Thieme

Effectiveness of Technology-Supported Ultrasound Training in Prenatal Diagnosis through an Adaptive Image Recognition Training System (AdaptUS)

Effektivität von technologieunterstütztem Ultraschalltraining bei der pränatalen Diagnostik mit einem adaptiven Bilderkennungs-Trainingssystem (AdaptUS)

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ABSTRACT

Background

Prenatal diagnostics, particularly ultrasound examinations, are vital for monitoring fetal development and detecting potential complications. Traditional ultrasound training often lacks adequate focus on image recognition and interpretation, which are crucial for accurate diagnostics. This study evaluates the effectiveness of the AdaptUS module, a technology-supported, adaptive learning platform designed to enhance ultrasound diagnostic skills in prenatal medicine.

Methods

A prospective cross-sectional study was conducted with 76 medical students from the German University Hospital, divided into an intervention group (n = 37) and a control group (n = 39). The intervention group engaged with the AdaptUS module, which adjusts its content based on in-

dividual performance. More precisely, it is a learning program for ultrasound images that, while not directly adaptive to the user's skill level, can be considered adaptive in the sense that incorrectly answered images are presented again for re-interpretation. However, the images are currently shown at random and are not yet adjusted to the user's abilities, ensuring that the challenge is consistent but not tailored to skill level. It is important to note that this is not an ultrasound image software, but rather an image interpretation software designed to help users improve their diagnostic skills through repeated exposure to medical images. In contrast, the control group did not receive this training. Both groups were assessed on their ultrasound diagnostic skills at the beginning and end of the semester using a series of 16 questions, which involved interpreting images correctly rather than a standard multiple-choice format. Statistical analysis was performed to compare the pre- and post-test results within and between the groups.

Results

The intervention group showed a significant improvement in their mean test scores, increasing from 70.9% to 86.0% ($p < 0.001$), while the control group's scores decreased slightly from 62.0% to 59.0%, though this change was not statistically significant. The difference in score improvements between the intervention and control groups was statistically significant ($p < 0.001$). The feedback from students in the intervention group was overwhelmingly positive, highlighting the system's flexibility in addressing individual learning needs and suggesting its potential for broader integration into medical curricula.

Discussion

The AdaptUS training module significantly enhances ultrasound diagnostic skills, particularly in prenatal medicine, by providing a personalized learning experience that addresses the gaps in traditional training methods. The success of AdaptUS underscores the importance of integrating adaptive learning technologies into medical education to bridge the gap between theoretical knowledge and practical application. Future research should explore the long-term impact of such training on clinical practice and consider incorporating advanced technologies like virtual reality to further enhance educational outcomes.

ZUSAMMENFASSUNG

Hintergrund

Eine gute pränatale Diagnostik, vor allem Ultraschalluntersuchungen, ist für die Kontrolle der fetalen Entwicklung und zur Erkennung möglicher Komplikationen essenziell. Beim herkömmlichen Ultraschalltraining stehen oft Bilderkennung und Interpretation, die für eine präzise Diagnostik ausschlaggebend sind, nicht genügend im Mittelpunkt. Diese Studie untersucht die Effektivität des AdaptUS-Moduls, ein technologieunterstütztes adaptives Lernprogramm, das zur Verbesserung der Fertigkeiten in der pränatalen Ultraschalldiagnostik entwickelt wurde.

Methoden

Es wurde eine prospektive Querschnittsuntersuchung mit 76 Studierenden der Medizin an einem deutschen Universitätskrankenhaus durchgeführt. Die Teilnehmenden wurden in eine Interventionsgruppe (n = 37) und eine Kontrollgruppe (n = 39) eingeteilt. Die Interventionsgruppe benutzte das AdaptUS-Modul, das seine Inhalte an individuelle Leistungen anpasst. Genau genommen handelt es sich dabei um ein Lernprogramm für Ultraschallbilder, das sich zwar nicht direkt an das Kompetenzniveau des Benutzers anpasst, aber sich dennoch insoweit adaptiert, indem es inkorrekt evaluierte Bilder für eine wiederholte Interpretation noch mal präsentiert. Im Moment werden die Bilder noch nach dem Zufallsprinzip vorgelegt und noch nicht an die Fertigkeiten der Benutzer angepasst. Damit wird sichergestellt, dass die Inhalte anspruchsvoll sind, auch wenn sie nicht an das individuelle Können des Benützers angepasst sind. Es muss hier angemerkt werden, dass es sich dabei nicht um eine Software zur Bearbeitung von Ultraschallbildern handelt, sondern um eine Bildinterpretations-Software, die entwickelt wurde, um die diagnostischen Fertigkeiten von Benutzern durch wiederholtes Vorzeigen von Ultraschallbildern zu verbessern. Die Kontrollgruppe erhielt dieses Training nicht. Beide Gruppen wurde hinsichtlich ihrer Fertigkeiten bei der Ultraschalldiagnostik am Anfang und am Ende des Semesters mithilfe einer Reihe von 16 Fragen evaluiert. Um die Fragen zu beantworten, mussten Ultraschallbilder richtig interpretiert werden, die nicht im Standard-Multiple-Choice-Format abgefragt wurden. Es wurde eine statistische Analyse durchgeführt, um die Ergebnisse vor und nach der Prüfung innerhalb und zwischen den Gruppen zu vergleichen.

