



Development of Interactive Markerless Augmented Reality Media for the Human Respiratory System in Grade VIII Junior High School Science

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ABSTRACT

This study aimed to develop and evaluate an interactive Markerless Augmented Reality (AR) learning medium for the human respiratory system topic in Grade VIII Junior High School science, addressing the limitations of conventional instructional media in visualizing abstract internal physiological processes that cannot be directly observed by students. A Research and Development (R&D) approach was employed using the 4D development model (Define, Design, Develop, Disseminate), with the media developed using Unity, Vuforia Engine, Blender, and Figma and delivered as an Android application; data were collected through material and media validation questionnaires, a student practicality questionnaire, and pre-test/post-test instruments analysed using the Normalized Gain (N-Gain) formula. Material validation yielded 96.25% (Very Valid), media validation reached 98.67% (Very Valid) after two iterative revision rounds, practicality testing with 32 Grade VIII students produced 94.69% (Very Practical), and effectiveness testing yielded a mean N-Gain of 0.62, categorized as Moderate according to Hake's (1998) framework and classified as Effective enough based on the percentage criteria applied in this study, with post-test mean (85.00) surpassing the minimum mastery criterion of 80. The developed media demonstrates strong potential as a promising model for technology-based science instruction at the junior high school level; however, the findings are subject to limitations as the study was conducted within a single school, covered a single content topic, was restricted to Android platform compatibility, and was evaluated within a single instructional session, which may limit the generalisability of the results. This study contributes an empirically validated Markerless AR application specifically developed for the human respiratory system, an abstract internal physiological topic at the Grade VIII level that remains comparatively underserved in existing AR-based science education research, with the integrated evaluation of validity, practicality, and effectiveness within a single 4D development cycle offering a methodologically complete quality-assurance framework for future AR media developers.

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INTRODUCTION

The rapid technological development in the Society 5.0 era has introduced a new paradigm in education: the optimal integration of technology into the learning process. According to Ayuwandani (2024), Society 5.0 has transformed human behavior and lifestyle

across various aspects of life, including education. In responding to these challenges, the education sector plays a vital role in improving the quality of human resources. Technology integration in education is therefore essential to create high-quality and meaningful learning experiences.

In practice, however, many Indonesian junior high school teachers still depend on conventional instructional media such as textbooks, printed modules, and whiteboard-based presentations. Learning media, broadly understood, encompasses any tool or channel used to deliver instructional content from teacher to student, and its effectiveness hinges on how actively it engages learners in the process (Hasan et al., 2021). While such conventional formats remain serviceable at a basic level, their static and repetitive nature makes them increasingly inadequate for sustaining meaningful engagement in today's digital learning environment. Beyond accessibility, media selection must be deliberately responsive to students' learning characteristics and contemporary educational demands (Mukarromah & Andriana, 2022), particularly given that the current generation of learners tends to engage more productively with instructional experiences that combine visual, auditory, and simulation-based elements rather than relying solely on text and verbal explanation (Jauza & Albina, 2025).

Observations conducted at SMP Negeri 29 Padang on November 17, 2025 revealed that science (IPA) learning was predominantly teacher-centered, relying heavily on lecture methods and basic presentation slides. Students reported that the learning process was monotonous and unengaging, which diminished their motivation and resulted in poor academic performance. Assessment data showed that the average scores of Grade VIII students in two classes were 50.21 and 55.35, both substantially below the minimum mastery criterion (KKTP) of 80.

Teaching the human respiratory system poses distinct instructional challenges at the junior high school level, given that the topic encompasses not only the anatomical structures of organs such as the nasal cavity, trachea, bronchi, and alveoli, but also dynamic physiological processes such as gas exchange that occur entirely within the body. Because these processes are invisible to students and cannot be directly experienced through conventional observation, learners often struggle to construct meaningful understanding from verbal explanation or static imagery alone. Topics of this nature, which bridge students' everyday bodily experiences with deeply abstract internal mechanisms, require instructional approaches that go beyond passive reception and offer direct, experiential engagement with the content (Simatupang et al., 2023).

