Robustness Enhancement in fMRI Gestational Age and Delivery Date Estimation with Frequency Regularization

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***Abstract*—Maternal mortality rates remain unacceptably high globally, with approximately 287,000 women losing their lives during and after pregnancy in 2020, as reported by the World Health Organization [20]. A significant number of these deaths are attributed to unanticipated childbirth, underscoring the critical need for accurate estimation of the delivery date. This project aims to enhance existing gestational age estimation methods by incorporating frequency regularization to improve robustness, particularly in emergency childbirth scenarios. Evaluation involves comparing dice scores before and after regularization, showcasing potential improvements in gestational age prediction accuracy and the broader applicability of frequency regularization across domains.**

***Index Terms*—Maternal mortality, gestational age estimation, frequency regularization.**

I. Introduction

A. Background

Maternal mortality continues to be a pressing global issue, with a substantial portion of deaths occurring due to unforeseen childbirth. The uncertainty surrounding delivery dates exacerbates risks, highlighting the importance of accurate gestational age estimation. This study addresses this challenge by proposing an enhancement to existing methods through frequency regularization. By bolstering the robustness of gestational age prediction, particularly in emergency situations, this approach aims to reduce maternal mortality rates and improve maternal and child health outcomes. Through comparative analysis, the efficacy of frequency regularization is examined, offering insights into its potential to enhance gestational age estimation across various contexts.

The estimation of delivery dates is pivotal in prenatal care and childbirth planning, yet existing methods often lack the robustness needed for real-life emergency scenarios. This project seeks to address this gap by introducing frequency regularization as a means to improve the reliability of gestational age prediction. By evaluating the performance of this approach against conventional methods using dice scores, this study not only contributes to advancing gestational age estimation but also explores the broader applicability of frequency regularization techniques. Ultimately, the findings hold promise for reducing maternal mortality rates and improving maternal and child health outcomes worldwide.

B. Literature Review

1) **Artificial Intelligence in Fetal Resting-State Functional MRI Brain Segmentation: A comparative analysis of 3D UNET, VNET, and HighRES-Net models**

Fetal brain imaging presents unique challenges due to the dynamic nature of the developing brain and surrounding environment. Traditional tools for fetal brain analysis often struggle with image quality and motion artifacts, hindering accurate segmentation. This literature [17] review focuses on a recent study that aims to tackle these challenges by employing artificial intelligence (AI) models for fetal resting-state functional MRI (rs-fMRI) brain segmentation. The approach taken by the study is notable for its utilization of 3D models, which better handle the volumetric nature of fMRI data compared to previous 2D models used in adult brain imaging. By focusing on functional MRI data, the study extends previous research and introduces additional complexities that arise from the dynamic nature of the fetal brain.

Methodologically, the study employs three AI models: 3D UNet, VNet, and HighRes-Net, and utilizes Optuna, an automated hyperparameter-tuning tool, for model optimization. Through a 5-fold cross-validation methodology, the study evaluates the performance of these models in fetal brain segmentation. Results of the study demonstrate promising outcomes, particularly with the VNet model, which exhibits strong segmentation performance. However, despite the overall success of the approach, certain limitations are apparent. The HighRes-Net model, while showing potential, did not perform as well as the VNet and 3D UNet models. Additionally, challenges such as image quality and head motion remain unresolved, highlighting areas for future improvement.

2) **A normative spatiotemporal MRI atlas of the fetal brain for automatic segmentation and analysis of early brain growth**

This paper [4] focuses on a study aimed at addressing the challenges associated with constructing atlases and segmenting neonatal brain images. The paper's objective is to develop robust methods for atlas construction, segmentation, and labeling in neonatal brain imaging, with a particular emphasis on accuracy and efficiency.The approach taken by the authors involves the development and application of advanced imaging and image processing techniques. Specifically, they utilize atlas-based segmentation methods, automated segmentation algorithms, and image labeling procedures. These methods are designed to enhance the accuracy and reliability of neonatal brain image analysis, ultimately contributing to a better understanding of brain development in early life stages.

