Feasibility and Reproducibility of a Structure-Guided Deep Learning Model for Automatic Detection of the Standard Sagittal Plane in First-Trimester Nuchal Translucency Assessment Using 3D Ultrasound

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Abbreviations

2D, 2-dimensional; 3D, 3-dimensional; AI, artificial intelligence; BMI, body mass index; CNN, convolutional neural network; CRL, the crown–rump length; DL, deep learning; MSP, mid-sagittal plane; NT, nuchal translucency

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Objectives—Accurate nuchal translucency (NT) measurement for assessing the risk of fetal genetic abnormalities requires precise acquisition of the mid-sagittal plane (MSP). However, achieving an appropriate MSP is technically challenging due to anatomical variability and operator dependence inherent in conventional 2-dimensional (2D) ultrasound. This study aimed to develop and validate a novel deep learning algorithm for automated fetal MSP extraction from 3-dimensional (3D) ultrasound volumes utilizing intracranial structure segmentation to overcome the limitations of conventional methods reliant on facial landmarks.

Methods—In this prospective study, we developed and evaluated "3D MSP-net," a convolutional neural network (CNN)–based model for automated MSP extraction, involving singleton pregnant women undergoing first-trimester NT screening. Using achieved 3D volume data, 3D MSP-net was validated against the conventional 2D manual method and a commercially available rule-based automated system (5D NT™). Two maternal-fetal medicine (MFM) specialists independently assessed the resulting MPSs to determine the performance for demonstrating the feasibility and high reproducibility of the 3D MSP-net.

Results—3D MSP-net achieved an MSP extraction success rate of 91.6%, comparable to that of the conventional 2D manual method and significantly superior to the rule-based 3D algorithm. NT measurements were comparable between the conventional 2D manual approach and MSPs derived from 3D MSP-net (1.4 ± 0.5 mm versus 1.4 ± 0.4 mm; $p = .444$). These results were reproducible on external validation. Moreover, the 3D MSP-net maintained robust performance even under challenging conditions, such as increased maternal body mass index and different scan deviation angles.

Conclusion—The 3D MSP-net, our artificial intelligence (AI) model that utilizes intracranial landmarks for MSP reconstruction, enables improved efficiency, standardization, and reliability for first-trimester fetal screening addressing a key challenge in prenatal diagnostics.

Key Words—3-dimensional ultrasound; artificial intelligence; automatic standard plane extraction; deep learning; mid-sagittal plane; nuchal translucency

Fetal nuchal translucency (NT) thickness is one of the most effective single markers for first-trimester aneuploidy screening.[1–3] It also facilitates the detection of structural abnormalities, genetic syndromes, and conditions such as twin-to-twin transfusion syndrome.[4–6] Its cost-effectiveness and accessibility make NT scan a key part of integrated screening strategies.[5,7,8]

Accurate and reproducible NT scan is highly dependent on strict adherence to standardized imaging guidelines.[9,10] A key requirement is the acquisition of a precise mid-sagittal plane (MSP) of the fetal head with clear visualization of anatomical landmarks, such as the echogenic tip of the nose, anterior rectangular shape of the palate, and translucent diencephalon in the center.[11]

Achieving an optimal MSP using conventional 2-dimensional (2D) ultrasound is technically challenging because of anatomical complexity, fetal position, and operator dependency. In contrast, 3-dimensional (3D) ultrasound enables volumetric reconstruction, offering a promising alternative approach to improve standardization.[12–16] Consequently, several studies have proposed models for MSP extraction from 3D ultrasound volumes and commercial software functions are available to locate the MSP from 3D ultrasound data.[12,13] However, most existing methods rely on rule-based algorithms that are prone to low accuracy and image artifacts, thereby limiting their reliability and clinical applicability in real-world practice.