Augmented Reality (AR) technology offers a promising solution to these pedagogical challenges. AR superimposes digital content onto the real world in real time, enriching users' perception of their physical environment (Carmigniani & Furht, 2011). In educational settings, this technology enables virtual three-dimensional objects to be integrated into the real-world environment through smartphones or tablets, making abstract scientific concepts more tangible and directly observable (Syed et al., 2022). A more advanced form is Markerless AR, which eliminates the need for physical markers such as QR codes or printed images by relying instead on the device's camera, computer vision algorithms, and motion sensors to detect flat surfaces and determine the position and orientation of virtual objects in real time (Mishra et al., 2021). One widely adopted implementation of this approach is Vuforia Engine's Ground Plane feature, which identifies horizontal surfaces through the device camera and anchors three-dimensional virtual objects onto them without any additional physical preparation. This makes Markerless AR considerably more practical for classroom use, since neither teachers nor students need to prepare or print any supporting materials before the session begins. Empirical testing of a Vuforia-based Markerless AR application found that

ground plane detection on Android devices was achieved at a mean speed of 1.541 seconds, with a camera distance of 100 cm identified as the optimal detection range (Ladiesga & Pranata, 2026).

Prior research supports the educational potential of Markerless AR across multiple science domains. At the product development level, Ramadhan & Chamsudin (2025) demonstrated that Markerless AR media for plant structure and function achieved material validation of 94.7%, media validation of 88.75%, and an N-Gain of 0.73, while Rifqi et al. (2025) confirmed strong student reception of Markerless AR for bone anatomy visualisation. Murdhani et al. (2023) similarly showed that Unity-based AR effectively introduced students to human organ systems, and Fanmita & Guspatni (2023) reported that Markerless AR enhanced students' understanding of atomic theory evolution in the field of chemistry. At the broader evidence level, Syahbania et al. (2025) underscored that AR has been utilised as an engaging and interactive learning medium across various school settings, while Candra et al. (2025) confirmed through systematic literature review that AR holds substantial promise for science education contexts. At the meta-analytic level, Prasetya et al. (2024) found that AR learning experiences positively impact student motivation and learning outcomes, and Gil et al. (2021) established through systematic review that AR substantially enhances learner engagement across diverse educational fields. Taken together, these findings consistently indicate that Markerless AR holds strong potential as a pedagogically meaningful medium across science education contexts at multiple levels.

The theoretical justification for employing interactive three-dimensional AR in science instruction rests on two complementary frameworks. First, Dale's Cone of Experience (1969) positions contrived experiences such as simulations and three-dimensional models substantially higher in learning effectiveness than purely symbolic or verbal representations, suggesting that students who interact with anatomically realistic AR models of internal organs will develop deeper conceptual understanding than those exposed solely to textbook diagrams or teacher narration. Second, Mayer's Cognitive Theory of Multimedia Learning (2020) posits that meaningful learning occurs when learners simultaneously process verbal and visual information through separate cognitive channels, and that well-designed multimedia presentations reduce extraneous cognitive load while enhancing the integration of new knowledge into existing schemas. The interactive features of Markerless AR, specifically the rotation and zoom functions, organ labelling, and audio narration, directly operationalize these dual-channel encoding principles by enabling learners to examine each respiratory structure from multiple spatial perspectives while receiving synchronized verbal reinforcement. Together, these frameworks provide a psycho-cognitive rationale for expecting that interactive three-dimensional AR will outperform conventional two-dimensional instructional media for abstract physiological topics whose core difficulty lies precisely in their internal, invisible, and spatially complex nature.

Despite the growing body of research on Markerless AR in science education, several gaps remain insufficiently addressed. Most existing studies have focused on topics in physics, chemistry, or elementary-level biology, with comparatively few targeting abstract physiological systems at the junior high school level within the Indonesian curriculum context. Furthermore, prior studies have rarely examined the combined validity, practicality, and effectiveness of a single Markerless AR product within the same developmental cycle, with most studies reporting only one or two of these quality dimensions. The human respiratory system, which involves internal anatomical structures and dynamic physiological processes invisible to the naked eye, represents a particularly underserved topic in AR-based media development. No published

study has specifically developed and empirically validated a Markerless AR application for this topic at the Grade VIII level in Indonesian junior high schools. Responding to this gap, the present study aims to develop an interactive Markerless Augmented Reality learning medium for the human respiratory system topic in Grade VIII science at SMP Negeri 29 Padang, and to evaluate its validity, practicality, and effectiveness through a complete 4D development cycle. By addressing all three quality dimensions within a single study, this research seeks to provide an empirically grounded and practically deployable contribution to technology-based science education in the Indonesian junior high school context.