Methodologically, the study employs a combination of manual and automated procedures for atlas construction, segmentation, and labeling. Manual labeling procedures are supervised and conducted by trained personnel, while automated segmentation algorithms are developed to assist in image analysis tasks. The study also utilizes various software tools and resources developed at research institutions to facilitate image processing and analysis. The results of the study demonstrate significant progress in neonatal brain image analysis, with improved accuracy and efficiency in atlas construction, segmentation, and labeling. The developed methods yield promising outcomes in terms of image quality, anatomical accuracy, and computational efficiency, laying a solid foundation for future research in this area.

However, despite the advancements made in the study, several limitations and areas for future improvement are identified. These include the need for further refinement of segmentation algorithms to handle complex anatomical structures and variations in neonatal brain images. Additionally, the study highlights the importance of addressing challenges related to image quality, noise, and artifacts, which can affect the accuracy of segmentation and labeling results.

3) **Deep predictive motion tracking in magnetic resonance imaging: Application to fetal imaging. IEEE Transactions on Medical Imaging**

Fetal brain motion tracking remains a challenging task in medical imaging, necessitating accurate and robust methodologies to monitor fetal development and detect potential anomalies. This paper [16] addresses this problem by proposing a novel approach that utilizes deep learning techniques to predict fetal head motion accurately. The methodology employed by this paper revolves around a many-to-many Seq2Seq model, which takes sequences of slices as input and estimates both angles and predictions. This model comprises an encoder-decoder architecture, with the encoder extracting sequence-of-image features using spatial encoder (CNN) blocks followed by a temporal encoder containing LSTM units and P blocks. The decoder network then utilizes LSTM units and P blocks to generate predictions based on the encoded features.

In evaluating their approach, this paper presents compelling results demonstrating the effectiveness of their model. Figures and tables depict comparisons between inferred results and ground truth sequences, boxplots of rotational mean squared error (MSE) loss, and analyses of average MSE for one-step and multi-step prediction tasks. The results indicate superior performance of their model compared to baseline methods, showcasing its accuracy and generalization capability across different gestational ages and motion patterns. Despite the promising results, there are areas for improvement in Singh et al.'s study. One potential limitation lies in the evaluation metrics used, as they primarily focus on MSE and may not fully capture the clinical relevance of fetal brain motion tracking. Additionally, the study could benefit from further validation on larger and more diverse datasets to ensure the model's robustness across various clinical scenarios.

4) **Automated Brain Masking of Fetal Functional MRI with Open Data**

The prominent challenge addressed by this paper [15] is the development of robust image analysis techniques capable of handling complex data characteristics inherent in brain imaging modalities. This paper proposes a method for mitigating intensity inhomogeneities in fMRI sequences, while the previous paper they referred to, Shattuck and Leahy (2002), introduced an automated cortical surface identification tool. These approaches represent significant strides in enhancing the quality and reliability of brain imaging data, thereby facilitating more accurate analyses. Furthermore, researchers have focused on elucidating the structural and functional dynamics of the developing human brain. Studies by Song et al. (2017) and Studholme (2011, 2015) have delved into mapping fetal brain development using MRI, shedding light on the spatiotemporal patterns of brain maturation.

Similarly, investigations into functional connectivity in the human fetal brain by Thomason et al. (2013, 2017) and Takahashi et al. (2012) have provided insights into the emergence of cerebral connectivity during early gestation. Methodological advancements have also been a focal point of research efforts, with Taha and Hanbury (2015) presenting metrics for evaluating 3D medical image segmentation and Tourbier et al. (2017) introducing automated brain localization and extraction techniques for fetal MRI reconstruction. These methodological innovations offer valuable tools for enhancing the accuracy and efficiency of brain imaging analysis.

