frontiers | Frontiers in Education

TYPE Review
PUBLISHED 13 December 2024
DOI 10.3389/feduc.2024.1448371

OPEN ACCESS

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RECEIVED 13 June 2024
ACCEPTED 30 November 2024
PUBLISHED 13 December 2024

CITATION
Liu J, Wu Z, Lan Y-Z, Chen W-J, Wu B-X, Chen W-T and Wu H-T (2024) Flipped classroom in physiology education: where are we and where are we heading?
Front. Educ. 9:1448371.
doi: 10.3389/feduc.2024.1448371

Flipped classroom in physiology education: where are we and where are we heading?

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Flipped classroom (FC) is considered a student-centered teaching method that improves internal active learning of students and their acquisition of knowledge and skills. Among many medical majors, physiology is quite important as a bridge between basic and clinical principles. However, the complex and abstract nature of physiology causes learning stress to students. As the use of FC is widespread across various majors and principles with beneficial effects, analyzing its application in physiology is important to comprehensively evaluate its effectiveness and advantages, as well as disadvantages, and to improve the specific procedures of FC conduction. This article reviews the research on FC utilization in physiology education and summarizes its effectiveness and feedback from both educators and learners, serving as a guideline to facilitate and promote the development of FC in physiology education.

KEYWORDS

flipped classroom, physiology, active learning, education, medicine

1 Introduction

How can we improve the efficiency of learning? How to evoke a positive learning attitude? Active learning is considered an important skill, reflecting students' self-driving and self-management abilities (Möser et al., 2023). Since the proposal of the concept of a classification system for educational objectives at the annual meeting of the American Psychological Society in 1948, testing specialists have tried to develop better methods to evaluate the learning effect of students not only through examination scores but also in relation to their occupational performance. Soon after the proposal, taxonomy of educational objectives, including six major categories, inspired diverse theoretical research methodologies, demanding evaluation based on internal evidence and external criteria (McFarlane, 1981). Unlike teacher-centered traditional lectures, which is also called lecture-based learning (LBL), diverse student-centered learning methods, including flipped classroom (FC) (Yang et al., 2023), problem-based learning (PBL) (Tripp et al., 2023), team-based learning (TBL) (Mulugeta and Zemedkun, 2023), and case-based learning (CBL) (Sawang et al., 2023), have been explored and developed to improve student's internal active learning and their acquisition of knowledge and skills (Xiao et al., 2023). Among these methods, the FC is a relatively novel teaching method that involves an inverted classroom, online tools, and a shift in learning objectives from recalling knowledge to applying skills and abilities in practice, as well as a transition from teacher-centered to student-centered learning strategies (Betihavas et al., 2016).

On the other hand, medical professionals need to both memorize and apply an expanding body of medical knowledge to meet the evolving requirements of healthcare. Stimulating the

active learning attitude of medical students at different learning phases will facilitate the learning processes in terms of competency and knowledge and benefit patients finally (So et al., 2023). In the medical curriculum, physiology is a core and basic component, related to normal physiological mechanisms occurring continuously. However, the context of physiology is relatively complex for students, posing a great challenge to educators in terms of improving students' critical thinking and self-directed learning skills, as well as their active engagement in the learning processes (Haramati, 2000). The combination of pre-class online lectures or materials and the offline FC provides a flexible and feasible model for students to understand this difficult subject, while allowing educators to supervise student's learning needs and behaviors (Zhang et al., 2019). Since the introduction of this teaching strategy, the FC has been used in physiology education across different majors and academic phases. This study aimed to investigate the attitudes of educators and learners, as well as to reveal the effect of FC application. It focused on the utilization of the FC in physiology education, aiming to lay the foundation for its potential to improve students' active learning in physiological education and provide theoretical evidence for the extensive application of the FC in basic medical education.

2 The characteristics and research of physiology education

As an important branch of biology, physiology is one of the most important basic courses in medical colleges, functioning as a bridge between basic theory and clinical practice. This discipline of physiology studies the normal physiological phenomena, structure, and function of the human body at cellular, tissue, organ, and organ system levels and investigates the homeostasis regulation, interaction, and physiological changes between the human body and the environment under normal circumstances. As a basic course, physiology involves the knowledge of biochemistry, physics, biology, and so on. Before starting the physiology course, students are advised to prepare this background knowledge to gain a deep understanding of physiology, which benefits the learning of subsequent disciplines closely related to clinical practice (Li et al., 2023). In a survey conducted by the program directors of neonatal-perinatal medicine (NPM), physiology was identified as the best to lend itself to a standardized national curriculum with the highest prioritization, followed by core scholarly knowledge, pharmacology, and ethics (French et al., 2018). Therefore, physiology plays an important connecting role in the understanding, evaluation, treatment, and prevention of diseases, which is critical for clinical medical staff in daily medical work.