METHOD

This study employed a Research and Development (R&D) approach. Sugiyono (2022) defines R&D as a research method used to produce a specific product and to test its effectiveness. The 4D development model proposed by Thiagarajan et al. (1974) was adopted, comprising four systematic stages: Define, Design, Develop, and Disseminate. The research was conducted at SMP Negeri 29 Padang with Grade VIII students as the primary subject population. This study was conducted with institutional approval from SMP Negeri 29 Padang. Informed consent was obtained from the school principal and the relevant class teacher prior to data collection. Given that participants included Grade VIII students (minors), parental and guardian consent was secured before the pre-test and post-test instruments were administered.

Procedures and Product Development

This study was conducted at SMP Negeri 29 Padang with eighth-grade students as the research participants. The implementation of each stage of the 4D development model is described as follows.

1) Define Stage

The Define stage involved four analytical steps: (1) curriculum analysis, which confirmed that the school implements the Merdeka Curriculum and that the human respiratory system is a core topic requiring media support; (2) teacher needs analysis, conducted through structured interviews, revealing inadequacy of existing media in visualizing abstract respiratory concepts; (3) student analysis, indicating a strong preference for visual, interactive, and smartphone-based learning tools while experiencing difficulty with abstract science content; and (4) concept analysis, determining that media content should cover inspiratory and expiratory processes, respiratory organ structures and functions, respiratory mechanisms, and respiratory disorders and health.

2) Design Stage

The Design stage produced a comprehensive prototype plan. Tools selected for development were: Unity (game engine), Vuforia Engine (Markerless AR SDK), Blender (3D object modeling), and Figma (user interface design). A flowchart was constructed to map the application's navigation structure, and storyboards were created to illustrate the layout and interaction flow of each screen. The application's main menu was designed to include: Learning Objectives, Markerless AR Scan, Study Materials, About the App, and Developer Profile. The Markerless AR feature was planned to enable placement of a three-dimensional respiratory system model onto flat surfaces detected by the camera, allowing 360-degree observation and interaction with labeled organ components.

3) Develop Stage

Three-dimensional assets of the human respiratory system were modeled in Blender and exported in .fbx format for integration into Unity. User interface assets from Figma were

imported into Unity, and Vuforia's Ground Plane feature was configured to enable Markerless AR surface detection. Interactive C# scripts were written in Visual Studio Code to program all button functions, navigation, page transitions, audio playback, organ rotation, and zoom interaction features. After feature testing and iterative validation-driven revision, the final application was built as an Android .apk file.

4) Disseminate Stage

The Disseminate stage represents the final phase of the 4D development model, aimed at distributing the developed product to a broader user base beyond the immediate research setting. At this stage, the Markerless AR learning medium, which had been established as valid, practical, and instructionally promising through the preceding evaluation phases, was formally distributed to the science teacher at the research school as the primary practitioner. Distribution was accompanied by structured usage guidance and hands-on application training to ensure that the teacher was equipped to operate the media independently and integrate it effectively into regular classroom instruction.

Data Collection and Analysis

Data collection in this study employed four instruments, each designed to address a specific research objective. The instruments were developed based on relevant theoretical frameworks and validated prior to use. Material and media validity were assessed through expert judgment, while practicality and effectiveness data were collected directly from students during the trial phase. A detailed overview of each instrument, including its respondents, assessed aspects, and purpose, is presented in Table 1.

Table 1. The Blueprint of Research Instruments

No.	Instrument	Assessed Aspects	Targeted Respondent
1	Material Validation Questionnaire	Content suitability, content accuracy, presentation, language	Material Experts
2	Media Validation Questionnaire	Ease of use, interactivity and features, display and visual quality, technical performance	Media Experts
3	Practicality Questionnaire	Display, ease of use, content presentation, utility	Students
4	Pre-test and Post-test	10 items aligned to learning objectives (cognitive domain)	Students

All questionnaires employed a five-point Likert scale. The validity and practicality percentages were calculated using the following formula:

$$P = \frac{f}{N} \times 100\%$$

Where P represents the percentage score, f is the total score obtained, and N is the maximum possible score. The results of Equation (1) were then classified based on the validity and practicality criteria. The classification categories are presented in Table 2 to ensure a consistent interpretation of the scores.