To overcome these limitations, artificial intelligence (AI) and recent advancements in deep learning (DL) have opened potential avenues for automated volume manipulation and image reconstruction.[17,18] However, the development of DL algorithms for fetal MSP extraction poses several challenges.[13,19,20] First, training models to accurately identify small anatomical structures, such as the nasal bone or skin tip, is difficult because of the inherent presence of artifacts, noise, and heterogeneity in fetal ultrasound images.[21,22] Second, the performance and reliability of these algorithms are highly dependent on the quality of the initial acquisition plane. Suboptimal fetal head positioning can obscure key facial landmarks, precluding the establishment of the necessary seed points for effective volume manipulation.[23]

Considering these challenges, we aimed to develop and validate a novel AI model based on a convolutional neural network (CNN) for the automated extraction of standard MSP from 3D ultrasound with a standardized protocol for optimal 3D volume acquisition.

Materials and Methods

Participants

This prospective study was conducted at 2 referral centers within the Yonsei University Health System (Severance Hospital and Yongin Severance Hospital), Republic of Korea, between June 2022 and August 2023 in singleton pregnant women undergoing first-trimester screening including NT measurements for prenatal genetic evaluation. The study was approved by the institutional review board (IRB No. 4-2022-0068) and conducted in accordance with the Declaration of Helsinki of 2013. All participants were referred by maternal–fetal medicine specialists for clinically indicated screening. Written informed consent was obtained prior to the ultrasound examination. Standard NT screening was subsequently performed. Maternal medical history and gestational age were identified from institutional patient records.

Data Acquisition and Implementation Details

All 2D and 3D ultrasound examinations were performed between 11 and 13 weeks of gestation when the crown–rump length (CRL) was 45–84 mm. Fetuses with an increased NT thickness (>3 mm), in prone position, presenting major congenital anomalies, or part of a multiple pregnancy were excluded to avoid confounding effects from marked anatomical deviation and to ensure rigorous and unbiased assessment.

Transabdominal ultrasound was conducted using the Hera W10 and Z20 ultrasound systems (Samsung Medison Co., Seoul, Korea) by 2 experienced operators (H.K and S.K) adhering to the Fetal Medicine Foundation protocol for NT measurement.[24] Both the 2D and 3D scans were obtained by the same operator for each participant.

Standard 2D transabdominal imaging was performed using a Samsung CA1-7A curved-array transducer (1–7 MHz). Standard MSP was acquired according to the criteria described by Nicolaides et al.[3,9,10] If an appropriate MSP could not be obtained within 20 minutes, the patient was asked to ambulate for a while for a repeat attempt. The time taken for the scan was recorded after the fetus adopted the optimal scanning position. 3D volumes were acquired using a 1–8-MHz volume transducer and stored for developing AI algorithm and subsequent analysis. Based on the analysis of failure cases identified in pilot study (Table S1), optimal 3D volume acquisition guidelines were established as follows:

- Acquire the volume using a sagittal sweep that includes both the fetal head and thorax.
- Ensure that the fetus is in a neutral position with clear differentiation of the fetal skin.
- Avoid acoustic shadowing over the NT region.
- Position the transducer parallel to the nasal bone in the supine position when the fetus faces the transducer.
- Scan angle ≤25° from the MSP.
- Scan quality: high–extreme.
- Perform volume acquisition only when the fetus is not moving.

The acquired 3D volumes from Severance Hospital were utilized for the development of the AI algorithm and subsequently for its validation through comparison with established methods.

