructor feedback. Outcomes included a common end-of-course microscopic structure identification examination, an anonymous questionnaire, and semi-structured interviews. No significant baseline differences were found between groups ( $P>0.05$ ). The intervention group scored  $86.37\pm5.48$  on the final examination, compared with  $80.72\pm6.31$  in the control group ( $P<0.001$ ). Among the 118 valid questionnaire respondents, 92.37% considered the blended model more effective than conventional laboratory teaching, 89.83% reported that preclass learning clarified the laboratory objectives, and 83.90% agreed that tiered inquiry improved their understanding of structure-function relationships. Interview comments echoed these findings, especially with regard to preparation, repeated review of morphological material, and participation during laboratory work. Within the setting studied, reorganizing preparation and laboratory activities in this way was associated with better examination performance and a favorable learning experience.

**Keywords:** Histology and embryology, Blended learning, Flipped classroom, Laboratory instruction, Medical education

## 1 INTRODUCTION

In histology and embryology, being able to recall a structural name is different from being able to find that structure on a slide and explain what its morphology means. Laboratory teaching is where these abilities are usually brought together. Students have to move repeatedly between microscopic imag-

es, anatomical terminology, and structure-function relationships; this process also provides the morphological foundation needed for later work in pathology, physiology, and clinical subjects. For that reason, laboratory sessions are a core component of the course rather than a simple supplement to lectures. Blended and online-offline approaches have been applied specifically in histology and embryology education [1, 2].



Table 1. Baseline characteristics of the two groups

| Characteristic             | Intervention group (n=126) | Control group (n=126) | Statistic            | P value |
|----------------------------|----------------------------|-----------------------|----------------------|---------|
| Age, years                 | 19.13±0.58                 | 19.09±0.61            | t=0.53               | 0.596   |
| Male, n (%)                | 58 (46.03)                 | 62 (49.21)            | χ <sup>2</sup> =0.26 | 0.613   |
| Entrance examination score | 628.46±18.72               | 626.91±19.34          | t=0.65               | 0.518   |
| Systematic anatomy score   | 82.15±6.48                 | 81.64±6.71            | t=0.61               | 0.540   |
| Pre-course test score      | 79.37±7.12                 | 78.91±7.46            | t=0.50               | 0.617   |

The difficulty is that this work has to be completed within limited laboratory hours. Part of each session is commonly spent introducing the specimen, reviewing key features, and helping students orient themselves under the microscope. Students who have prepared little before class may spend additional time deciding where to begin or distinguishing similar structures. When much of the session is used for these basic tasks, there is less opportunity to compare specimens, discuss why structures differ, or connect morphology with function and simple clinical problems. The result can be a laboratory class that emphasizes identification more than interpretation.

A flipped format offers one way to redistribute these activities. Similar blended approaches have been implemented across several areas of undergraduate medical education [3, 4]. Material needed for initial orientation can be studied before class, while the laboratory remains the place for microscope work and direct interaction with instructors and peers. An online platform also allows students to revisit visual material and gives instructors information about completion and common errors. Studies of learner readiness, acceptance, and self-directed or faculty-guided hybrid learning indicate that engagement with the online component is an important part of implementation [5, 6]. Flipped and blended models have also been reported in hepatology, epidemiology and biostatistics, and other platform-supported medical education settings [7-9]. This combination is relevant to a morphology-based course because students can first become familiar with important landmarks and difficult distinctions in digital form and then test that preparation against actual slide observations in class. More recent work has extended hybrid teaching to digital-intelligence-supported, AI-assisted, case-based, and other combined modalities in medical, dental, and graduate education [10-12].

We developed a teaching sequence that combined preclass learning through Rain Classroom with tiered face-to-face laboratory tasks. The present study compared this model with conventional laboratory teaching in six parallel classes. We assessed the final microscopic structure identification examination as the main objective outcome and used questionnaire and interview data to describe how students experienced the new arrangement. In discussing the findings, we considered whether the sequence of preparation, observation, feedback, and progressively more demanding tasks was consistent with several commonly used learning theories.

2 PARTICIPANTS AND METHODS

2.1 Study design

We used a quasi-experimental design in which the intact class served as the unit of intervention. This choice reflected the way the laboratory course was actually delivered at the university: laboratory capacity, teaching sequence, instructor assignment, and routine administration were organized by class. Individual students were therefore not randomized. Instead, the two teaching formats were implemented across six parallel classes.