Table 2. Validity and Practicality Test Criteria.

Interval	Criteria
81% – 100%	Very Valid / Very Practical
61% – 80%	Valid / Practical
41% – 60%	Fairly Valid / Fairly Practical
21% – 40%	Less Valid / Less Practical
0% – 20%	Not Valid / Not Practical

The effectiveness of the learning media was measured using the Normalized Gain (N-Gain) formula:

$$N - Gain = \frac{Posttest\ Score - Pretest\ Score}{Maximum\ Score - Pretest\ Score}$$

The N-Gain scores were classified according to the criteria proposed by Hake (1998), as presented in Table 3.

Table 3. N-Gain Interpretation Criteria

N-Gain Score	Criteria
$g > 0.70$	High
$0.30 \leq g \leq 0.70$	Moderate
$g < 0.30$	Low

The calculation results are then expressed as percentages and analyzed based on the product effectiveness criteria according to Kawuwung & Mamahit (2023), as presented in Table 4 below:

Table 4. Criteria for Interpreting N-Gain Effectiveness

Percentage %	Criteria
<40	Ineffective
40 - 50	Less effective
56 - 75	Effective enough
>76	Effective

RESULTS AND DISCUSSION

Result

The development process produced an interactive Markerless Augmented Reality learning medium for Grade VIII science, specifically on the human respiratory system topic at SMP Negeri 29 Padang. The final product, developed into an Android application, was constructed through a combination of digital tools, namely Unity as the main development platform, Vuforia Engine for Markerless AR functionality, Blender for creating three-dimensional objects, and Figma for designing the user interface. The development was carried out systematically through the 4D model, which provided a structured framework for producing an educational medium that was both pedagogically relevant and technically functional. In the define stage, the researcher identified that science learning in the school was still dominated by conventional methods, while students had difficulty understanding abstract respiratory system concepts such as organ structures and gas exchange processes. In the design stage, a flowchart and storyboard were prepared to organize the application structure, including the learning objectives, AR scan feature, learning materials, application information, and developer profile. During the development stage, the three-dimensional respiratory system model was created and integrated into the application, along with interactive features such as rotation, zoom, audio guidance, and surface detection without markers. The dissemination stage was conducted after the product had passed validation, practicality testing, and effectiveness testing, showing that the media was suitable for classroom use and capable of supporting students' understanding of abstract science content.

Validation Results

Material validation was conducted by the Grade VIII IPA teacher at SMP Negeri 29 Padang. The four assessed aspects, namely content suitability, content accuracy, presentation, and language, yielded an overall validity percentage of 96.25%, categorized as Very Valid, with no revision recommendations. Media validation was carried out by two expert validators through two rounds of assessment. Following iterative revisions addressing recommendations such as the addition of 3D object rotation, organ labels, font size adjustments, and a music on/off

feature, both validators reached a final validity percentage of 98.67%, categorized as Very Valid. A summary of the validation results is presented in Table 5.

Table 5. Summary of Validation Results

No.	Validator	Percentage	Criteria
1	Material Experts	96.25%	Very Valid
2	Media Experts I	98.67%	Very Valid
3	Media Experts II	98.67%	Very Valid

These validation outcomes confirm that the Markerless AR media meets scholarly quality standards for both content and technical aspects. Valid AR learning media is generally expected to address multiple quality dimensions, including visual display quality, interface clarity, AR feature stability, and interactivity, all of which were systematically addressed in this study (Lestari & Dafik, 2025).

Practicality Test Results

Practicality testing was conducted with 32 Grade VIII students at SMP Negeri 29 Padang during a regular IPA learning session. Students operated the application independently and subsequently completed the practicality questionnaire. Results across all four aspects are presented in Table 6.