However, the content of physiology is vast and abstract. Importantly, students may sometimes feel bored during physiology lessons. It is difficult for students to understand and master the knowledge of physiology in a short time, let alone apply it (Surapaneni, 2023). Stimulating students' interest in physiology and further improving the quality and efficiency of the teaching process in physiology classrooms are urgent challenges for all physiology educators. Meanwhile, the shift from knowledge transmission to competency-based curricula in medical education also requires training for physiology instructors in active-learning methodologies. In India, a series of the International Union of Physiological Sciences workshops on physiology education techniques were conducted to address previous issues, presenting case-based learning, problem-based learning, and the flipped classroom as potential methodologies for improving active learning attitudes (Chandran et al., 2020).

It has been pointed out that research has the potential to deal with a spectrum of issues relevant to physiology education at all academic levels, such as helping physiologists improve their teaching skills (Modell, 1989). Kline et al. designed an experimental approach based on a question not typically addressed in general textbooks of physiology and conducted a sandwich course through a pre-lab interactive tutorial for reviewing, a lab experiment for solutions, and a post-lab tutorial for analyzing. With this sandwich course, a kind of preliminary FC, upper-level science students gained a better understanding of a complex renal response regarding homeostasis, the main concept of physiology (Kline et al., 2000). To foster critical thinking in students during physiology learning, Abraham et al. developed a clinically oriented physiology teaching (COPT) strategy for undergraduate medical students. They found that the implementation of COPT improved student performance in examinations and received positive feedback (Abraham et al., 2004). Other teaching tools, such as asynchronous online discussions and collaborative projects (Taradi and Taradi, 2004), an applied supplemental course (Richardson and Birge, 2000), Quantitative Circulatory Physiology (QCP), a mathematical model of integrative human physiology (Abram et al., 2007), a peer-to-peer escape room activity (Carrasco-Gomez et al., 2023), Anki, a free and open-source flashcard program utilizing spaced repetition for quick and durable memorization (Levy et al., 2023), and physiology quiz competition (Mistry et al., 2023), have proven to be useful in teaching physiology for memory retention and/or critical thinking.

It has been reported that the previous background in elementary physiology did not offer an advantage for learning an upper-division physiology course (Richardson, 2000), indicating the importance of the teaching process in facilitating the understanding of physiology for medical students. Interestingly, Gilkar et al. demonstrated that during learning physiology, incorporating buzz sessions into lectures is liked and preferred by both learners and educators. These sessions help enhance communication, reasoning skills, and collaborative learning among students (Gilkar et al., 2023). To offer students the opportunity to engage in the learning process, Baashar et al. used an Audience Response System (ARS) integrated into anatomy and physiology lectures. This significantly improved session quiz scores and allowed students to actively engage and participate in the teaching process by responding to questions and receiving instant, anonymous feedback from educators (Baashar et al., 2023). These findings suggest that suitable interactive teaching methods and efficient interaction between educators and learners can facilitate the learning process of students, stimulate their interests, activate their inner eagerness for knowledge, and improve their retention of knowledge accordingly. The process of the FC involves a series of planned interactions and the collection of student responses, which help engage students in the physiological learning process.

3 The description of the flipped classroom

The flipped classroom (FC), also known as the inverted classroom, was first introduced by two high school chemistry teachers, Bergmann and Sams, who uploaded their teaching videos on the internet in 2007.

In the same year, the Khan Academy was founded, offering online teaching services for the first time, which drew increasing attention to reversing traditional education (Parslow, 2012). Although the main purpose of all teaching methods is to impart knowledge to students, the FC is different from traditional education in terms of its teaching form and focus.

In LBL, the educator prepares the lecture using PowerPoint, videos, and textbooks for 2–3 class hours each time, transmitting knowledge to students during class. However, in the FC, the educator must prepare learning materials for students' self-learning before class. During classroom interaction, the educator guides the designed processes, encourages the participation of students, and provides additional explanation, while learners share their pre-class learned knowledge in groups and participate in question/answer sessions. Even after FC teaching, online interaction continues regarding homework and learning feedback (Figure 1).

Since the launch of Khan Academy, online learning materials have rapidly prospered and developed, with platforms such as Medscape,[1] XuetangX,[2] CMOOC,[3] and YouTube[4] contributing to medical education (Mahajan et al., 2019). All these online videos and courses can be used as supplementary materials for the FC, including pre-class materials for students, which facilitate the design and implementation of the FC. It is widely accepted that the FC can promote active learning in students and lead to increased academic performance in science, particularly among undergraduates. Even students who choose to skip classes and focus only on the final examination benefit from the FC. However, the workload in the FC may diminish the interest of students if there is insufficient time for pre-class and post-class activities. To summarize the previous use of the FC in physiology education, the following section will discuss its application across different majors.

1 www.medscape.com
2 www.xuetangx.com
3 www.cmooc.com
4 www.youtube.com

4 The application of the FC in physiology education

4.1 Clinical undergraduate students

Clinical medicine students encounter a wide range of patients with diverse diseases and clinical manifestations. The nature of clinical medicine dictates that its medical education focus on the integration of theoretical knowledge and practical skills, while also training students to solve clinical problems. In clinic teaching, case analysis and discussion are commonly used to provide students with appropriate exposure to real patients and diseases, helping them understand and analyze clinical problems and develop their clinical thinking and decision-making skills (Hoang and Lau, 2018; Jagpal et al., 2022). However, for basic subjects such as physiology, the clinical background of students is often quite limited, which can hinder their ability to think critically about clinical problems, although mastering basic knowledge should be the core part.