Ergebnisse

Die Interventionsgruppe wies eine signifikante Verbesserung bei den durchschnittlichen Testergebnissen auf, die von 70,9% auf 86,0% stiegen ($p < 0,001$); dagegen gingen die Testergebnisse der Kontrollgruppe sogar leicht von 62,0% auf 59,0% zurück, obwohl diese Veränderung statistisch nicht signifikant war. Der Unterschied in den Testergebnissen zwischen der Interventions- und der Kontrollgruppe war statistisch signifikant ($p < 0,001$). Das Feedback der Studierenden in der Interventionsgruppe war durchweg positiv, was für die Flexibilität des Systems beim Eingehen auf individuelle Lernbedürfnisse und für dessen potenzielle Integration in den medizinischen Lehrplan spricht.

Diskussion

Das AdaptUS-Trainingsmodul trägt erheblich zur Verbesserung der Fertigkeiten bei der Ultraschalldiagnostik bei, vor allem in der Pränatalmedizin, indem es eine personalisierte Lernerfahrung vermittelt, die versucht, bestimmte Lücken in den traditionellen Ausbildungsmethoden zu schließen. Der

Erfolg von AdaptUS zeigt, wie wichtig die Integration von adaptiven Lerntechnologien in die medizinische Ausbildung sein kann, um Lücken zwischen theoretischem Wissen und dessen praktischer Anwendung zu schließen. Die zukünftige Forschung sollte die langfristigen Auswirkungen eines solchen Trainings auf die klinische Praxis untersuchen und eine mögliche Einführung fortgeschrittener Technologien wie virtuelle Realität in die medizinische Ausbildung prüfen, um damit die Ausbildungsergebnisse weiter zu verbessern.

Introduction

Prenatal diagnostics are a critical component of modern obstetrics, playing a vital role in the ongoing assessment of fetal development and overall health [1]. Among the array of diagnostic tools available, ultrasound examination is particularly important due to its non-invasive nature and its capability to provide real-time visualization of the fetus [2]. This technique is essential for the early detection of fetal anomalies, as well as for identifying potential complications that could impact both maternal and fetal outcomes. Furthermore, ultrasound is not only fundamental for the aspects outlined but also serves as an essential tool for the accurate estimation of fetal weight and the evaluation of fetal well-being. While these factors may be broadly categorized under the term "complications," their distinct importance warrants explicit mention to highlight their critical role in comprehensive prenatal assessment and clinical management.

The rapid advancement in imaging technologies has significantly transformed prenatal diagnostics, leading to a higher demand for precise and accurate diagnostic skills among medical students and doctors. As imaging technologies continue to evolve, the necessity for rigorous ultrasound education, particularly within the specialized field of prenatal medicine, has become increasingly apparent [3]. This demand underscores the importance of developing and implementing effective training programs that can equip healthcare providers with the necessary skills to perform and interpret ultrasound examinations with a high degree of accuracy.

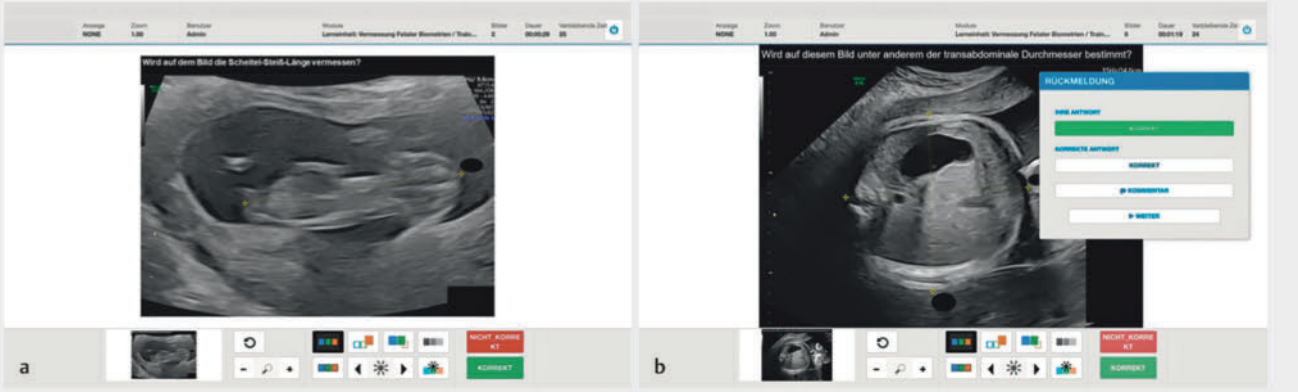
Historically, ultrasound training has predominantly been delivered through in-person classes and workshops [4]. These traditional methods are only effective to a certain extent, often falling short in addressing the comprehensive needs of modern ultrasound education. They often lack personalized, adaptive feedback which allows for targeted and continuous skill development as provided by good adaptive learning systems [5]. Specifically, there is a notable deficiency in training focused on image recognition and interpretation—two critical skills that are essential for accurate prenatal diagnostics. This gap in training is concerning because the ability to accurately interpret ultrasound images is fundamental to the early detection and diagnosis of fetal conditions. Without adequate training in image recognition, healthcare professionals may struggle to apply their theoretical knowledge effectively during clinical practice, potentially leading to missed diagnoses or incorrect interpretations.