A total of 948 datasets were partitioned into training, validation, and test sets in an approximate 8:1:1 ratio. Specifically, 800 volumes were allocated for model development (training and validation), while 148 volumes were used for testing. The training set was used to optimize model weights, while the validation set was used for hyperparameter tuning and model calibration. Data augmentation was performed using random adjustments to contrast and brightness, as well as rotation and horizontal flipping. Ground-truth (GT) annotations for key anatomical landmarks essential for MSP identification—including the fetal head, NT, diencephalon, nasal bone, and tip—were independently generated for each case by 2 experts using the open-source software ITK-SNAP (www.itksnap.org). All annotations were subsequently reviewed and validated by 2 additional experts whom are maternal-fetal medicine specialists with more than 10 years of clinical experience specifically in prenatal ultrasound and fetal diagnosis (J.Y.K and Y.J.J) to ensure consistency and accuracy. The 148 volumes reserved for testing were strictly independent of the training and validation processes. This testing set was subdivided into an internal validation set ($n = 95$), and an external validation set ($n = 53$), acquired from Yongin Severance Hospital, to evaluate the model against established methods and to assess the generalizability of the model (Figure 1).

3D MSP-Net; Anatomical Structure-Based Deep Neural Network for Detecting MSP with 3D Ultrasound

The proposed AI model, 3D MSP-net, mirrors the clinical diagnostic process, in which clinicians identify the MSP by spatially recognizing essential 3D anatomical structures (Figure 2). Accordingly, the framework consists of 2 sequential modules. The first module is a 3D segmentation model that delineates key anatomical structures related to the MSP, including the fetal head, NT, diencephalon, nasal bone, and nasal tip. The second module incorporates a detection algorithm that determines the MSP by leveraging the geometric relationships among these segmented landmarks. Specifically, it calculates the midpoints and principal component vectors of the landmarks to define the plane. Consequently, the proposed method provides improved explainability and reliability in MSP detection, distinguishing it from conventional approaches.

Validation and Performance Evaluation of 3D MSP-Net for Automatic MSP Extraction

To assess the performance and feasibility of a novel AI model, 3D MSP-net, in extracting the MSP from fetal head volumes for NT measurement, we performed a comparative analysis with 2 established methods: (1) 2D MSP: manually acquired MSP images[9]; (2) rule-based MSP: a previously established rule-based algorithm using 3D volume, as implemented in Volume NT™ software[12]; and (3) 3D MSP-Net: anatomical structure-based deep neural network for detecting MSP with 3D ultrasound volume. In particular, the 2D manually acquired MSP, the MSP derived from 3D volumes using a rule-based algorithm, and that generated by 3D MSP-net were evaluated for conformity with the standard MSP. The MSP from 3D volumes was extracted using the 5D Viewer software (version 2.01; Samsung Medison Co., Ltd., Seoul, Korea), in which both a rule-based MSP and 3D MSP-Net were implemented. The software was also used for the display and 3D visualization of ultrasound volume data acquired from the ultrasound system.

For assessment, 2 independent experts audited all output results to ensure the appropriateness of the identified structure. The assessment was considered valid only when both experts reached a consensus. Each image was categorized as success or unacceptable. The presence of key anatomical landmarks essential for defining standard MSP, such as clear visualization of the diencephalon, rectangular configuration of the palate, and distinct delineation of the fetal skin, was considered critical for diagnostic adequacy.