The university had assigned students to these classes before the study. The research team did not reorganize classes on the basis of sex, previous grades, learning ability, or student preference. Three classes received the blended intervention and three continued with conventional laboratory teaching. Both groups followed the same syllabus and textbook, covered the same laboratory content, received the same total laboratory hours, and completed the same final assessment. The same course team was responsible for instruction in both groups so that the principal planned difference was the teaching format.

2.2 Participants

The participants were 252 undergraduates enrolled in six parallel classes in a clinical medicine program during the 2025–2026 academic year. The three intervention classes included 126 students (58 male and 68 female), and the three control classes also included 126 students (62 male and 64 female). All participants completed the full histology and embryology laboratory course.

Table 1 summarizes the baseline variables. None of the measured characteristics differed significantly between the intervention and control groups, including age, sex, entrance examination score, systematic anatomy score, and pre-course test score (all P>0.05).

2.3 Sample size estimation

Sample size was estimated in G\*Power 3.1 for an independent-samples t test. We specified a two-sided α of 0.05, power of 0.80, and an anticipated medium effect size (Cohen’s d=0.50), which gave a minimum requirement of 64 students per group. Because teaching was delivered to intact classes and some questionnaire or outcome data could potentially be unavailable

## Blended teaching workflow: online flipped classroom + offline laboratory

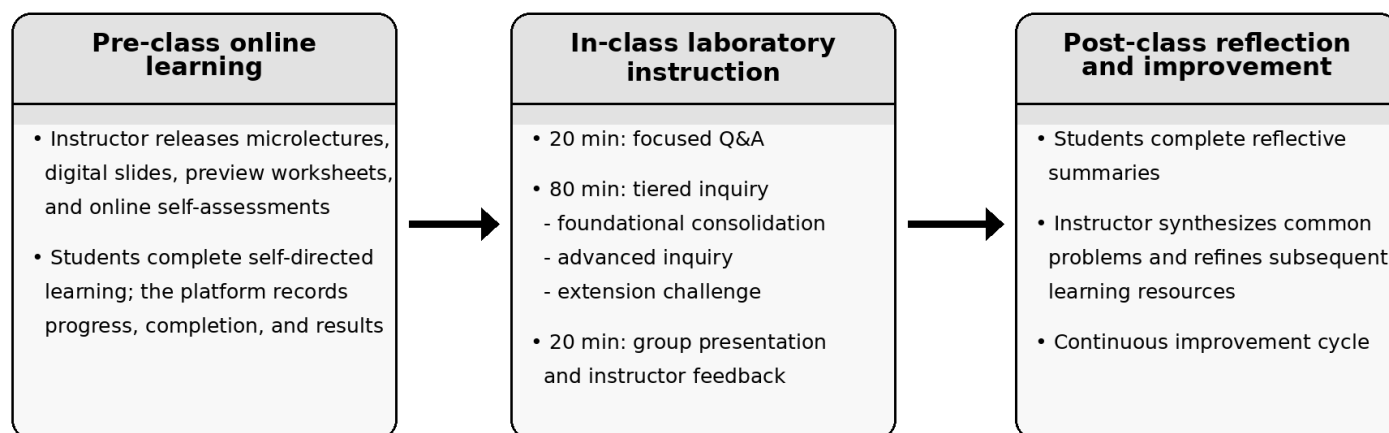


**Figure 1. Workflow of the blended teaching model.**

ble, all eligible students in the selected classes were retained. The final sample was 126 students per group.

## 2.4 Teaching interventions

### 2.4.1 Intervention group

For the intervention group, online preparation and laboratory work were designed as consecutive parts of the same lesson rather than as two independent teaching activities. Each cycle included preclass study in Rain Classroom, a face-to-face laboratory session with tiered tasks, and postclass reflection and feedback.

Before a laboratory session, instructors posted microlecture videos, digital slides, preview worksheets, and self-assessment questions in Rain Classroom. The videos generally lasted 20–30 min and focused on key structures, difficult distinctions, common observation errors, and structure-function relationships relevant to the upcoming laboratory task. Students were asked to complete the videos and self-assessment before class. Rain Classroom recorded viewing progress, completion, and response accuracy. Instructors reviewed these records before the laboratory period and selected frequently missed points for focused explanation in class.