To address these educational shortcomings, there has been a growing interest in the development and adoption of technology-enhanced training methodologies that leverage adaptive learning systems [6]. These systems are designed to personalize the learning experience, adjusting to the unique competencies and needs of each learner [7]. By doing so, they provide a more tailored educational experience that can better prepare healthcare professionals for the complexities of prenatal ultrasound diagnostics. Adaptive learning platforms offer a range of training modalities, including simulation-based training, virtual and augmented reality (VR/AR) experiences, as well as web-based platforms, all of which are essential in bridging the gaps identified in traditional ultrasound education [8].

Despite advancements in training methodologies, the "satisfaction of search" effect remains a persistent challenge in diagnostic imaging, particularly in radiology and prenatal diagnostics. This cognitive bias occurs when detecting one abnormality reduces the likelihood of identifying additional abnormalities, potentially leading to incomplete or incorrect diagnoses, which is especially concerning in prenatal care where multiple undetected anomalies can have serious implications for both mother and fetus [9]. To address this issue, ultrasound training programs need to incorporate strategies that directly target this bias, such as including cases with multiple abnormalities to encourage continuous vigilance and teaching techniques to maintain focus and prevent mental fatigue.

Rapid decision-making is another critical component of effective ultrasound diagnostics. In clinical settings, doctors must quickly and accurately interpret ultrasound images, a skill that can be significantly enhanced through simulation-based training. Such hands-on methods allow students to repeatedly practice in a controlled environment, building the confidence and competence required for timely and accurate evaluations in high-pressure situations [10].

Evaluating recognition performance in ultrasound training involves various methods that offer insights into cognitive processes. Signal Detection Theory (SDT) is often used to differentiate between true signals and noise, providing key metrics like sensitivity and specificity [11]. SDT is a framework used to quantify the ability to distinguish between information-bearing signals and background noise. It provides key metrics like sensitivity and specificity, which are essential in evaluating the accuracy of diagnostic systems. SDT also considers the decision-making process under uncertainty, accounting for both hits (correctly identifying a signal) and false alarms (incorrectly identifying noise as a signal). However, when the assumptions of SDT, such as normal distribution and equal variance, are not met, non-parametric measures like A′ offer alternative performance evaluations. A′ is a statistic that provides a robust estimate of a system's discriminative ability without relying on the parametric assumptions required by traditional SDT metrics [12]. Additionally, reaction time serves as an important indicator of cognitive processing efficiency, with shorter times



▶ **Fig. 1** The AdaptUS-E-Learning platform. **a** A screenshot presenting the question the user is prompted to answer within the learning system. **b** A screenshot showing the feedback provided to the user based on their answer, indicating whether it was correct or incorrect and offering additional explanations.

reflecting more effective recognition skills [13]. Together, these methods provide a comprehensive understanding of image recognition processes, helping to identify areas for improvement in training.

By integrating adaptive image recognition technology with advanced simulation and feedback mechanisms, AdaptUS provides a rigorous and personalized approach to ultrasound education. While the system is adaptive in that incorrectly interpreted images are revisited for further practice, it currently does not adjust image difficulty based on individual skill levels. However, this structured repetition still supports effective learning, and future advancements could further refine its adaptability. Overall, AdaptUS leverages essential elements of adaptive learning to significantly enhance the diagnostic skills of medical students and doctors in the complex field of prenatal diagnostics.

Material and Methods

Technological implementation

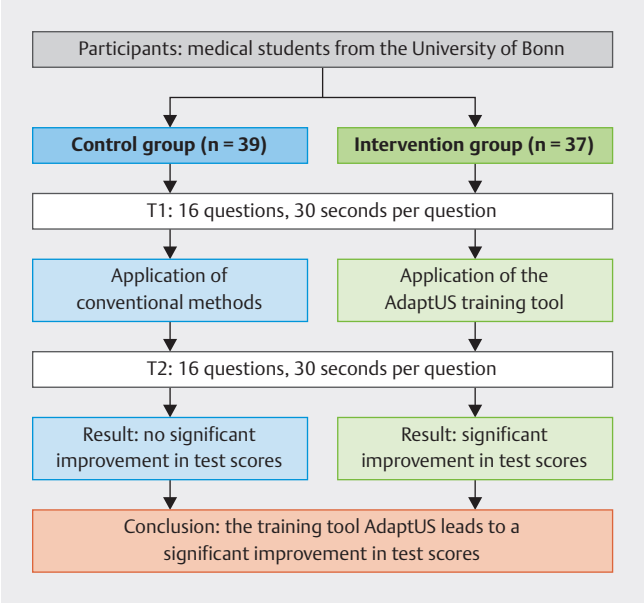
The development of AdaptUS was undertaken in collaboration with the Center for Adaptive Security Research and Applications (CASRA), a Swiss company known for its development of advanced training solutions in various domains. AdaptUS leverages the X-Ray Tutor 4 (XRT4) system (Version 2.18.1, produced by APSS Software & Services AG), which was originally developed for training in aviation security. The XRT4 system supports the visualization of single-view, dual-view, and 3 D computed tomography (CT) images, and is compatible with multiple web browsers without requiring additional plugins, thus allowing for a highly customizable and versatile training environment.