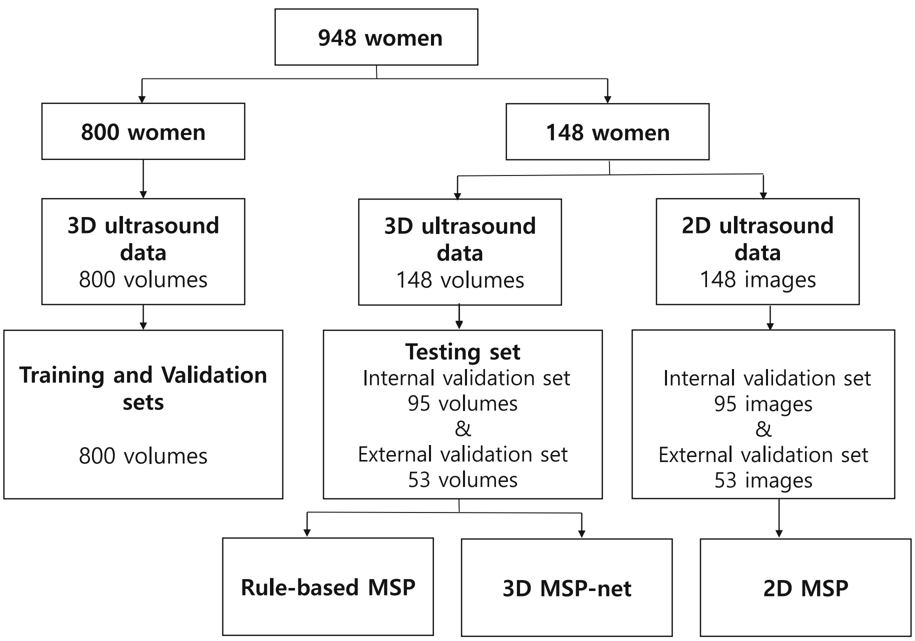
Statistical Analysis

The success rates of MSP extraction were compared across different methods. The proportion of successful MSP extractions, defined as "success," was calculated for each method: 2D MSP, rule-based MSP, and 3D MSP-Net (Figure 3). To compare the success rates among the 3 methods, Cochran's Q test was performed. When a significant difference was found, pairwise comparisons between methods were conducted using McNemar's test with Bonferroni correction for multiple testing. Factors potentially influencing the success of MSP extraction, such as maternal BMI, deviation angle, and CRL, were assessed by comparing success rates across categories using chi-squared test or Fisher's exact test, as appropriate. All statistical analyses were performed using SPSS Statistics version 29.0 (IBM Corp., Armonk, NY, USA). Statistical significance was set at *P*-value <0.05.

Results

After excluding cases with suboptimal or incomplete data, 800 volumes were utilized for the development of the 3D MSP-Net. For model performance evaluation, an independent testing set was established from 148 women, providing both 2D images and 3D volumes. This set was further partitioned into an internal

Figure 1. Study flowchart illustrating allocation of dataset.



validation cohort ($n = 95$) and an external validation cohort ($n = 53$), acquired from a different institution (Yongin Severance Hospital) to evaluate the model against established methods and to assess the model's generalizability across both 2D and 3D modalities.

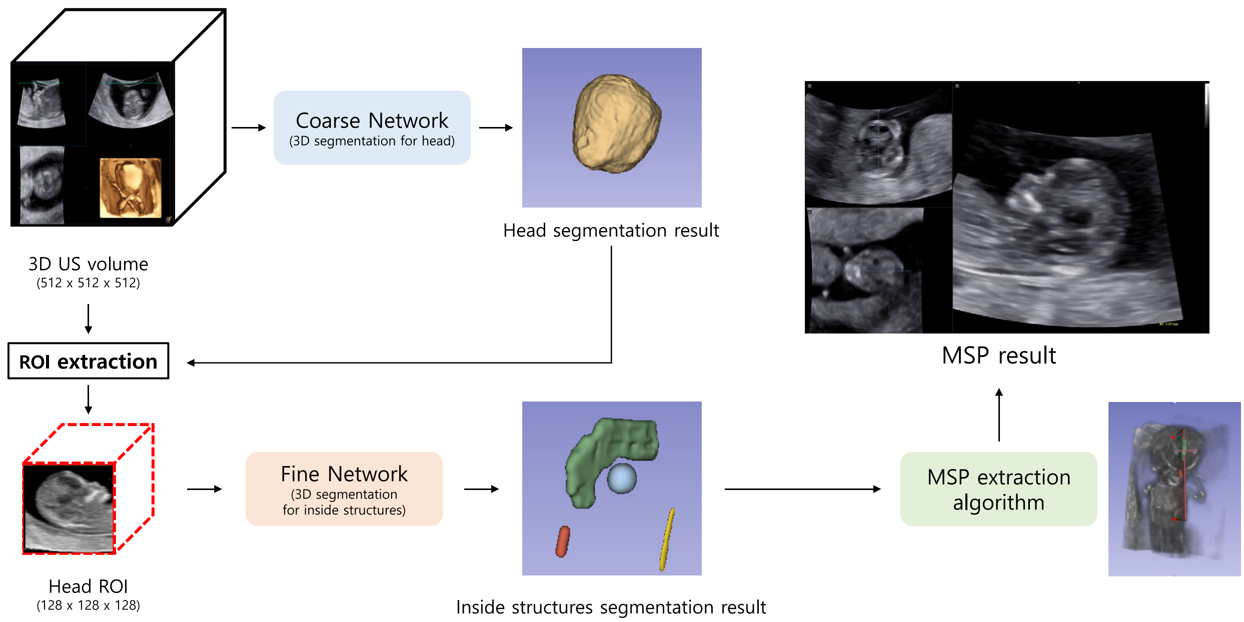
The mean gestational age at the time of NT assessment was 12.2 ± 0.7 weeks, and the mean CRL was 60.8 ± 9.1 mm. The mean NT thickness measured using 2D ultrasound was 1.4 ± 0.5 mm, while the mean NT measured using the 3D MSP-net was 1.4 ± 0.4 mm (Table 1). While there was no statistically significant difference between the NT measurements obtained using the 2D method and those obtained from the MSP extracted by the 3D MSP-Net ($p = .444$), the duration required for image acquisition was significantly shorter with the 3D volumes than with 2D ultrasound ($p < .01$) (Table S2).