Despite the progress made, several challenges and areas for improvement persist. One notable limitation is the presence of dataset bias in medical imaging, as highlighted by Tommasi et al. (2015), which can hinder the generalization performance of deep learning models (Zech et al., 2018). Additionally, while significant strides have been made in characterizing structural and functional aspects of brain development, gaps remain in understanding the complex interplay between genetic, environmental, and epigenetic factors. In conclusion, the literature review underscores the multifaceted nature of brain imaging and analysis research, spanning methodological innovations, insights into brain development, and challenges in data interpretation. Future advancements in the field will likely entail addressing dataset biases, refining analysis methodologies, and integrating multi-modal imaging approaches to achieve a more comprehensive understanding of the developing brain.

5) **Review of deep learning and artificial intelligence models in fetal brain magnetic resonance imaging**

Recent developments in deep learning and artificial intelligence (AI) have shown promising potential for enhancing fetal brain magnetic resonance imaging (MRI). This paper [18] review delves into the pressing issues surrounding fetal brain MRI, aiming to address challenges such as automated segmentation, reconstruction, motion tracking, image enhancement, and gestational age prediction. The approach adopted in this paper involves synthesizing findings from various studies in the field, including those focusing on automatic segmentation and reconstruction of the fetal cortex, high-resolution MRI through super-resolution reconstruction, and automated 3D fetal brain segmentation using deep learning techniques. These studies collectively highlight the feasibility and efficacy of employing AI models to analyze fetal brain MRI data, offering insights into methodologies and outcomes.

Methodologically, the review draws upon a diverse array of research methodologies, encompassing deep learning algorithms, neural networks, and convolutional neural networks (CNNs). These methodologies enable the automatic segmentation of fetal brain structures, reconstruction of MRI images, and prediction of gestational age, thereby facilitating prenatal diagnosis and clinical decision-making. The results of the reviewed studies underscore the potential of deep learning and AI models to revolutionize fetal brain MRI analysis, with notable achievements in automated segmentation accuracy, reconstruction quality, and predictive capabilities. These advancements hold promise for improving prenatal diagnosis accuracy and enhancing patient care. However, despite the progress made, several limitations and areas for future improvement persist. Challenges include inter-observer variability, the need for rigorous evaluation of segmentation algorithms, and limitations in automatic landmark localization. Additionally, further research is needed to refine brain tissue segmentation techniques and enhance template-based brain localization and extraction for fetal MRI reconstruction.

6) **Frequency regularization: reducing information redundancy in convolutional neural networks**

This paper [23] addresses the issue of information redundancy within convolutional neural networks (CNNs) used for computer vision tasks. The main objective is to propose a frequency regularization technique aimed at restricting the redundancy of information within CNNs, thereby enhancing their efficiency and performance.

The approach involves maintaining the tensors of parameters in the frequency domain, where the high-frequency components are truncated during training. This is achieved through a dynamic tail-truncation strategy, which improves the stability of network training. The proposed technique is applied to various state-of-the-art network architectures, including UNet for image segmentation and generative adversarial networks (GANs) for image generation.

The methodology includes evaluating the proposed frequency regularization technique on different network architectures using various datasets and evaluation metrics. For image segmentation tasks, the Dice score is used for evaluation, while the Fid value is utilized for image generation tasks.

The results demonstrate promising outcomes, with significant reductions in the number of parameters while maintaining high performance levels. For example, in the case of UNet for image segmentation, over 99 percent of parameters can be truncated in the frequency domain while still achieving high Dice scores. Similarly, in the case of GANs and variational autoencoders (VAEs) for image generation, the proposed approach achieves comparable results with significantly reduced parameter counts.

7) **FreeNeRF: Improving Few-Shot Neural Rendering with Free Frequency Regularization**

This paper [22] under review addresses the challenge of improving few-shot neural rendering through the introduction of Free Frequency Regularization. The authors aim to enhance the stability and accuracy of neural rendering models when presented with limited input data, which is crucial for applications such as scene reconstruction from sparse views. To achieve this, they propose a novel approach that incorporates frequency regularization, restricting the input to low-frequency components during training to stabilize scene representations before refining details with high-frequency signals.