For its application in prenatal ultrasound education, the XRT4 system has been repurposed by CASRA itself and extensively modified to support the specific visual and cognitive tasks involved in ultrasound diagnostics. This web-based adaptive learning platform was meticulously designed to provide personalized training in prenatal ultrasound diagnostics. The platform dynamically adjusts its content and exercises in real-time to address the specific learning needs of each user, with a focus on critical areas such as fetal anatomy, biometry, and the identification of fetal pathologies. ▶ **Fig. 1** presents a selection of sample questions from the e-learning module.

Study design and participants

This study employed a prospective cross-sectional design with a controlled intervention to evaluate the effectiveness of an adaptive learning module specifically designed to enhance ultrasound diagnostic skills among medical students. The project was conducted at the Department of Obstetrics and Prenatal Medicine at the University Hospital Bonn and reported in accordance with the Strengthening the Reporting of Observational Studies in Epidemiology (STROBE) guidelines [14]. The study was meticulously carried out in accordance with the ethical standards of the institutional research committee and adhered to the guidelines of the 1964 Helsinki Declaration and its subsequent amendments. Ethical approval for the study was obtained from the Ethics Committee of the University Hospital Bonn, under the approval number 233/23-EP. All participants provided informed consent prior to their involvement in the study.

The study cohort consisted of undergraduate medical students from the University Hospital Bonn, specifically those in their fifth year of the six-year medical program. The participants were systematically divided into either the interventional cohort or the control group (see ▶ **Fig. 2**). Both groups were subjected to two standardized assessments: one prior to the intervention (T1) and another following the intervention (T2) with the AdaptUS system or a conventional ultrasound course. Each assessment comprised 16 questions that spanned a range of topics pertinent to ultrasound diagnostics, including fetal biometry, pathology, and anatomical structures, along with practical image interpretation tasks. These assessments were designed to evaluate participants' knowledge and diagnostic accuracy. To simulate real-world diagnostic conditions, participants were allotted 30 seconds to respond to each question. Accompanying each question was an ultrasound



▶ **Fig. 2** The study design of the adaptive image recognition system.

image, and participants were required to determine whether the provided statement or interpretation related to the image was correct or incorrect. No immediate feedback was provided after each response during this test. The assessment was conducted as a written test performed on a computer, further mimicking the conditions encountered in actual diagnostic practice.

Participants were assigned to the intervention and control groups based on their enrollment in the gynecology course, but both groups had a comparable baseline knowledge level in ultrasound diagnostics. This was ensured by selecting students from the same academic year with similar prior education and exposure to ultrasound topics. Therefore, differences in outcomes are attributable to the AdaptUS system rather than any pre-existing disparities.

Students of the interventional group, enrolled in the gynecology course, were informed that their final exam would include ultrasound images covered by the AdaptUS system, encouraging them to engage with the platform. Further, they were encouraged to rely on traditional methods, including textbook learning, in-person lectures, and direct clinical experience, rather than newer simulation-based or digital training techniques. The control group was composed of volunteers from the same academic cohort not in the course, also studied with traditional methods, without access to the AdaptUS system.

All participating students shared a common theoretical background, which included a weekly obstetrics lecture series. The lecture content was supplemented by weekly slide uploads, which students could access for review. Additionally, all students took part in a one-week, full-day internship focused on gynecology and obstetrics. This internship provided students with foundational knowledge and included hands-on examination courses, allowing them to apply theoretical knowledge in practical settings. This week concluded with an Objective Structured Clinical Examination (OSCE), designed to assess students' practical skills, alongside a written exam covering the topics discussed in the lectures.

The intervention group in this study, composed of students enrolled in the obstetrics course during the semester, was granted complimentary access to the adaptive learning program. This program was designed to offer personalized learning experiences tailored to individual needs, aimed at improving the students' ultrasound diagnostic skills. As part of the study protocol, students in the intervention group were required to complete both the pre-test and post-test assessments to measure their progress. The control group, on the other hand, did not have access to the adaptive learning program during the study period but participated in the same assessments as the intervention group. To ensure fairness and provide an opportunity for learning, the control group was offered access to the adaptive learning system after the study concluded.

To ensure consistency in data collection, both tests were conducted under standardized conditions. T1 was administered at the beginning of the semester, establishing a baseline of ultrasound competence, while T2 was administered at the end of the semester, following the intervention period for the experimental group. Participants were instructed to complete the assessments independently within the allotted timeframe, and the use of reference materials was strictly prohibited to preserve the integrity of the results.