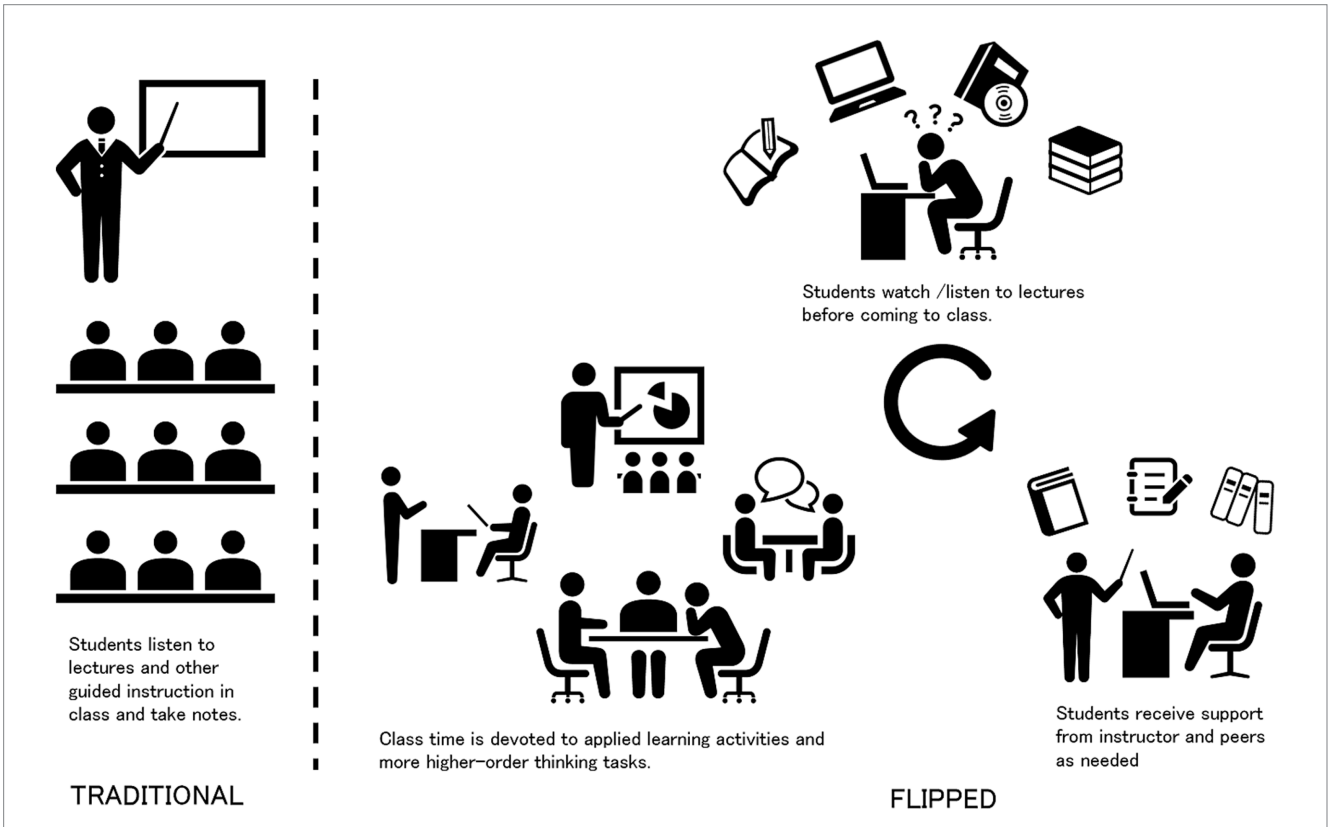

FIGURE 1
Schematic diagram of the traditional lecture versus the flipped classroom.

To improve the interests and learning outcomes of students, the reform of medical education has progressed rapidly, including the adoption of the FC. Zhang et al. developed a Small Private Online Course (SPOC) with "simple and practical" videos of less than 10 min, an extension of a Massive Open Online Course (MOOC) for physiology education. The videos consisted of concept introductions and explanations, classical examples, and a summary for systematic learning of each topic. The application of the SPOC in an FC teaching model for clinical undergraduate students revealed significantly increased test scores, along with 87.8% student satisfaction with the SPOC-based FC approach (Zhang et al., 2019). Even when divided into four grades, this three-step learning process—'pre-class self-study, in-class knowledge internalization, and after-class ability extension'—improved the percentage of students achieving high post-class scores. This improvement may be linked to the increased learning efficiency of the SPOC-based flipped classroom (FC) compared to traditional textbook learning (Zhang et al., 2019). Lu et al. used the "Xueyin Online" platform to collect students' regular performance data from the FC and traditional lecture groups, and they also evaluated their examination scores (Lu et al., 2023). The results were similar to those obtained in previous research, showing that improved learning effectiveness of students in physiology courses was correlated with their regular performance.