The methodology employed involves training neural rendering models using the DietNeRF and RegNeRF codebases as baselines. These codebases implement variations of the Neural Radiance Fields (NeRF) architecture, with DietNeRF utilizing a plain NeRF architecture and RegNeRF employing a mipNeRF variant. Training is conducted with the Adam optimizer over a specified number of iterations, with learning rate schedules and gradient clipping to ensure stable training. Occlusion regularization is also applied to improve scene reconstruction quality.

The results presented in the paper demonstrate the effectiveness of the proposed Free Frequency Regularization approach in improving the accuracy of few-shot neural rendering models. Comparative evaluations against baselines such as mipNeRF show notable improvements in scene reconstruction quality and normal vector estimation accuracy. However, limitations such as over-regularization leading to incomplete reconstructions and the presence of artifacts in remote areas suggest areas for future improvement.

8) **Modulating regularization frequency for efficient Compression-Aware Model training**

Efficient model compression has become imperative in deep learning research due to the increasing demand for deploying models on resource-constrained devices. The paper "Modulating Regularization Frequency for Efficient Compression-Aware Model Training" [10] addresses the challenge of achieving high compression ratios while preserving model accuracy. The primary focus is on exploring the impact of tiling and Singular Value Decomposition (SVD) on weight distributions in convolutional neural networks (CNNs). The approach involves dividing weight matrices into tiles of various sizes and compressing them using SVD to achieve the desired compression ratio. Through empirical experiments on ResNet-32 with the CIFAR-10 dataset, the authors demonstrate the effectiveness of the proposed tiling technique combined with occasional regularization in preserving model accuracy.

The methodology entails comprehensive experiments on different CNN models, including ResNet-32, VGG19, and ResNet-34, using various datasets such as CIFAR-10 and ImageNet. The experiments involve training convolutional layers with different compression techniques and evaluating the resulting model accuracy. Results indicate that tiled SVD, enabled by occasional regularization, outperforms other compression techniques in terms of both training loss and test accuracy. However, the relationship between tile size and model accuracy for each compression ratio remains unclear, suggesting a need for further exploration and optimization.

9) **Improving Native CNN Robustness with Filter Frequency Regularization**

This paper [12] addresses the challenge of enhancing the robustness of Convolutional Neural Networks (CNNs) by leveraging the relationship between shapes and frequencies. It identifies a prevalent issue where neural networks tend to rely more on textures rather than shapes for classification tasks, leading to non-robust behavior due to the localized nature of texture information. In contrast, human vision tends to prioritize global shape information for robust perception. To tackle this problem, the paper proposes a novel regularization approach based on the behavior of Discrete Cosine Transform (DCT) and its correlation with shapes. By observing that the DCT of a rectangular pulse (representing a shape in 1D) results in amplitude decay as frequency increases, the regularization method aims to encourage the dominance of low-frequency components in shaping the filters of CNNs. This approach directly induces a shape bias into the network's learning process, thereby potentially improving its robustness by focusing on global shape information.

The methodology involves developing a regularization term, as presented in Equation 7 of the main paper, which encourages lower frequencies to have maximal amplitudes lower than those of higher frequencies. Additionally, the regularization term aims to promote low amplitudes for high frequencies, effectively shaping the spectral content of the CNN's filters to prioritize shape information. In terms of results, the paper presents evidence of the effectiveness of the proposed regularization technique in improving the robustness of CNNs. Visualizations and mathematical analyses demonstrate how the DCT of shape functions correlates with frequency spectra, providing theoretical insights into the regularization approach.

However, the paper lacks comprehensive empirical evaluations across various datasets and network architectures to establish the generalizability and effectiveness of the proposed method in diverse scenarios. Additionally, future improvements could involve exploring adaptive regularization strategies that dynamically adjust the regularization strength during training based on the characteristics of the dataset or network. Furthermore, investigating the computational efficiency and scalability of the proposed approach could be beneficial for its practical application in real-world settings.