In internal validation set, there was a statistically significant difference in the success rates to obtain adequate MSP among the 3 methods (Cochran's Q = 17.515, $p < .001$). After Bonferroni correction, 3D MSP-Net showed significantly higher success rate to MSP extraction compared to rule-based MSP (adjusted $p < .05$). The external validation yielded comparable results to those of the internal validation (Cochran's Q = 7.600, $p = .022$) (Table 2).

In a performance comparison of between 3D MSP-Net using 3D volumes and human operators using conventional 2D ultrasound (2D MSP), the success rate of MSP acquisition was comparable in both the internal validation dataset (91.6% versus 90.5%, $p = 1.000$) and the external validation dataset (94.3% versus 83.0%, $p = .301$). These findings indicate that the 3D MSP-net significantly improved the success rate of clinically acceptable MSP acquisition, while substantially reducing the acquisition time compared to conventional 2D ultrasound.

In performance comparison of 3D MSP-net and rule-based algorithm (rule-based MSP) using 3D volume, the 3D MSP-net demonstrated significantly higher MSP extraction success rates than those of the rule-based MSP. In the internal validation dataset, the success rate increased from 70.5% for the rule-based MSP to 91.6% for the 3D MSP-net ($p < .001$). Similarly, in the external dataset, the success rate improved from 75.0 to 94.3% ($p = .019$). These findings suggest that the AI model enables more consistent and accurate MSP extraction than the rule-based model.

Figure 2. Framework illustration of 3D MSP-net: the artificial intelligence (AI) model for mid-sagittal plane (MSP) extraction from 3-dimensional (3D) ultrasound volume. It is divided into the following 2 modules: (a) 3D segmentation module with coarse network and fine network and (b) MSP extraction algorithm. ROI, region of interest; US, ultrasound.



To assess the factors potentially affecting MSP extraction using the AI model, success rates were analyzed according to maternal body mass index (BMI), deviation angle, and CRL. The success rate was not significantly associated with maternal BMI, deviation angle of volume acquisition, and CRL (Table 3).

Discussion

Main Findings

We present 3D MSP-Net, a generalizable DL-based framework designed to automatically extract 2D standard planes from 3D ultrasound volumes. Our 3D MSP-net leverages the entire 3D dataset to accurately identify the MSP, which addresses the inherent variability often associated with manual acquisitions while maintaining consistent NT measurements. This objectivity in detecting the MSP not only reduces operator dependence but also shortens the time required for image acquisition, while enhancing diagnostic accuracy.