Another study in India also confirmed the improved effectiveness of physiology learning, with an increase in mean post-test scores in the FC group compared to the CBL model, under a competency-based undergraduate curriculum (Kumar et al., 2022). Even when the online FC model was conducted without face-to-face interaction between teachers and students, the learning effectiveness of physiology education was significantly improved by the FC model for high-achieving students (Xu et al., 2023). Liu et al. modified the process of the FC and implemented a partially flipped physiology classroom (PFC) with 71 students majoring in clinical medicine. Interestingly, students in the PFC group achieved significantly higher scores on the deep learning approach, while students in the traditional lecture group achieved high scores on the surface learning approach, indicating that the PFC model enhanced the motivation for deep learning in physiology education (Liu et al., 2024). Even among underachieving students, the mean post-test score was significantly higher than the pre-test score, and approximately 39% of students strongly agreed that the FC teaching model provided adequate and relevant materials that were easy to learn, while many students strongly believed that the FC teaching model facilitated their understanding of the subject (Shireesha et al., 2024).

For individual physiological systems, as well as gastrointestinal and renal physiology, the final exam scores improved with the flipped methodology. However, the improvements were not significant for repeaters, compared to new students with similar prior knowledge and English proficiency (Sánchez et al., 2020). Interestingly, although the improvement in examination results was significant in the flipped groups with new students, there were no significant differences in stress levels between the groups, measured by awakening salivary cortisol and self-perceived stress scores. The stress during physiology learning was proposed to be consistent across all students, regardless of the methodology used, reflecting the considerable stress experienced during the learning process of physiology (Sánchez et al., 2020). Another study conducted in Iran confirmed that the FC method improved the learning and performance of medical students in the gastrointestinal physiology course (Seidi et al., 2024). Similar results were found among Indian medical undergraduate students learning cardiovascular physiology (Prabhavathi et al., 2024). However, educators should pay more attention to the specific factors related to learning stress, as this may help students better adapt to physiology learning.

While the previous investigations focused on the short-term effect of the FC in physiology courses, Ji et al. designed a quasi-experimental study with two random classes, a traditional lecture as the control group and FC teaching as the experimental group, to evaluate both the short- and long-term effects of the FC (Ji et al., 2022). The physiology courses were all conducted in the fourth semester using different teaching methods, while the results were evaluated based on the examination scores from basic courses and clinical courses in the fourth through seventh semesters. The FC improved the students' learning effectiveness, as evidenced by a high average score in physiology, but had no effect on the other three basic courses in the same semester. However, for the basic and clinical courses in the fifth through seventh semesters, the final examination scores were significantly higher in the experimental group than in the control, except for the surgery pandect. These findings indicate the promising potential of the FC in physiology education to enhance the learning effectiveness of students, not only in physiology courses but also in follow-up medical courses (Ji et al., 2022).

According to taxonomy of educational objectives, lower-order cognitive skills (LOCS), such as knowledge and understanding, and higher-order cognitive skills (HOCS), such as application, analysis, synthesis, and evaluation, are both important for clinical medicine students (Xu et al., 2023). In addition to examination scores, Paralikar et al. evaluated the acquisition of HOCS in medical students during physiology learning with either the FC or a traditional lecture, using multiple-choice questions based on clinical vignettes (Paralikar et al., 2022). The clinical vignettes involved different physiological systems, such as long-term regulation of blood pressure and cardiovascular reflexes, which were related to the multiple-choice questions and reflected the application and analysis abilities of the students. With the personalized learning experience in the FC model, the students gained a better understanding of the course materials and developed essential HOCS (Paralikar et al., 2022).

4.2 Dental students

As we know, dental education involves a high degree of practical skill acquisition, requiring hands-on training in specific fields and a combination of theoretical knowledge and practical experience. Since the COVID-19 pandemic, the compulsory shift of dental education to online learning has posed sudden challenges for both educators and learners, with diverse learning modalities (Elbadawi, 2023). It was found that satisfaction levels with online dental education were variable, and issues such as evening lectures and technical difficulties should be addressed with tailored interventions (Elbadawi, 2023).

To address the varying performances among dental students, Xiao et al. implemented the FC model once on the topic of the autonomic nervous system in physiology education for the 3-year Doctor of Dental Surgery program. They used a flipped classroom model (1-h online presentation plus 1-h assignment with 30-min discussion) or a 2-h lecture with a 30-min question-and-answer session to replace a

3-h lecture at the end of the first quarter in this program. Although this FC model was only implemented once, the mean quiz score of the students in the flipped approach group was significantly higher than that of the non-flipped group (80% vs. 69%, with $p < 0.001$) (Xiao et al., 2018). Importantly, with content-based questions, the students in the flipped approach group had a higher mean score compared to the non-flipped group, indicating that the flipped approach improved the average performance of the students and narrowed the gap between the low- and high-performing students (Xiao et al., 2018).