Table 6. Practicality Test Results by Students

No	Aspect	Percentage	Criteria
1	Visual Appearance	96.09%	Very Practical
2	Ease of Use	92.19%	Very Practical
3	Content Presentation	94.79%	Very Practical
4	Usefulness	98.75%	Very Practical
Average		94.69%	Very Practical

A practicality score of 94.69% indicates that students found the developed Markerless AR media straightforward to operate and genuinely accessible within a regular classroom setting. The application was tested on 32 students' personal Android devices, each meeting the minimum technical requirements of Android 10.0 or higher, at least 4 GB of RAM, an octa-core processor, a minimum 8-megapixel camera, and gyroscope and accelerometer sensor support, all of which are necessary for optimal Markerless AR surface detection and three-dimensional visualisation. Vuforia Engine's Ground Plane feature, which was employed in this study, detects horizontal surfaces through the device camera and anchors virtual objects in the user's physical environment without requiring any printed marker or QR code. Although minor variation in surface detection speed was observed across devices, this is consistent with empirical findings reporting that ground plane detection on Android devices averages 1.541 seconds and is influenced by factors such as camera distance and lighting conditions (Ladiesga & Pranata, 2026).

Effectiveness Test Results

Effectiveness was evaluated using pre-test and post-test instruments, with the N-Gain Score calculated for each of the 32 students. Pre-tests were administered before the learning session and post-tests immediately following the use of the Markerless AR media. A summary of results is presented in Table 7.

Table 7. N-Gain Effectiveness Results

Indicator	Score
Average Pre Test Score	60.94
Average Post Test Score	85.00

Average N-Gain	0.62
Criteria	Moderate

The mean pre-test score of 60.94 increased to 85.00 on the post-test, yielding a mean N-Gain of 0.62 (62%), categorized as Moderate improvement and classified as Effective enough. Seven students achieved High improvement (N-Gain ≥ 0.75), while no student fell into the Low improvement category, suggesting that learning outcome improvements were observed consistently across all student achievement levels within this trial.

The learning gains observed in this study are broadly consistent with the outcomes reported in comparable AR-based science education research. Three-dimensional AR media has been shown to meaningfully improve student motivation and academic performance among digitally native learners (Carolina, 2022), and AR-based instructional tools have similarly been found to strengthen elementary students' grasp of science concepts through immersive visual exploration (Muzanni et al., 2024). These convergent findings suggest that the positive outcomes recorded in this study are not incidental but reflect a broader pattern of AR effectiveness across different educational levels and content areas.

The specific gains achieved in this study can be partially attributed to the interactive design features embedded in the developed media. The rotation and zoom functions enabled students to examine each respiratory organ from multiple angles, supporting the kind of spatial reasoning that static diagrams cannot facilitate. Simultaneous audio narration reinforced the visual content through a second sensory channel, consolidating understanding beyond what text alone can achieve. This design approach directly responds to the nature of respiratory system content, which demands experiential engagement precisely because the processes involved, gas exchange, diaphragm contraction, and pressure-driven airflow, occur inside the body and remain inaccessible to direct observation (Simatupang et al., 2023). Learning experiences built around simulated, hands-on interaction with anatomically realistic models have long been regarded as more effective than purely symbolic or verbal instruction for content of this kind (Dale, 1969), and the outcomes of this study provide empirical support for that theoretical expectation.

Final Product Features

The Main Menu screen provides access to five core features of the application: (1) Capaian Pembelajaran, which presents the learning objectives aligned with the Grade VIII Merdeka Curriculum for science; (2) Scan Markerless AR, the primary AR feature that uses the device camera to detect flat surfaces and place an interactive 3D model of the human respiratory system, which students can rotate 360 degrees and zoom in and out for detailed examination of the organs; (3) Materi, which provides structured textual and visual information about the respiratory system; (4) Tentang Aplikasi, which explains the application's purpose, development background, and technical information; and (5) Profil Pengembang, which displays the developer profile. Navigation between menus is intuitive and supported by audio feedback, and a music on/off toggle is available on all screens.

The Markerless AR feature represents the core innovation of this media. Unlike conventional marker-based AR, this feature does not require a printed image or QR code; instead, it detects flat surfaces through Vuforia Engine's Ground Plane technology. Once a surface is detected, a fully animated 3D model of the human respiratory system, including the nasal cavity, pharynx, larynx, trachea, bronchi, bronchioles, and lungs, is rendered in the user's physical environment. Each organ is labeled with its name and function, and students can interact with the model through intuitive touch gestures, enabling spatial understanding that is not achievable through conventional two-dimensional instructional media.