The face-to-face laboratory period lasted 120 min. Approximately 20 min at the beginning were used to address problems identified in the online work. Students then spent 80 min completing three levels of task. Foundational tasks concentrated on locating and identifying core structures; advanced tasks required comparison and functional explanation; extension tasks introduced straightforward pathological or clinical situations that required students to apply morphological knowledge. The remaining 20 min were used for group reporting and instructor feedback on observations, reasoning, and task completion.

### 2.4.2 Control group

The control classes followed the laboratory format routinely used in the course. The instructor first introduced the objectives, observation requirements, slide characteristics, and key identification points. Students then worked independently at the microscope, with the instructor circulating to answer questions and provide guidance. A brief summary of the main content was given before the end of the session. Teaching hours, content, textbook, syllabus, and final assessment were identical to those in the intervention group.

## 2.5 Instructional workflow

Information from one stage of the blended lesson was used to plan the next. Before class, students accessed the assigned materials and completed the online questions, after which instructors reviewed platform records for common difficulties. The laboratory session began with those difficulties rather than with a full repetition of the preparatory material. Students then moved from core identification tasks to group inquiry and extension problems, followed by group reporting and feedback. After class, reflective summaries and recurrent problems were used to refine later resources and tasks.

As shown in **Figure 1**, the model operated as a repeating preparation-laboratory-feedback cycle, with the preclass work intended to inform rather than replace face-to-face teaching.

## 2.6 Outcome measures

### 2.6.1 End-of-course microscopic structure identification examination

At the end of the course, both groups sat the same microscopic structure identification examination. The 100-point examina-

**Table 2. Completion of online learning activities in the intervention group**

| Indicator                                   | Result     |
|---------------------------------------------|------------|
| Mean microlecture completion rate           | 91.46%     |
| Mean online self-assessment completion rate | 94.82%     |
| Mean online self-assessment score           | 84.73±8.64 |
| Preclass worksheet submission rate          | 90.21%     |
| Mean online learning time, min/session      | 34.58±9.27 |

tion covered representative tissues, microscopic organization of organs, and structure-function relationships. The course team prepared one examination paper and a common scoring rubric. Answer sheets were anonymized with identification numbers, and raters used the same predetermined answers and scoring criteria for structure-identification items.

### 2.6.2 Questionnaire survey

Students in the intervention group were invited to complete an anonymous questionnaire after the course. The 23 items covered five areas: acceptance of the teaching model, learning interest and motivation, self-directed learning ability, depth of conceptual understanding, and communication and collaboration. Each item was rated from 1 (strongly disagree) to 5 (strongly agree).

Before formal use, five histology and embryology instructors and two medical education researchers reviewed the questionnaire. Their comments were used to revise wording, the placement of items within dimensions, and correspondence with the course objectives. I-CVI values after this review ranged from 0.86 to 1.00, and the S-CVI/Ave was 0.94. In the study sample, Cronbach's  $\alpha$  was 0.912 for the complete questionnaire and 0.824–0.887 for the five individual dimensions.

### 2.6.3 Semi-structured interviews

Questionnaire scores could not fully describe how students used the blended activities, so we also conducted semi-structured interviews. Eighteen intervention-group students were purposively selected to represent different levels of academic performance: six high-performing, six moderate-performing, and six with a comparatively weak academic foundation. The interview sample included eight male and ten female students. Interviews lasted about 15–25 min and addressed preclass preparation, microlectures, laboratory tasks, group work, perceived gains, and suggestions for improvement.

The interview records were read repeatedly and coded inductively. Comments that recurred across interviews were grouped into themes. These themes were then considered together with the questionnaire findings when we interpreted students' experiences of the intervention.

## 2.7 Ethical considerations

The study was conducted within routine curriculum reform and teaching quality evaluation. No additional clinical procedures were introduced, no biological specimens were collected from participants, and no privacy-sensitive information was obtained. Questionnaire data were anonymous, while academic performance data were de-identified before analysis and used for educational research and course improvement. Students were informed of the study purpose, data use, and voluntary nature of participation, and informed consent was obtained.