4.3 Nursing students

As a practical field, nursing also relies on hands-on training based on basic knowledge. The COVID-19 pandemic affected the implementation of on-campus practical training and hospital-based clinical training (Akiyama et al., 2023). Bingen et al. designed a physiology course incorporating FC principles, self-regulation, and off-campus activities to explore the use of self-regulated learning strategies in nursing students (Bingen et al., 2019). To evoke the students' interests, they set up an introductory program called "Warm-up Week" before the semester began, focusing on how to study within the FC model and be familiar with digital tools and their learning groups. After the iterative implementation of the education program, it was found that the majority of the students preferred viewing online lectures from their teachers over learning from textbooks, which promoted their self-regulated learning process (Bingen et al., 2019). In another study, the same research group focused on the on-campus activities of nursing students during physiology FC education, finding that the FC could enhance the nursing students' confidence in and mastery of physiology (Bingen et al., 2020).

A quasi-experimental study was conducted on the respiratory system in anatomy and physiology education with two classes of 112 first-year nursing students (Joseph et al., 2021). As expected, the mean score on the final examination for the students in the FC group was significantly higher than that of the control group, reflecting better performance in the FC group. Meanwhile, the investigators also administered a brief online questionnaire to assess student satisfaction with FC compared to didactic lectures. Although 68–78% of the students agreed or strongly agreed that the application of the FC improved their learning and interest in physiology education, a small percentage, ranging from 2 to 12%, disagreed or strongly disagreed with the utilization of the FC (Joseph et al., 2021). However, in a study focused on Clinical Physiology 1 and 2, the flipped teaching model did not improve the examination scores compared to the students in the online courses. In addition, the investigators highlighted the issue of student resistance to active learning citing discomfort with uncertainty about the correct answer and related concerns (Anderson and Jacobson, 2023).

In addition to theoretical courses, the physiology laboratory is also an important component of physiology principles. To explore the utilization potential of the FC in physiology laboratory courses and its impact on students' performance, Meng et al. implemented non-traditional classrooms (NTC), combining e-learning, peer teaching, and FC principles for nursing students (Meng et al., 2022). The pre-class e-learning had a more positive effect on the students than the textbook-based preview, with enhanced mean scores on the pre-class tests and an increase in B graders. Importantly, the performance during the laboratory class also improved in the NTC group, with reduced time consumption and higher success rates, which were linked to the virtual experiments and self-paced procedural skill videos (Meng et al., 2022). The results suggest that the FC model is an effective pedagogy for physiology education, both in theoretical and laboratory courses for nursing students.

4.4 Pharmacy students

The pharmacy profession is quite different from the field of clinical medicine as it focuses on the principles and practices of drug therapy management, drug interaction, and pharmacology. Pharmacists are trained to provide medication information, counseling, and dosage recommendations to patients and cooperate with doctors for the best treatment strategies (Buhler et al., 2024). Before learning pharmacological principles, anatomy and physiology are crucial courses for pharmacy students, contributing to better retention and long-term retrieval of knowledge when facing complex cases (Dias et al., 2020).

To explore the effect of the FC on pharmacy students' physiology learning, Gopalan et al. carried out a series of studies focusing on the effect of the FC in pharmacy programs (Gopalan et al., 2020; Gopalan and Klann, 2017; Gopalan, 2019). They first reported the results for students in their professional *year 1*, after completing a preprofessional sophomore-level anatomy and physiology course. As this course covered different systems of physiology, the flipped classroom model was applied to the immune system for the first time, followed by neuro, endocrine, and cardiovascular physiology, while the final unit on renal, respiratory, and exercise physiology was covered using the unflipped format. The performance of the students on the flipped questions was found to be 17.5% higher than on the unflipped lecture questions ($p < 0.0001$). When the class was divided into the upper and lower 50th percentiles, both groups showed higher correct response rates in the flipped classroom (FC) format compared to the unflipped format, with increases of 13.91 and 12.02%, respectively. This suggests that flipped teaching benefits both higher and lower achievers (Gopalan and Klann, 2017).

Next, the researcher focused on the undergraduate sophomore-level physiology course, specifically an Introductory Physiology course, and implemented the FC with 653 students during the second year of their pre-pharmacy program. As expected, the exam scores of the students in the FC group were significantly higher compared to those in the control group, except for *semesters 3* and *4*. However, the students in the FC model group reported feeling rushed as they had to seek additional pre-class resources beyond the provided reading materials (Gopalan, 2019). Building on the previous advantages and disadvantages observed during FC implementation, Gopalan et al. aimed to refine the implementation of the FC for pharmacy students. They incorporated pre-class reading assignments and PowerPoint slides, along with ample opportunities for the students to ask questions, creating an interactive lecture format that is comparable to the FC model. To promote the participation of the students, peer evaluations were also carried out, allowing the students to assess their teammates with scores and specific explanations. During the implementation of the FC, the researchers also restructured the curriculum to reduce off-class workload based on the students'

feedback. Interestingly, the new format of the FC also showed a significant difference between the groups, with the students being able to prepare for class and gain more from the course (Gopalan et al., 2020). This series of investigations provided valuable research findings and reflections on the use of the FC for physiology education in pharmacy students, highlighting inconsistencies that should be addressed and refined during the implementation process.