Figure 1. Media Display

Discussion

From the content perspective, the material validity score of 96.25% demonstrates that the learning content was accurate, curriculum-aligned, and appropriately sequenced for Grade VIII learners. The human respiratory system encompasses structures and processes that are inherently invisible to the naked eye, including gas diffusion across the alveolar membrane, ciliary movement in the trachea, and the coordinated contraction of the diaphragm and intercostal muscles, all of which pose significant comprehension challenges when conveyed solely through two-dimensional illustrations or verbal description. The three-dimensional AR presentation employed in this study directly addressed this limitation by rendering anatomically accurate, interactive organ models in the user's physical environment. This approach aligns with the theoretical framework of Dale's Cone of Experience (1969), which positions contrived simulations considerably higher in learning effectiveness than purely symbolic or verbal representations. Comparatively, Ramadhan & Chamsudin (2025) reported a material validity

score of 94.7% for their Markerless AR application on plant structure and function at the elementary level, while Rifqi et al. (2025) similarly confirmed high expert content validity for a bone anatomy AR application. The present study's score of 96.25% is marginally higher than both, which may be attributed to the use of a practising Grade VIII IPA teacher as the material validator, an individual with direct familiarity with the Merdeka Curriculum requirements, combined with an iterative content review process that ensured every learning objective was explicitly addressed in the media content. It should be acknowledged, however, that material validation in this study was conducted by a single expert. While the validator's direct familiarity with the Merdeka Curriculum and Grade VIII science instruction is a relevant strength, the robustness of the content validation would be further enhanced in future studies by involving an additional external expert in science education or biology, whose perspective would complement curriculum-alignment judgements with deeper subject-matter scrutiny.

In terms of media quality, the final media validity score of 98.67% and the student practicality score of 94.69% collectively reflect a design that was both technically rigorous and user-responsive. The two-round iterative validation process, through which both media validators provided specific recommendations before reassessing the revised product, resulted in targeted improvements including the addition of a 3D object rotation feature, organ labelling, font size adjustments, and a music on/off toggle. These refinements directly strengthened the application's usability and navigability. When compared with analogous studies, Ramadhan & Chamsudin (2025) reported a media validity of 88.75% using a single-round validation process, while Yanti et al. (2025) employed the User Experience Questionnaire (UEQ) to evaluate a Markerless AR central nervous system application and reported scores in the "good to excellent" range. The present study's media validity score of 98.67% exceeds both, suggesting that the two-round iterative revision protocol adopted here is a procedurally superior approach for achieving high technical and design quality. On practicality, the student score of 94.69% indicates that Grade VIII students were able to operate the application independently with minimal instruction, and rated all four assessed dimensions, namely visual appearance, ease of use, content presentation, and usefulness, as Very Practical. Notably, the usefulness dimension obtained the highest score at 98.75%, which implies that students perceived the media as genuinely supporting their learning rather than functioning merely as a novelty. This finding reflects the view that genuine practicality is achieved when students perceive a learning tool as not only accessible but meaningfully supportive of their educational goals (Cahaya et al., 2024).

The effectiveness results further confirm the instructional value of the developed media. The increase from a pre-test mean of 60.94 to a post-test mean of 85.00, yielding a mean N-Gain of 0.62, indicates that students demonstrated observable learning outcome improvement following a single session using the AR application. Critically, the post-test mean of 85.00 exceeded the school's minimum mastery criterion (KKTP) of 80, indicating that the intervention was not merely effective in a relative sense but sufficient to bring the majority of students to the expected competency threshold. The N-Gain of 0.62 falls within the Moderate category according to Hake (1998) criteria and is classified as Effective enough based on the applied percentage criteria. When situated alongside comparable studies, Ramadhan & Chamsudin (2025) reported a higher N-Gain of 0.73 for their Markerless AR plant structure application at the elementary level. The comparatively moderate N-Gain in the present study may be partially explained by the inherently greater conceptual complexity of the human respiratory system, a topic that demands understanding of not only anatomical structures but also dynamic physiological mechanisms such as pressure-driven airflow and alveolar gas diffusion, relative to

plant morphology, which is primarily descriptive and structural. Furthermore, a single-session trial design, while standard in development research, limits cumulative exposure and precludes the consolidation benefits associated with repeated practice. This interpretation is supported by Prasetya et al. (2024) meta-analytic evidence indicates that AR learning effectiveness is positively moderated by both duration and frequency of exposure, suggesting the present N-Gain of 0.62 likely represents a conservative estimate of the media's full instructional potential under conditions of sustained, curriculum-integrated use.