Table 1. Study Population Characteristics

Characteristic	Value	*p*
Maternal age (years)	34.5 ± 4.1	
GA at examination (weeks)	12.2 ± 0.7	
CRL (mm)	60.8 ± 9.1	
BMI (kg/m^2)	21.9 ± 3.5	
NT measurement (mm)		.444
2D images	1.4 ± 0.5	
3D volume	1.4 ± 0.4	
Duration for MSP acquisition (minute)[a]		<.001
2D image	5.0 (1.0–39.0)	
3D volume	1.0 (0.7–1.5)	

Data were presented mean ± SD or median (range). GA, gestational age; CRL, crown–rump length; BMI, body mass index; NT, nuchal translucency; 2D, 2-dimensional; 3D, 3-dimensional; AI, artificial intelligence.
[a]Duration for MSP acquisition was defined as the time recorded after the fetus assumed the optimal scanning position.

Traditional 2D imaging techniques require precise angle adjustments and timing to obtain an optimal MSP, which can introduce variability due to operator expertise. In contrast, 3D MSP-Net analyzes the complete volume, ensuring the selection of the

Figure 3. Transabdominal ultrasound images comparing the mid-sagittal plane (MSP) of a fetus in the first trimester. Cases of successful and non-acceptable MSP acquisition are shown for 3 models: 2D MSP, MSP obtained by the conventional 2-dimensional approach; rule-based MSP, MSP extracted from 3-dimensional (3D) volumes using a rule-based algorithm; and 3D MSP-Net, MSP extracted from 3D volumes using the AI model. A,B,C, Successful MSP acquisition. D,E,F, Non-acceptable MSP acquisition.