## 2.8 Statistical analysis

Statistical analyses were carried out in SPSS 26.0. Continuous data are presented as mean  $\pm$  standard deviation and were compared between groups with independent-samples *t* tests. Categorical data are shown as frequencies and percentages and were compared with  $\chi^2$  tests. Questionnaire results were summarized by mean score, standard deviation, and the proportion of responses rated 'agree' or 'strongly agree'. Cronbach's  $\alpha$  was used to examine internal consistency. A two-sided  $\alpha$  of 0.05 was used as the threshold for statistical significance.

## 3 RESULTS

### 3.1 Completion of online learning activities

Most intervention-group students completed the assigned online preparation (**Table 2**). The mean microlecture completion rate was 91.46%, and the mean online self-assessment completion rate was 94.82%; the mean self-assessment score was 84.73±8.64. Performance varied somewhat by laboratory topic. The digestive and urinary system sessions produced comparatively more errors, particularly on distinctions between morphologically similar tissues and on questions requiring structure-function reasoning.

These records were used during teaching rather than treated as a separate outcome alone. Instructors reviewed where errors clustered and used that information to select the issues addressed at the start of the following laboratory session.

### 3.2 Comparison of final microscopic structure identification examination scores

Mean final examination score was 86.37±5.48 in the intervention group and 80.72±6.31 in the control group, a difference of 5.65 points (**Table 3**). The independent-samples *t* test yielded  $t=7.59$  ( $P<0.001$ ). The standardized between-group difference was also large (Cohen's  $d=0.96$ ).

On the common end-of-course examination, the intervention classes therefore achieved higher microscopic structure identification scores than the control classes.

**Table 3. Comparison of final microscopic structure identification examination scores**

| Group              | n   | Score, mean $\pm$ SD | Mean difference | t    | P value | Cohen's d |
|--------------------|-----|----------------------|-----------------|------|---------|-----------|
| Intervention group | 126 | 86.37 $\pm$ 5.48     | 5.65            | 7.59 | <0.001  | 0.96      |
| Control group      | 126 | 80.72 $\pm$ 6.31     |                 |      |         |           |

**Table 4. Reliability analysis of the questionnaire dimensions**

| Dimension                         | Number of items | Cronbach's $\alpha$ |
|-----------------------------------|-----------------|---------------------|
| Acceptance of the teaching model  | 4               | 0.842               |
| Learning interest and motivation  | 5               | 0.861               |
| Self-directed learning ability    | 5               | 0.887               |
| Depth of conceptual understanding | 5               | 0.873               |
| Communication and collaboration   | 4               | 0.824               |
| Overall questionnaire             | 23              | 0.912               |

**Table 5. Questionnaire dimension scores in the intervention group**

| Dimension                         | Score, mean $\pm$ SD |
|-----------------------------------|----------------------|
| Acceptance of the teaching model  | 4.43 $\pm$ 0.51      |
| Learning interest and motivation  | 4.29 $\pm$ 0.58      |
| Self-directed learning ability    | 4.36 $\pm$ 0.55      |
| Depth of conceptual understanding | 4.26 $\pm$ 0.61      |
| Communication and collaboration   | 4.18 $\pm$ 0.64      |
| Overall evaluation                | 4.30 $\pm$ 0.49      |

### 3.3 Questionnaire reliability and validity

Of 126 questionnaires issued to the intervention group, 118 were valid, corresponding to a 93.65% valid response rate. Cronbach's  $\alpha$  was 0.912 for the full 23-item questionnaire. Across the five dimensions,  $\alpha$  values ranged from 0.824 to 0.887 (Table 4).

The content-validity results were I-CVI=0.86–1.00 and S-CVI/Ave=0.94, supporting satisfactory agreement between the reviewed items and the intended evaluation content.

### 3.4 Questionnaire findings

All five questionnaire dimensions had mean scores above 4.00. Acceptance of the teaching model was rated highest (4.43 $\pm$ 0.51), followed by self-directed learning ability (4.36 $\pm$ 0.55). Communication and collaboration had the lowest dimension mean, although it remained relatively high at 4.18 $\pm$ 0.64 (Table 5).