In addition to the competence tests, demographic data including age, gender, and previous ultrasound experience were collected via a pre-study questionnaire. This data was used to control for potential confounding variables in the analysis.

Furthermore, student feedback was collected using a 7-point Likert scale questionnaire, where participants rated their satisfaction with various aspects of the training.

The results were depicted through various visual representations, including bar charts, box plots, and histograms, which were created using R Version 4.4.1 (R Foundation for Statistical Computing, Vienna, Austria) and Apple Key Note Version 14.1 (Apple Inc, San Cupertino, USA).

Statistical analysis

Statistical analysis was performed using Jamovi software (version 2.3.28). Descriptive statistical analysis of the demographic data of the participants as well as the assessment results was performed by calculating the mean and standard deviation (SD) as well as the median. The normal distribution within the intervention group was assessed using the Shapiro-Wilk test, which confirmed the appropriateness of using a paired t-test for this group. The control group's data exhibited a non-normal distribution, necessitating the use of both the paired t-test and the Wilcoxon signed-rank test for analysis. The scores of both groups at T1 were compared using a Mann–Whitney U test. To compare the differences in test scores between the intervention and control groups, an unpaired t-test was conducted. P values < 0.05 were considered statistically significant.

Results

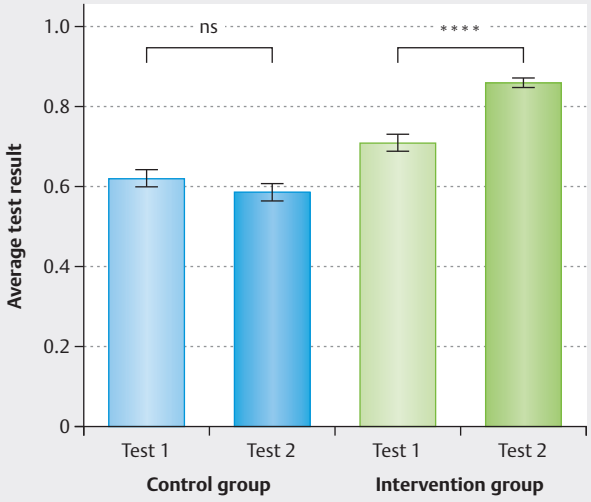
The study sample comprised 76 medical students. Complete demographic data, including age and other relevant variables, were available for all participants included in the analysis. The intervention group consisted of 37 students with a mean age of 24.9 ± 1.6 years (see ▶ **Table 1**). The ages ranged from a minimum of 23 years to a maximum of 25 years. The control group comprised 39 students (33 females, 6 males) with a mean age of 24.1 ± 1.6 years ranging from 21 to 28 years. The proportion of female students was notably high in both groups, with 84.6 % of the control group and 73 % of the interventional group identifying as female. All students enrolled in the study were in the 5th year of their 6th year medical degree.

In the assessment T1 prior to the intervention, students in the intervention group achieved a mean score of 70.9 % (SD ± 12.9 %), with a median score of 68.8 % (see ▶ **Fig. 3**). In comparison, the control group averagely reached a score of 62.0 % (SD ± 12.0 %) and a median score of 63.0 %. A Mann–Whitney U test showed a significant difference in the scores in T1 between the groups, with a U-statistic of 470.0 and a p value of 0.045, indicating that the two groups had statistically different starting points before the intervention.

Following the AdaptUS module, the intervention group's mean score improved significantly to 86.0 %, with a median score of 87.5 % and a reduced SD of ± 7.28 %. Conversely, the control group exhibited a slight decline, with a mean score of 59.0 %, a median score of 60.0 %, and a standard deviation of ± 12.0 %.

Statistical analysis demonstrated a significant enhancement in ultrasound competence within the intervention group, as evidenced by the results of a paired t-test, which yielded a p value of less than 0.001 (see ▶ **Fig. 3**). The normality of the differences in scores between pre- and post-intervention was confirmed by the Shapiro–Wilk test ($W = 0.964$, $p = 0.273$), justifying the use of the paired t-test for this analysis.

In contrast, the control group did not exhibit a statistically significant improvement in ultrasound competence. The paired t-test for the control group produced a t-statistic of 1.867 with a p value of 0.071, suggesting no significant change. Additionally, the Shapiro–Wilk test indicated that the data from the control group did not follow a normal distribution. Consequently, the non-parametric Wilcoxon signed-rank test was conducted, which also showed no significant improvement ($W = 101.0$, p value = 0.058, ▶ **Fig. 3**).



▶ **Fig. 3** Test results of control and intervention group in T1 and T2, respectively. Bars show the mean test result (in percent) and error bars indicate the corresponding standard error. Paired t-test (intervention group) and Wilcoxon-signed-rank test (control group) were performed to compare T1 and T2 results within the control and intervention groups (ns: not significant, *p < 0.05, **p < 0.01, ***p < 0.001, ****p < 0.0001).