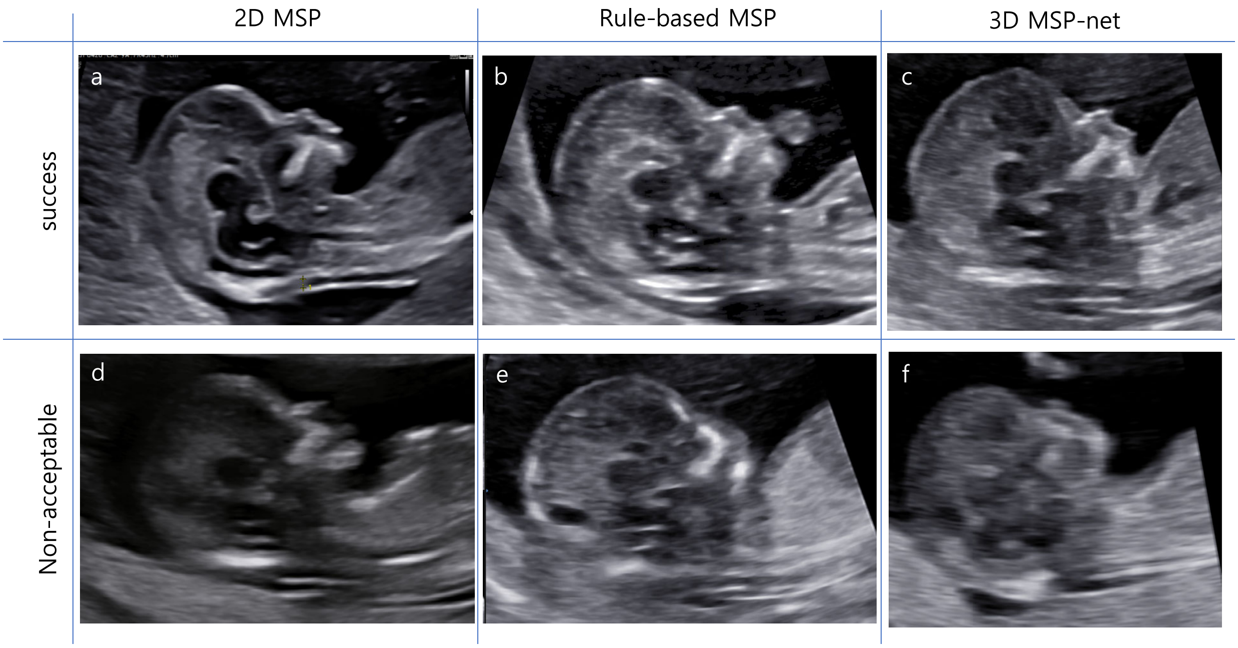


Table 2. Comparison of Success Rates for Mid-Sagittal Plane (MSP) Extraction: 2-Dimensional Ultrasound (2D) and 3-Dimensional (3D) Ultrasound Using Rule-Based Algorithm and the Artificial Intelligence Model

	2D MSP	Rule-Based MSP	3D MSP-Net	*p*
Internal validation ($n = 95$)				
Success	86 (90.5)	67 (70.5)	87 (91.6)	<.001
Non-acceptable	9 (9.5)	28 (29.5)	8 (8.4)	
External validation ($n = 53$)				
Success	44 (83.0)	40 (75.5)	50 (94.3)	.022
Non-acceptable	9 (17.0)	13 (24.5)	3 (5.7)	

Data were presented *n* (%). MSP, mid-sagittal plane.

Table 3. Success Rates of Mid-Sagittal Plane Extraction Using the Artificial Intelligence Model, According to Influencing Factors

Type of Case	*n*	Success Rate	*p*
Maternal BMI (kg/m^2)			.919
<25	82	75 (91.5)	
≥25	13	12 (92.3)	
Deviation angle (°)			.364
≤10	55	52 (94.5)	
11–20	30	26 (86.7)	
21–25	8	8 (100)	
>25	2	1 (50)	
CRL (mm)			.080
<50	9	9 (100)	
50–59	42	38 (90.5)	
60–69	26	25 (96.2)	
70≤	18	15 (83.3)	

BMI, body mass index; CRL, crown–rump length.

most diagnostically optimal plane across the entire dataset. This advantage was clearly demonstrated by the model's consistent performance across different datasets, underscoring the generalizability of the framework with reducing required time for acquisition.

The established rule-based MSP extraction algorithms using 3D volumes, which assume head symmetry across the sagittal plane, face significant challenges in clinical practice. This assumption is often invalid due to natural fetal brain asymmetry, even in the first trimester,[25,26] as well as low image contrast and small regions of interest typical of fetal head ultrasound. These factors can limit the accuracy and robustness of rule-based approaches for MSP extraction from 3D ultrasound data. Our 3D MSP-Net outperformed the rule-based MSP in cases of suboptimal fetal positioning or asymmetric anatomy in real-world clinical situations. The 3D MSP-Net stems from its ability to learn complex nonlinear features directly from vast datasets, enabling it to generalize effectively despite variations in fetal presentation, image quality, and subtle anatomical asymmetries.

Owing to the established clinical importance of NT measurement, several studies have applied DL techniques to standard plane detection in fetal ultrasound. Compared with previous methods for fetal MSP detection using 3D volume with AI-assisted algorithm, our proposed framework offers several notable advancements in terms of structure, accuracy, and clinical applicability. Tsai et al[27] proposed a 2-stage framework combining DL-based seed point localization with Generative Adversarial Network (GAN)-based MSP segmentation using a 3D binary mask. While their approach demonstrated potential performance, it involved multiple networks, segmentation, and object detection across multiple views and required transformation matrix-based post-processing to derive the final 2D MSP. This indirect inference via voxel-wise 3D masks increases the model complexity and the risk of cumulative errors. By contrast, our model adopts a streamlined end-to-end architecture that directly detects the MSP by leveraging key anatomical landmarks and eliminating the need for multistage refinement or geometric transformation. By incorporating prior knowledge of structures, such as the nasal bone, NT region, and diencephalon, our method ensures clinical relevance and interpretability. Namburete et al[28] addressed fetal head alignment using a multitask pose estimation framework to register 3D ultrasound data to a canonical reference space. Although effective for brain imaging, their approach was not designed for MSP extraction and lacked direct localization of midline features critical for NT measurement. Furthermore, a template-based alignment is less suitable for real-time clinical workflows. By contrast, our AI model directly predicts anatomical structures, providing a robust and computationally efficient solution. With a lightweight design that allows inference in less than 1 second, the model is well-suited for integration into clinical ultrasound systems. Collectively, these advantages establish our method as a technically superior and clinically viable alternative for MSP detection in the first trimester.