Among the 118 valid respondents, 109 (92.37%) judged the blended model to be more effective than conventional laboratory teaching, and 104 (88.14%) were satisfied with the overall arrangement (Table 6). A total of 101 students (85.59%) reported greater learning interest and initiative. Preclass learning was reported to clarify laboratory objectives by 106 students (89.83%); 99 (83.90%) agreed that the tiered inquiry tasks improved their understanding of structure-function relation-

ships; and 96 (81.36%) felt that group discussion improved communication and collaboration.

The responses were most favorable for the overall model and for the preparatory component. They also identified specific weaknesses. In particular, some students preferred shorter microlectures and asked for additional digital-slide material and more detailed explanations after incorrect online answers.

### 3.5 Interview findings

Five themes recurred in the interviews. They largely paralleled the questionnaire findings but provided more detail about when the model was helpful and where students encountered difficulties.

#### 3.5.1 Online preparation strengthened goal orientation for laboratory learning

A common interview comment was that preparation changed what students did during the first part of the laboratory session. Under the conventional format, some students recalled arriving at the microscope without a clear starting point. After viewing the microlectures and completing the Rain Classroom questions, they were more likely to know which structures they needed to find and which distinctions deserved attention. Students with a weaker academic foundation mentioned this particularly often and described feeling less uncertain when laboratory work began.

One student stated: "In previous laboratory classes, even after the instructor had finished explaining, I sometimes still did not know where to begin. Now I watch the video before class, so at least I know which structures I need to find. My goals are much clearer when I enter the laboratory".

#### 3.5.2 Microlectures and digital slides facilitated repeated morphological learning

Students valued being able to return to the visual material outside the scheduled laboratory period. This was useful for structures that they found difficult to distinguish, including hepatic lobules and portal areas, renal corpuscles, digestive glands, and blood vessels. Rather than relying on a single explanation given in class, they could review the same feature several times and at their own pace.

Video length, however, was a frequent point of criticism. Several students considered the 20–30-min microlectures too

**Table 6. Students' main evaluations of the blended teaching model**

| Evaluation item                                                             | Agree/strongly agree, n/N | Percentage |
|-----------------------------------------------------------------------------|---------------------------|------------|
| The new model was more effective than conventional laboratory teaching      | 109/118                   | 92.37%     |
| Satisfied with the overall instructional arrangement                        | 104/118                   | 88.14%     |
| The online and face-to-face components were well integrated                 | 102/118                   | 86.44%     |
| Willing to use a similar model in subsequent courses                        | 103/118                   | 87.29%     |
| The model increased learning interest and initiative                        | 101/118                   | 85.59%     |
| Preclass learning clarified the laboratory objectives                       | 106/118                   | 89.83%     |
| Microlectures supported repeated review of key and difficult content        | 105/118                   | 88.98%     |
| Online self-assessment helped identify learning weaknesses                  | 98/118                    | 83.05%     |
| Tiered inquiry deepened understanding of structure–function relationships   | 99/118                    | 83.90%     |
| Clinical scenario tasks promoted knowledge application                      | 94/118                    | 79.66%     |
| Group discussion improved communication and collaboration                   | 96/118                    | 81.36%     |
| Preferred shorter individual microlectures                                  | 53/118                    | 44.92%     |
| Preferred additional digital slides and explanations of incorrect responses | 78/118                    | 66.10%     |

long for quick preparation or later review, even though they regarded the content as comprehensive. A preferred format was a set of 5–10-min segments, each dealing with one structure, difficult point, or common mistake.

### 3.5.3 Tiered inquiry tasks promoted understanding of structure–function relationships

The tiered tasks were described as different from laboratory work that ended once a structure had been located and named. Foundational tasks made sure that essential structures were identified, while the advanced tasks required students to compare observations and explain functional implications. The extension tasks added simple pathological or clinical contexts, requiring students to use the observed morphology in a problem rather than simply report a label.

Several students expressed the difference in practical terms: they were now expected to explain why a structure had a particular appearance and how that appearance related to function. In their view, this extra step made the laboratory exercise less dependent on memorized names and more dependent on comparison and reasoning.