4.5 Health Science undergraduate students

The Bachelor of Health Science degree is a specialized program in medical education, and graduates with this degree can be employed in assistant departments in hospitals, such as in clinical science laboratories, heart laboratories (ECG and cardiac catheter laboratories), and sleep clinics (EEG), working as clinical scientists or technicians (Yudkin et al., 2003). Meanwhile, cardiorespiratory and renal physiology is a core subject requirement in the Clinical Technologies major. Therefore, Rathner et al. enrolled ~60 students to complete advanced neuroscience before the commencement of cardiorespiratory and renal physiology in *semester 2*. Although the study was designed around a flipped classroom model, incorporating active learning questions, peer-to-peer discussions, and recruiting high-performing undergraduates as teaching assistants, it was unfortunate to find that the students rejected these flipped classroom team-based learning workshops. By midsemester, the number of students attending the workshops had decreased to only five. Therefore, the feedback from the students was largely negative, with comments such as "a lazy excuse," "too much content," "so many active learning questions," "did not like the online lecture aspect of this unit," "rushed through," "Nothing," and "a burden" (Rathner and Schier, 2020). Such results prompt deeper reflection on the application of the FC model in specific majors.

4.6 Graduate students

After completing their undergraduate education, graduates should work on improving various aspects of their post-graduation competencies, including both LOCS and HOCS (Sim et al., 2023). E-learning is a feasible method for healthcare professionals to improve their skills after graduation, with high levels of satisfaction reported (Iino et al., 2023). For the first time, Tune et al. investigated the effectiveness of the FC model for medical graduate students in physiology education (Tune et al., 2013). They employed three systems in physiology: cardiovascular, respiratory, and renal physiology. Although only 27 graduate students with similar backgrounds were enrolled in this program, the breakdown of the scores on the identical exams for the students in the traditional and modified flipped courses was significant. The students in the modified FC course achieved high scores in the cardiovascular, respiratory, and weighted cumulative sections, with an average of >12 percentage points. Importantly, the majority of the students in the modified FC course consistently watched the lecture videos before attending class. All students recommended the routine quizzes at the beginning of each session, which motivated their pre-class preparation and facilitated in-class discussions about key concepts (Tune et al., 2013). However, despite the application of the FC being reported effective in undergraduate education, the utilization of the FC in graduate medical education is less common (French et al., 2020). Importantly, such investigations should be further conducted, considering the limited sample size.

As mentioned previously, the program directors of NPM placed physiology as the highest priority within the standardized national curriculum (French et al., 2018). To measure the effectiveness of and preference for the FC in NPM fellowships within the standardized national curriculum, a multicentered equivalence, cluster-randomized controlled trial (RCT) was conducted to compare physiology education through traditional didactic methods or FC education (Gray et al., 2022). Finally, 530 fellows from 61 NPM fellowships participated in this trial, with more fellows in both groups preferring group discussions. However, the FC fellows tended to rate classroom effectiveness more positively (Gray et al., 2022), which prompted further consideration of the use of the FC in physiology education, not only for undergraduates but also for graduate fellows. With the standardized national curriculum, the FC is considered a reasonable alternative to traditional didactic methods in physiology education (Gray et al., 2022). Recently, this research group gathered educator preferences through an online survey and compared demographic data along with pre- and post-intervention educator responses (Johnston et al., 2024). Interestingly, after the intervention, the educators in both groups expressed a preference for using the FC in physiology education, citing interactivity, learner enthusiasm, and learner-centeredness as key reasons. However, challenges such as limited time, content expertise, and enthusiasm among faculty should be addressed with dedicated efforts in the future (Johnston et al., 2024).

5 The feedback of the FC from participants

French et al. specified that physiology education is an area of study benefiting from spending class time on clinical applications rather than traditional lectures, suggesting that FC is highly effective in reinforcing physiological concepts for medical students (French et al., 2020). However, in addition to the examination score and/or performance of students, the experiences of both educators and learners throughout the entire process should be considered as the teaching process becomes more complicated and demanding when moving from traditional lectures to pre-, in-, and post-class sessions. Educators have to prepare videos, upload pre-class materials online, and design pre- and post-quizzes or questionnaires for discussion. Meanwhile, learners are required to begin their learning activities several days before the practical class and invest extra time and energy, even after the practical class. Therefore, in addition to the surveys used to evaluate exam scores and/or student performance mentioned above, the following research focused on feedback regarding the FC from various perspectives.

5.1 The feedback from educators

To evaluate the attitudes and opinions of educators implementing the FC, a research group carried out a series of studies on physiology education for NPM. Firstly, French et al. conducted two educational programs that paired online videos with the FC at five institutions with fellowship programs accredited by

the Accreditation Council for Graduate Medical Education (ACGME), which were peer-reviewed accordingly. Instead of traditional lectures, the educators guided the fellows and facilitated fellow-led discussions on NPM-related clinical cases, exercises, and discussion questions after the fellows viewed the online videos independently, along with pre- and post-video assessment questions (French et al., 2018). Using open-ended questions, the educators reported that the provided materials (video modules and FC guides) reduced the time required for FC preparation. Instead of designing FC strategies and recording videos, the educators spent more time evaluating the provided materials and focusing on key physiological principles within a clinical context. Not surprisingly, the educators proposed the FC as an effective, productive, and efficient education method to collaborate with learners on their comprehension, cognition, and learning skills (French et al., 2018). Shortly thereafter, they carried out a cross-sectional study of NPM fellows and faculty educators who had e-learning experience with the respiratory physiology FC.