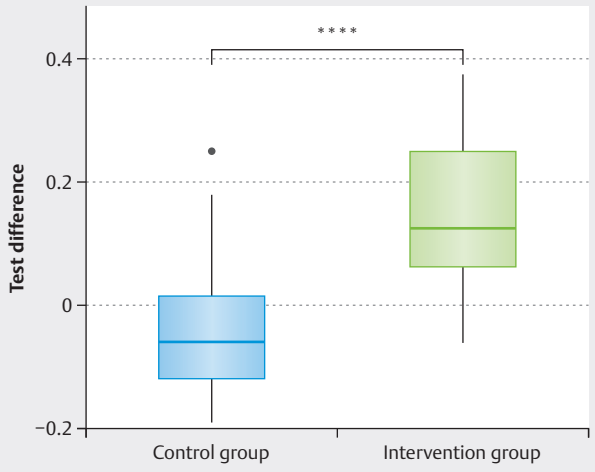
Further comparative analysis between the two groups was performed using an unpaired t-test to evaluate the differences in score improvements. This analysis revealed a significant difference in the extent of improvement between the intervention and control groups, with the t-test yielding a t-value of − 7.056 and a p value of 1.202×10^{-9} (see ▶ **Fig. 4**).

Feedback

The feedback gathered from the participating medical students regarding the AdaptUS system was generally positive, with students reporting improvements in their ultrasound diagnostic skills. Many students attributed these improvements to the system's

▶ **Table 1** Basic demographic characteristics of study participants.

Group	Number of students	Gender distribution		Mean age ± SD (years)	Assessments and Intervention
		Female	Male		
Intervention group	37	27	10	24.92 ± 1.6	T1 AdaptUS, T2
Control group	39	33	6	24.1 ± 1.6	T1, T2

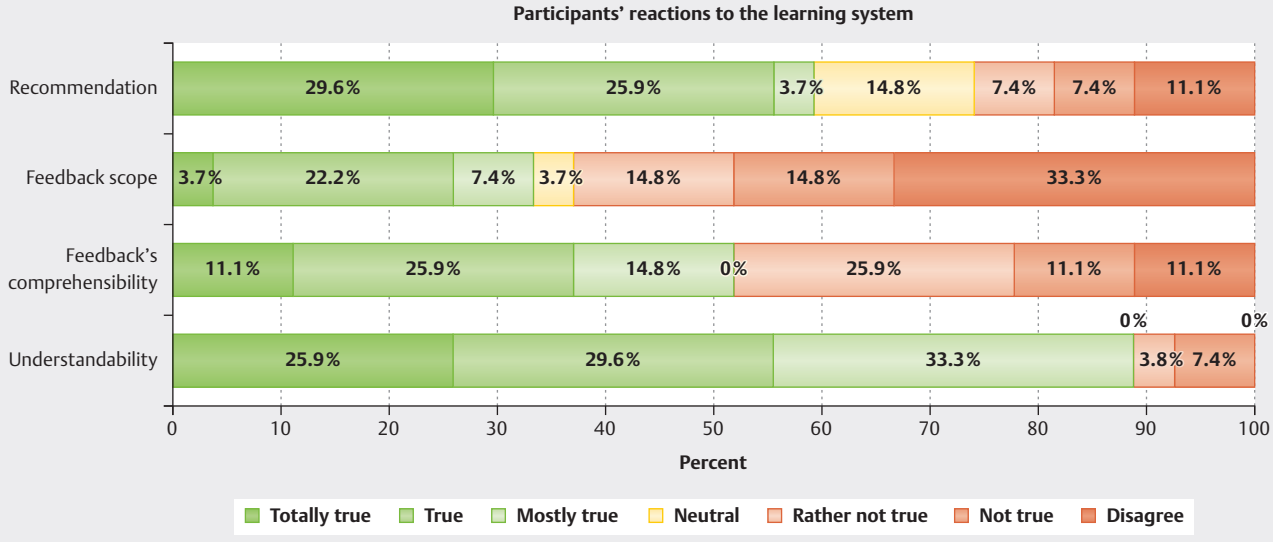


▶ **Fig. 4** Boxplots of differences between T2 and T1 for the control and the intervention group. Borders of the box indicate lower and upper quartiles; middle line indicates the median. Length of the whiskers is maximal 1.5 interquartile ranges. An unpaired t-test was performed to compare the learning improvement between the control and intervention groups (ns: not significant, *p < 0.05, **p < 0.01, ***p < 0.001, ****p < 0.0001).

flexible nature, which allowed for personalized learning by focusing on areas of identified weakness in ultrasound diagnostics. 55.29 % of the participants would recommend the learning tool for future courses and expressed their support for the broader integration of adaptive learning systems, such as AdaptUS, into the medical curriculum. Item v41 and Item v42 were perceived to be very comprehensible by the majority of participants, while Itemv43 was rated less comprehensible. The detailed responses on the learning system can be seen in ▶ **Fig. 5**.