### 3.5.4 Group discussion enhanced classroom participation and collaborative learning

Discussion within the groups gave students opportunities to justify what they saw rather than only record an answer. While comparing slides or preparing a report, students sometimes discovered that classmates had interpreted the same feature differently, which prompted them to recheck the specimen or their notes. Some interviewees therefore described the session as less solitary than conventional microscope work.

This benefit was not uniform across groups. Students reported weaker participation when no one had a defined responsibility. They suggested assigning roles such as observation recorder,

structure annotator, presenter, or problem summarizer so that each group member had a clear task.

### 3.5.5 The teaching platform and feedback mechanisms require further optimization

Rain Classroom was generally considered useful, but the interviews also revealed practical frustrations. Network instability and video playback occasionally interfered with online study. The more consistent concern was feedback after self-assessment: students wanted an explanation of an incorrect response and guidance on what morphological feature to review, rather than only a correct/incorrect result.

Interviewees also noted that platform completion was an imperfect measure of preparation. A student could finish or submit an activity without necessarily studying it carefully. For future use, the online work may need to be tied more visibly to the subsequent laboratory task, with additional reminders or checks for students who require more external structure.

## 4 DISCUSSION

### 4.1 The blended teaching model was associated with improved laboratory learning outcomes

The clearest between-group difference was the final microscopic structure identification score. Intervention-group students scored 5.65 points higher on average, with a large standardized effect size ( $d=0.96$ ). Because the study was not individually randomized, this difference should not be attributed to the teaching model without qualification. Nevertheless, the result is consistent with the way the intervention changed the use of laboratory time: students encountered key structures before class, and the face-to-face period could begin with specific difficulties instead of repeating all introductory material. The direction of the finding is also consistent with reports of favorable outcomes or feasibility for blended and flipped

approaches in histology and other medical education settings [13-15].

This redistribution matters in a morphology course. Finding and naming a structure is only the first step; students also need to compare features and connect what they see with function. In the intervention classes, those latter activities were built into the advanced and extension tasks. The online component was therefore not intended to substitute for microscope work. Its role was to prepare students for a laboratory session in which more time could be spent observing, comparing, explaining, and discussing. The examination result is best interpreted in the context of this combined sequence rather than as an effect of online study in isolation.

#### **4.2 Interpretation based on cognitive load theory**

The course places several demands on a novice at the same time. While viewing an unfamiliar microscopic field, a student may need to recall terminology, locate a landmark, judge spatial relationships, and decide which morphological features are functionally important. Cognitive load theory provides one way to consider why the timing of preparation may matter when these tasks are performed together.

In the present model, students saw the principal structures and common sources of confusion before using the microscope in class. They could pause or repeat those explanations online, something that is difficult to do during a fixed laboratory demonstration. By the time they examined the slide, at least some terminology and visual landmarks were already familiar. This sequencing may have reduced unnecessary processing during the initial search for structures and allowed more attention to be directed to comparison and explanation. We did not measure cognitive load directly, so this remains an interpretation rather than a demonstrated mechanism.

#### **4.3 Interpretation based on self-regulated learning theory**

The design also gave students several opportunities to judge their own preparation. The preclass requirements were visible in Rain Classroom, and self-assessment results showed students which items they had missed before the laboratory session. At the same time, instructors could see recurring errors across the class and use them when planning the opening questions for the next session. In that sense, the same platform information supported both student monitoring and instructor adjustment. This emphasis on learner monitoring is consistent with work on self-directed learning readiness and faculty-guided self-directed study in preclinical education [16, 17].

Questionnaire responses fit this pattern: 89.83% of respondents said that preclass learning clarified the laboratory objectives, and 83.05% said that self-assessment helped them recognize learning weaknesses. These are perceptions rather than

direct measures of self-regulated learning, and the interviews also showed that not every student engaged equally deeply with the online work. Because learner acceptance and engagement can vary, these perceptions should be interpreted cautiously [18]. The findings therefore suggest a useful structure for self-monitoring, but not that self-regulation was uniformly improved.

#### **4.4 Interpretation based on the revised Bloom's taxonomy**

The division of tasks can also be viewed through the revised Bloom's taxonomy. Before class, students mainly encountered terminology, representative structures, and common recognition errors. During the laboratory period, they had to use that preparation to compare specimens, explain structure-function relationships, and work through simple clinical or pathological situations.