Among 172 respondents out of 373 eligible participants (47% response rate), positive attitudes toward educational content and case discussions were very high, as was support for the national standardization of NPM physiology education (92%). Both faculty and fellows endorsed encouraging strengths rather than challenges during the FC experience (Gray et al., 2021). With these encouraging results, they designed and carried out a randomized controlled trial (RCT) to evaluate the effectiveness and learner preferences for FC versus traditional didactics physiology teaching in ACGME-accredited NPM fellowship programs. The preference for using the FC in physiology teaching increased by 17% among FC educators, while professional satisfaction was affected by challenges such as limited available time to create and/or deliver educational content, limited content expertise, lack of enthusiasm, and lack of perceived value in education. Therefore, to promote the utilization of the FC in physiology education, these issues should be noticed and addressed, including adequate trainee preparation, educational time, and the development of facilitation skills in educators (Johnston et al., 2024). With the development of FC utilization in physiology education, they launched a mixed-methods, cross-sectional study involving faculty educators who participated in an RCT on FC physiology education in NPM. With a 25-question survey about effective strategies for FC facilitation, it was found that more than half of the educators had not received prior training in FC facilitation. In addition, unprepared learners disrupted the learning environment, highlighting the importance of clear expectations and adequate time for learner preparation. Interestingly, they reported that creating a safe learning environment and engaging learners in critical thinking would facilitate effective FC sessions (Falck et al., 2024).

In addition to facilitators and observers, Rehman et al. also consulted with the leadership of the Department and the University while conducting flipped-style teaching in the respiration and circulation module, aiming to merge case-based discussion with small-group discussions in the form of FC activity (Rehman et al., 2020). Importantly, not only the facilitators and observers but also the leadership discussed and highlighted the usefulness of the FC in connecting basic science concepts of cardiovascular physiology and pathology, through student engagement and increased participation, to build understanding of the key concepts (Rehman et al., 2020).

5.2 The feedback from learners

However, how to set up a safe learning environment? What aspects should be considered for the FC design during physiology education? The voice of learners should be paid special attention to. As pre-class activities are very important for the in-class experience in the FC, Persky et al. explored the impact of prepared materials on pre-class learning time before the FC experience. Based on the self-reported results, an average of 3.2 h was spent preparing by reading the materials in TBL format, which was positively correlated with word count, the number of tables/figures, and overall page length. Interestingly, the time spent was much greater than predicted, indicating the deep involvement of students in pre-class activities (Persky and Hogg, 2017). However, in this study, the investigators did not evaluate the association between pre-class study time and in-class performance or the exam scores of the students. Meanwhile, as the authors mentioned, the primary limitation of this study was the self-reported nature of study time, which could be addressed using online materials with monitoring or timing methods. Xu et al. provided different types of pre-class materials and conducted three formal surveys, revealing a significant divergence in student preferences for different durations of the provided pre-class videos. It was found that the selection of videos with different durations, pre-, in-, or post-class, was significantly associated with the characteristics of the videos themselves, indicating the individualization of students in the online FC. Therefore, the design and construction of online FC teaching should pay more attention to the requirements of different student groups (Xu et al., 2022). Regarding the performance of students under different teaching models, Lu et al. found a significant correlation between usual performance and final exam scores in the flipped classroom but not in the traditional teaching groups. These findings were consistent with the results of an anonymous questionnaire survey, which showed that 77.85% of students agreed that their knowledge acquisition improved with the FC teaching model (Lu et al., 2023).

The majority of survey studies have mainly focused on learners' attitudes. A survey covering online courses in physiology, pathology, and pharmacology revealed that the majority (86.9%) of students agreed to participate in polls during online classes and that 88.9% recommended using the polls again. These results provided a strong foundation for interactive teaching using the FC (Bawazeer et al., 2023). As mentioned above, 75% of Omani nursing students were satisfied with the FC approach compared to traditional lectures (Joseph et al., 2021). Along with a nine-item electronic survey, a 15-min interactive peer-led FC session on physiology education for intensive cancer medicine residents received positive feedback from the participants. The residents reported that the session sparked their interest in learning and promoted their knowledge and understanding (Zante et al., 2020). In another 5-year investigation using a deep learning approach, focusing on the FC and PBL in physiology education for students registered nurse anesthetists (SRNAs), the majority of students favored these deep learning approaches to enhance their critical thinking skills (Walker et al., 2021). During the COVID-19 pandemic, the transition from offline to online education became compulsory. Although the majority of the participants had never taken a course using a similar FC method, the 49 students who

completed a 3-week online "Basic Concepts in Neurophysiology" course reported positive feedback for the FC model, including increased study frequency during the social distancing period (Carrazoni et al., 2021). Even in a short seminar, resident participants with high learning motivation reported having increased motivation during the post-seminar period. They recognized their insufficient knowledge of operating a mechanical ventilator and the importance of learning respiratory physiology before engaging in experiential learning (Takeda et al., 2023). In contrast, after a 3-h theory session on the FC approach, 20 student participants completed a two-part questionnaire with 22 Likert-style questions and five open-ended questions. All students disagreed that the FC was more engaging than traditional lectures. Among all the participants, 80% would not recommend the FC model to a friend. The flexibility of learning and time constraints were identified as factors related to the disappointed responses (Christopher, 2018).