Students also provided several suggestions for enhancing the AdaptUS system. These included incorporating more complex ultrasound images to further challenge and develop advanced diagnostic skills, as well as optimizing the system for mobile use to increase accessibility and flexibility. Additional feedback highlighted the need for detailed explanations of incorrect answers and clearer descriptions of image content during exercises. These suggestions were aimed at addressing knowledge gaps and improving understanding of ultrasound diagnostics (see ▶ **Table 2**).

In conclusion, the feedback indicated that the AdaptUS system had a positive impact on students' diagnostic skills and offered insights into potential areas for improvement to better meet the needs of learners. Implementing these suggestions may further enhance the educational value of the platform and its application in medical education programs.



▶ **Fig. 5** The figure summarizes participant feedback on various aspects of the learning system. It includes data from the Item "I would recommend the image interpretation training to other medical students", which measures the likelihood of recommending the system, with responses ranging from "totally true" to "disagree," reflecting generally positive feedback. Additionally, the figure presents data for the Items "The questions asked are understandable to me.", "The feedback on the incorrectly answered questions is comprehensible", and "The extent of the feedback is sufficient", assessing the clarity of the system and the feedback on incorrect answers. Responses also span from "totally true" to "disagree," showing overall satisfaction with both understandability and feedback. Further details regarding the feedback can be found in the attachment.

▶**Table 2** Summary of the feedback of the participants.

Feedback category	Details	Design consideration
Overall sentiment	Positive	User-centric design
Skill improvement	Significant improvements in ultra sound diagnostic skills	Detailed feedback for incorrect answers
Curriculum integration	Potential benefits for medical curriculum integration	Accommodates various learning paces and styles
Novelty of system	Novel use of adaptive image-interpretation in fetal medicine	Ensure deeper understanding of ultrasound diagnostics
Suggested enhancements	Incorporate more complex images, optimize for mobile use	Enhance effectiveness of AdaptUS tool

Discussion

The results of this study demonstrate that an adaptive imaging training module significantly enhances ultrasound diagnostic skills among medical students, particularly in the specialized area of fetal medicine. This finding is supported by the substantial improvements in test scores observed in the intervention group. The effectiveness of ultrasound as a diagnostic tool in gynecology and fetal medicine is well-documented, as it plays a crucial role in monitoring fetal development and detecting potential complications [15]. Numerous training systems have been developed to improve proficiency in ultrasound diagnostics, and the evidence suggests that structured training programs are particularly effective.

Experiential learning models focused on fetal ultrasound have shown that students can markedly improve their ability to interpret ultrasound images and conduct examinations following structured training sessions [16]. Early exposure to ultrasound technology is essential for building a solid foundation that prepares students for future clinical practice, as demonstrated by improvements in visual-spatial skills and understanding of anatomical relation [17]. For example, studies have highlighted that ultrasound training programs incorporating hands-on practice and guided sessions not only enhance students' competence in identifying and diagnosing fetal conditions but also boost their confidence in using this technology in real-world settings [18].

Beyond gynecology, the application of ultrasound learning systems across various medical disciplines underscores their versatility and importance in medical education. Structured tutorial systems, especially in general medical training, have been found to significantly improve residents' understanding and application of ultrasound techniques [19]. These systems offer targeted, structured training that bridges the gap between theoretical knowledge and practical application, which is crucial for the accurate interpretation of ultrasound images. In radiology, for example, the integration of portable ultrasound devices during anatomy sessions has been shown to significantly enhance medical students' understanding of anatomical structures and their spatial relationships by providing real-time visualization [20].

The findings of this study underscore the critical need to integrate adaptive learning methodologies within medical curricula, especially in fields that require hands-on training. Adaptive learning tools like the AdaptUS module are crucial for bridging the gap between theoretical knowledge and practical application, thereby enhancing the overall standard of patient care. These tools not only facilitate the acquisition of technical skills, such as ultrasound diagnostics, but also reinforce theoretical concepts through visual and interactive learning methods. This is particularly important in medical education, where students must transition from highly theoretical coursework to practical, hands-on experiences.

One of the key advantages of the AdaptUS program is its online accessibility, which allows students to engage with the material remotely. This flexibility is particularly valuable as it opens up the possibility for broader application and could be a critical feature in expanding future studies to include a more diverse participant pool [21]. However, the current version of the program does not include pathologies in the ultrasound findings, which is a limitation that should be addressed in future updates. Including a wider range of diagnostic scenarios would provide a more comprehensive training experience and better prepare students for real-world clinical situations.

Although feedback is provided after assessments, ensuring that students do not reinforce incorrect techniques during training remains a significant challenge. It is crucial to develop strategies that prevent the learning of incorrect practices, which could be carried into clinical settings. Future iterations of the program could benefit from incorporating a hybrid approach to error detection and correction, where incorrectly interpreted images are revisited both within the same training session for immediate reinforcement and in subsequent sessions to strengthen long-term retention and mastery.