Taken together, the findings of this study make several interconnected contributions to the literature on AR-based science education in the Indonesian junior high school context. First the study extends prior work by providing empirical evidence that Markerless AR can be developed as a valid, practical, and instructionally promising medium specifically for internal physiological topics, a content category that has received comparatively less attention in AR development research than structural, geometric, or elementary-level biological topics (Ramadhan & Chamsudin, 2025; Rifqi et al., 2025; Lestari & Dafik, 2025). By focusing on the human respiratory system, a topic defined by processes that are both abstract and physically invisible, this study fills a domain-specific gap in the AR-based instructional media literature and provides evidence that the benefits of Markerless AR generalise beyond the topic types previously studied. Second, the study demonstrates the methodological value of conducting a complete three-dimensional quality evaluation covering validity, practicality, and effectiveness within a single 4D development cycle. Many comparable studies report only one or two of these quality dimensions (Yanti et al., 2025; Nadila et al., 2024), limiting their generalisability as quality-assurance frameworks. The present study's integrated approach offers a potentially replicable procedural model that future AR media developers can adopt to produce more comprehensively evaluated products. Third, the iterative two-round expert validation process employed here yielded media validity scores of 98.67%, which is notably higher than the single-round validation scores reported by Ramadhan & Chamsudin (2025) at 88.75%, suggesting that iterative consultation with expert validators is a critical procedural factor in achieving high-quality AR educational media. Notwithstanding these contributions, the study's limitations must be acknowledged: the research was restricted to a single school, a single content topic, Android-only compatibility, and a single instructional session. Furthermore, the use of a single material validator, while contextually appropriate given the validator's curriculum expertise, represents a methodological limitation with respect to the breadth of content scrutiny applied.

CONCLUSIONS

This study successfully developed an interactive Markerless Augmented Reality learning medium for the human respiratory system topic in Grade VIII Junior High School science, following the 4D development model. The media was built using Unity and Vuforia Engine, with 3D assets created in Blender and UI components designed in Figma, yielding a fully functional Android .apk application. Material validation reached 96.25% (Very Valid), media validation achieved 98.67% (Very Valid) after two rounds of iterative expert revision, practicality testing produced 94.69% (Very Practical), and effectiveness testing yielded a mean N-Gain of 0.62, categorized as Moderate according to Hake (1998) framework and classified as Effective enough based on the percentage criteria applied in this study. These findings confirm that the developed Markerless AR media is valid, practical, and effective as an innovative learning medium for abstract science concepts at the junior high school level. More broadly, this study suggests that a two-round iterative expert validation protocol is associated with higher media quality outcomes

compared to single-round approaches reported in comparable development studies, and that Markerless AR is a potentially effective instructional medium specifically for internally abstract physiological topics that are otherwise difficult to convey through conventional two-dimensional representation, though broader implementation and extended trials are needed to confirm these findings across diverse contexts. Notwithstanding these contributions, the study's findings should be interpreted within its scope: the research was conducted at a single school, addressed a single content topic, was restricted to Android platform compatibility, and involved a single instructional session. Future studies should pursue broader multi-school implementation, extended curriculum-integrated use, and cross-platform development to more fully establish the generalisability and long-term instructional impact of Markerless AR for junior high school science education.

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AUTHOR CONTRIBUTION STATEMENT

GMJ contributed to the conceptualization of the study, product development, data collection, data analysis, and preparation of the original manuscript draft. AH contributed to research supervision, methodological guidance, project administration, and manuscript review and editing. FM contributed to academic guidance, validation support, interpretation of findings, and manuscript review and editing. R contributed to validation support, technical feedback on the developed media, interpretation support, and manuscript review and editing. All authors have read and approved the final version of the manuscript and agree to be accountable for the accuracy and integrity of the work.

AI DISCLOSURE STATEMENT

The authors declare that no generative artificial intelligence tools were used to conduct the research, analyze the data, interpret the findings, or generate the substantive content of the manuscript. The learning media was developed using Unity, Vuforia Engine, Blender, and Figma as technical development and design tools, while the research design, product development decisions, data collection, data analysis, interpretation, and manuscript preparation were carried out by the authors. Any use of digital software in this study was limited to media development, interface design, three-dimensional object creation, and application implementation, and did not replace the authors' scholarly judgment or responsibility.

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