6 Reflection and re-thinking of the FC in physiology education

The COVID-19 pandemic significantly accelerated the development of online teaching and learning approaches. Although the shift from offline to online was feasible, the advantages and challenges should not be overlooked. Interestingly, live interaction in a mixed model is more dynamic than recorded lectures, relying on internet connectivity (Camargo et al., 2020). Hew et al. suggested that, as a promising teaching method, the FC is considered to be more effective than traditional lectures in medical education, as an overall analysis revealed favorable attitudes toward the application of the FC among medical students (Hew and Lo, 2018). The current study reviewed the investigation of the application of the FC in physiology, which is a key bridge course between basic and clinical principles. However, among the preferred uses of the FC in physiology education, the disagreeing response should also be acknowledged and addressed promptly.

One explanation for the improved positive student perception is the flexibility of pre-class activities as students have the freedom to choose the time, location, and pace that works best for them. However, the internal driving force for learning is not the same for everyone, resulting in varying levels of preparation for in-class discussions, ranging from good to poor, or even complete non-preparation, which can disrupt the learning environment (Falck et al., 2024). Another advantage is the increased active learning time in class through discussions based on clinical cases, exercises, or questions. This section of the FC places high demands on educators in terms of their knowledge of key concepts, familiarity with previewed materials, on-site control capabilities, and communication skills, all of which are essential to ensure that the class proceeds smoothly. The efficient training of educators will facilitate the comparison and evaluation of the FC process by different educators (Gray et al., 2021). In other words, individualization applies to both learners and educators, influencing the application and effectiveness of the FC in physiology education.

Other challenges include the FC itself, which requires extensive material preparation, such as designing and recording videos, developing clinical cases, formulating related questions for discussions, and creating questionnaires and assessment quizzes for videos or the FC process. Online databases offer a wealth of teaching resources that can facilitate the implementation of the FC in medical education. However, the quality of materials and their suitability for diverse groups should be evaluated. For example, MacDonald et al. introduced a video podcast that conveyed information through animated content, which was available to learners on demand and just-in-time for practice (MacDonald et al., 2020). They investigated the efficacy of this module as an educational tool for second-year medical students and found a 48% improvement in their average scores, along with positive feedback, such as "This module effectively taught concepts related to pulmonary physiology and pneumothorax" and "The animated format of this module was useful for illustrating concepts related to pulmonary physiology and pneumothorax." (MacDonald et al., 2020).

Importantly, approval from the ethics committee should be obtained before conducting the FC investigation to protect students' rights to be informed and to privacy. All of these require additional time and effort from educators, which necessitates support from the college or departments. Sufficient support will facilitate the application and refinement of the FC, making it more appealing to learners. French et al. provided a quite feasible system to promote the application of the FC in physiology education through relatively standardized mini-videos and FC guides (French et al., 2018). The materials provided to educators make the implementation of FC easier and more time-efficient. In addition, alternative learning models should be considered for learners as not all students are convinced of the potential of the FC. This presents high demands on educators, who must address the individual needs of learners.

7 Conclusion

Current evidence suggests that the use of the FC model in physiology education leads to greater effectiveness in learners compared to traditional lectures across different disciplines. The improvement effects include enhanced performance and exam scores in the short term, as well as better knowledge retention and increased active learning ability in the long term. In the future, the FC is a promising teaching method to stimulate students' intrinsic motivation for learning and strengthen academic exchange during the physiology education process. However, those implementing the FC model must be mindful of the variations in active learning attitudes among individual learners.

Author contributions

JL: Conceptualization, Data curation, Formal analysis, Funding acquisition, Investigation, Methodology, Project administration, Resources, Writing – original draft, Writing – review & editing. ZW: Data curation, Formal analysis, Investigation, Writing – original draft. Y-ZL: Data curation, Formal analysis, Investigation, Writing – original draft. W-JC: Data curation, Formal analysis, Writing – review & editing. B-XW: Writing – review & editing. W-TC: Writing – review & editing. H-TW: Conceptualization, Data curation, Formal analysis,

Funding acquisition, Investigation, Methodology, Project administration, Resources, Supervision, Writing – original draft, Writing – review & editing.

Funding

The author(s) declare that financial support was received for the research, authorship, and/or publication of this article. This work was supported by the Special Grant for Key Area Programs of the Guangdong Education Department (No. 2021ZDZX2040) and the 'Dengfeng Project' for the construction of high-level hospitals in Guangdong Province—First Affiliated Hospital of Shantou University College Supporting Funding (No. 202003-10).

Conflict of interest

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.

Publisher's note

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