The significant improvement in ultrasound skills facilitated by the AdaptUS training module has important implications for prenatal care. Accurate and early identification of fetal pathologies is vital for effective monitoring, timely interventions, and strategic planning for delivery. Enhanced diagnostic proficiency can lead to more reliable detection of conditions, potentially reducing the incidence of misdiagnoses [22]. This reduction in diagnostic errors not only alleviates undue stress for expectant parents but also safeguards the health of both the mother and fetus. Therefore, improving ultrasound skills through adaptive training directly enhances the quality of patient care by minimizing errors and improving anomaly detection capabilities. This, in turn, strengthens the trust between patients and healthcare providers, which is essential for managing the complexities of pregnancy.

In addition to the quantitative improvements observed, the positive feedback from students underscores the effectiveness of

the AdaptUS module in medical education. Participants highlighted the flexible nature of the system, which tailored its content to address individual weaknesses—an aspect that traditional training methods often overlook. This personalized learning experience not only enhanced their ultrasound diagnostic skills but also reinforced the theoretical knowledge necessary for accurate image interpretation, effectively bridging the gap between theory and practical application. Many students agreed that incorporating adaptive learning technology into medical curricula, particularly in fields like fetal medicine, would significantly benefit future clinicians. This sentiment is consistent with existing literature that underscores the value of early and structured exposure to ultrasound technology in building a strong foundation for clinical practice [19].

Students also provided several suggestions for enhancing the AdaptUS system, including the addition of more complex cases, extended image presentation times, clearer instructions for probe positioning, and the ability to revisit specific modules. These recommendations reflect the broader trend in medical education toward creating flexible, user-centered learning environments that accommodate various learning paces and styles. Moreover, the integration of mobile accessibility and improved text readability would support the growing demand for remote learning tools, as evidenced by the increasing popularity of online and gamified learning platforms in medical education. By addressing these areas for improvement, the AdaptUS tool could further enhance its impact, similar to other successful educational innovations that blend interactive learning with traditional methodologies. The combination of these features not only promotes the accurate interpretation of ultrasound images but also strengthens the ability to apply this knowledge in clinical settings, ultimately improving patient care outcomes.

While the findings of this study are promising, several limitations must be acknowledged. The participant pool was limited to a single medical faculty, which may impact the generalizability of the results. Furthermore, the reliance on specific tests to assess ultrasound competence might not fully capture the diagnostic spectrum required in clinical practice, highlighting the importance of hands-on training to ensure practical skills and real-world application are adequately addressed. Future research should consider incorporating practical examinations and expert evaluations to provide a more comprehensive assessment of competencies. Additionally, expanding the demographic scope of the research and investigating the long-term impact of adaptive ultrasound training on clinical accuracy and patient safety are essential areas for further study. Integrating virtual reality (VR) technologies into the learning framework could also enhance the educational impact by offering immersive and interactive training environments.

Moreover, the study did not account for prior experience with fetal ultrasound among participants in both the intervention and control groups, which may have influenced the learning outcomes. This is a key limitation, as pre-existing knowledge could lead to unequal starting points among participants. Additionally, the statistical analysis revealed a significant difference in the baseline performance (T1) between the intervention and control groups ($p = 0.045$), suggesting that the groups did not have equal starting points before the intervention. This imbalance at the outset may have influenced the observed improvements, and future studies should aim for better matching of participants or statistically control for baseline differences. Finally, the individual motivation of the students, which can significantly affect learning success, was not measured or controlled for. This could have introduced variability in the effectiveness of the intervention.

Conclusion

This study provides robust evidence supporting the efficacy of an adaptive image recognition training module in significantly enhancing ultrasound diagnostic skills, particularly in the field of prenatal medicine. The results demonstrate that medical students who engaged with the AdaptUS system showed marked improvements in their ability to accurately interpret ultrasound images compared to those who did not receive this adaptive training. These findings are particularly relevant given the critical role of ultrasound in monitoring fetal development and diagnosing potential complications in obstetrics and gynecology.

The AdaptUS module's success highlights the importance of incorporating adaptive learning technologies into medical education, especially in areas that require the integration of theoretical knowledge with practical skills. The personalized approach of AdaptUS, which adjusts content based on individual performance, effectively addresses the gaps often seen in traditional ultrasound training methods. This adaptability not only enhances the acquisition of technical skills but also reinforces the underlying theoretical concepts necessary for accurate diagnostic interpretation.

Declarations

Funding: There was no funding to declare.

Ethics approval: This study was performed in line with the principles of the Declaration of Helsinki. Approval was granted by the Ethics Committee of University Bonn (Approval Number 233/23-EP).

Consent to participate: Informed consent was obtained from all individual participants included in the study.

Contributors' Statement

TS: Conceptualization, Methodology, Writing – Original Draft, Writing – Review & Editing. SM: Study Design, Instructional Design. KK: Software Development & Technical Support. AW: Conceptualization, Resources, Writing – Review & Editing. RN: Writing – Review & Editing. JW: Writing – Review & Editing. BS: Writing – Review & Editing, Resources. FR: Conceptualization, Methodology, formal analysis, Writing – Original Draft, Writing – Review & Editing.

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Conflict of Interest

The authors declare that they have no conflict of interest.

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