Strengths and Limitations

To the best of our knowledge, this is the first study to apply an end-to-end DL architecture for automated MSP detection from 3D fetal ultrasound volumes in the first trimester. A key strength of 3D MSP-Net is its ability to address one of the main limitations of NT screening—operator dependence and time constraints. By referencing stable intracranial structures, the model enables accurate MSP reconstruction, even when the nasal bone is not visible during scanning. This capability significantly reduces the number of failed or rescheduled examinations. Furthermore, the successful acquisition of a proper mid-sagittal view facilitates early anatomical assessment of the fetal brain, thereby enhancing diagnostic prediction in the first trimester. Importantly, the performance of the 3D MSP-Net was not significantly influenced by maternal BMI, deviation angle, or CRL, suggesting robust applicability even in patients with high BMI, where obtaining the MSP using conventional 2D ultrasound is often difficult. Nevertheless, this study has some limitations. First, the spatial resolution of 3D ultrasound volumes is lower than that of 2D imaging, which may limit visual clarity. Second, because the model was trained on normal fetal datasets, its performance may differ in cases with structural anomalies affecting key anatomical landmarks. Although fetuses with increased NT are clinically important, these cases were excluded because the study was specifically designed to reflect routine clinical practice, where most fetuses have normal NT and to avoid confounding effects from marked anatomical deviation and to ensure rigorous and unbiased assessment. However, cases with increased NT are also challenging for manual 2D scanning, and accurate MSP acquisition may likewise be compromised. Furthermore, such cases often require detailed evaluation by experienced clinicians to assess associated structural anomalies, which may not be suitable for automated analysis. In addition, our algorithm does not rely on only NT-related anatomical landmarks but instead determines orientation using stable intracranial structure to identify MSP by optimizing alignment to achieve symmetry. Therefore, its performance is not inherently affected by the absolute NT thickness. Lastly, the proprietary nature of volume data formats limits interoperability across ultrasound systems from different manufacturers.

Clinical and Research Implications

This study introduces a novel model that enables more accurate and efficient extraction of MSP from fetal head 3D ultrasound volumes, facilitating reliable first-trimester NT assessment. The proposed approach mimics the clinical decision-making process, in which clinicians identify the MSP by spatially recognizing key anatomical landmarks. By leveraging the geometric relationships among these structures, the model enhances explainability and reliability in real-world settings. Furthermore, it demonstrates superior robustness and accuracy compared with conventional 2D manual techniques and existing 3D-based methods, supporting its potential for clinical translation and broader research applications.

Conclusion

Currently, no AI model automatically extracts the fetal MSP from first-trimester 3D ultrasound volumes by leveraging geometric relationships among intracranial anatomical structures. This study proposes a novel AI model that demonstrates performance comparable to expert-acquired 2D MSP and a rule-based algorithm, with consistent robustness across internal and external validations. The model accurately identifies high-quality MSP, enabling reliable NT measurement. 3D MSP-net, DL-based MSP extraction from 3D volumes, has the potential to reduce operator dependence, shorten acquisition times, and improve standardization through enhanced accuracy, efficiency, and generalizability, thereby facilitating broader clinical adoption.

Data Availability Statement

The data that support the findings of this study are available on request from the corresponding author. The data are not publicly available due to privacy or ethical restrictions.

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