Accordingly, the online-offline division reflected more than where learning occurred. It was also used to order the cognitive demands of the lesson. Recognition and basic understanding came first; application and analysis were emphasized later through the advanced and extension tasks. This progression was an explicit feature of the teaching design, although the study did not test individual levels of Bloom's taxonomy as separate outcomes.

#### **4.5 Interpretation based on constructivism and experiential learning**

The laboratory component also required students to check prior understanding against direct observation. Digital material could provide an initial image of a structure, but students still had to locate that structure on a specimen, decide whether their interpretation was correct, and discuss discrepancies with peers or the instructor. This aspect of the intervention is compatible with constructivist and experiential accounts of learning because understanding was revised through observation and interaction rather than accepted only from an explanation.

Students' interview comments illustrate this process. They described comparing slide findings, explaining the basis for an identification, and changing an interpretation after discussion. Group reporting then required them to make their reasoning explicit. The instructor continued to provide explanation, but also organized tasks and responded to the difficulties that emerged. Thus, online preparation and direct laboratory experience were deliberately linked rather than treated as parallel activities.

#### **4.6 Implementation challenges and directions for optimization**

The intervention also created work that is easy to overlook when considering only student outcomes. The teaching team

had to produce and update microlectures, digital slides, self-assessment items, and tiered task sheets. Student engagement with the preclass work was uneven, and platform completion could not show how carefully an activity had been studied. In addition, students repeatedly asked for shorter videos and more informative feedback after incorrect answers. These issues are important for judging whether the model can be sustained beyond a single implementation.

Several changes appear feasible on the basis of this feedback. The 20–30-min microlectures could be split into 5–10-min units so that each video has one clear purpose. Self-assessment feedback could explain why an answer is incorrect and point students back to the relevant morphological feature. The connection between the online questions and the next laboratory task should also be made explicit, which may discourage superficial completion. For group work, assigned roles and clearer criteria could reduce passive participation. At the course-team level, a shared repository would allow materials to be revised collectively instead of recreated by individual instructors.

#### 4.7 Limitations

Several limitations affect the interpretation of these findings. First, all students came from one university, and the results may differ in programs with other curricula, laboratory resources, or student populations. Second, classes rather than individual students were assigned to the two teaching conditions. Although measured baseline variables were similar, unmeasured class-level differences and confounding cannot be excluded. Third, the questionnaire captured students' perceptions and, despite satisfactory content validity and internal consistency, was not subjected to a more extensive construct-validation analysis. Finally, outcomes were measured at the end of the course. We do not know whether the score difference persisted, improved later learning in pathology or clinical courses, or translated into longer-term retention.

Future studies should therefore examine the model across more than one institution and over more than one cohort. Longer follow-up, repeated implementation across semesters, objective competency measures, and learning-process data would help determine which parts of the intervention are most useful and whether the observed effects are maintained. Longer-term evaluation can also provide information beyond immediate course outcomes, as illustrated by multi-year evaluation of innovative education modalities [19].

#### 5 CONCLUSION

Reorganizing the laboratory course so that basic preparation occurred before class and microscope time was used for targeted explanation and tiered inquiry was associated with higher end-of-course structure-identification scores in this cohort. Students also reported clearer preparation goals and generally

positive experiences with the model, while identifying practical problems with video length, feedback, and uneven participation. These findings suggest that the blended sequence may be a feasible approach to use limited histology and embryology laboratory time, but the class-level design and single-institution setting require cautious interpretation. Broader implementation and longer follow-up are needed before the model's effects can be generalized.

#### DECLARATIONS

##### Author contributions

Junfeng Jiang and Minjuan Wu contributed to the conception of the study; Ye Liu wrote the manuscript and performed the analysis.

##### Funding

This research received no external funding.

##### Data availability

The data that support the findings of this study are available from the corresponding author upon reasonable request and with appropriate protection of participant confidentiality.

##### Ethics approval and consent to participate

This study was exempted from ethical review by the Ethics Committee of Naval Medical University, because it was considered a non-invasive educational teaching reform study without human biological samples or confidential clinical data. Written informed consent was obtained from all participants.

##### Consent for publication

All authors have reviewed and approved the final manuscript.

##### Competing interests

The authors declare that they have no competing interests.

##### Acknowledgements

Not applicable.

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