10) **Robust Learning with Frequency Domain Regularization**

This paper [5] addresses the pressing challenge of improving the robustness of machine learning models, particularly in handling unseen data. The authors propose a novel approach that focuses on explicit removal of unimportant frequency components during model training. This method aims to enhance model performance by identifying and suppressing irrelevant activations in the spectral domain using binarized masks. The approach described in the paper involves pinpointing the valid frequency range relevant to the training set across different layers of the model. By doing so, the method ensures that the model learns to prioritize important frequency components while disregarding noise and background information. Notably, this method differs from conventional techniques such as Band-limited training and spectral dropout by avoiding indiscriminate dropping of high-frequency components and eliminating the need for hyperparameters like keep-percentage for masking.

The methodology employed in the paper involves training spectral domain masks for each class, potentially improving performance and facilitating implicit transformations among categories in different datasets. However, the implementation of inter-class masks requires architectural modifications, which remain an area for future investigation. The results presented in the paper demonstrate promising outcomes in terms of model robustness and generalization across different domains. By explicitly targeting important frequency components, the proposed regularization method shows improvements in model performance on unseen data. However, the paper lacks extensive empirical evaluation across diverse datasets and model architectures, which could provide deeper insights into the method's effectiveness and generalizability.

11) **Semi-Supervised Learning for Fetal Brain MRI Quality Assessment with ROI consistency**

This paper [21] describes a novel semi-supervised deep learning approach proposed for fetal brain MRI quality assessment. This method addresses the challenge of motion artifacts by detecting problematic slices during brain volume scans. It utilizes a mean teacher model with a focus on consistency between student and teacher models across the entire image, alongside a region of interest (ROI) consistency loss to prioritize the brain region. This approach was evaluated on a dataset of labeled and unlabeled fetal brain MRI images, demonstrating a 6% improvement in accuracy compared to supervised learning and outperforming other semi-supervised methods. Additionally, the method was successfully implemented and tested on an MR scanner, showcasing its potential for real-time image quality assessment and reacquisition during fetal MRI scans, thus potentially enhancing imaging workflow efficiency.

12) **Achieving accurate estimates of fetal gestational age and personalised predictions of fetal growth based on data from an international prospective cohort study: a populationbased machine learning study**

Preterm birth is a significant global health issue, with current methods for estimating fetal gestational age often proving inaccurate [3]. This study introduces a machine learning approach utilizing ultrasound-derived fetal biometric data to enhance gestational age estimation and predict future growth trajectories. By focusing on intervals between ultrasound visits rather than relying on the mother's last menstrual period, the algorithm achieves remarkable accuracy, narrowing the prediction interval to within 3 days between 20 and 30 weeks of gestation. Additionally, six-week growth forecasts are accurate to within 7 days, aiding in the identification of at-risk fetuses and potentially improving individual pregnancy management. At a population level, this approach promises to refine fetal growth charts and health assessments. Upon publication, the algorithm will be available for research purposes via a web portal, offering potential benefits to both clinical practice and population health.

13) **Machine learning for accurate estimation of fetal gestational age based on ultrasound images**

Accurately determining gestational age is crucial for effective obstetric care, especially when the last menstrual period is uncertain. While ultrasound measurement is currently the best method, its accuracy diminishes in later trimesters due to increased fetal size variation. To address this, we employ advanced machine learning techniques that analyze standard ultrasound images without relying on direct measurements. Our model, trained and validated on independent datasets, demonstrates high accuracy even in cases of intrauterine growth restriction. In the second and third trimesters, our machine-learning model outperforms traditional ultrasound-based methods, estimating gestational age with mean absolute errors of 3.0 and 4.3 days, respectively. This approach offers improved accuracy compared to existing methods for dating pregnancies in later stages [11].

14) **Ultrasound-based gestational-age estimation in late pregnancy**

    This study [13] aimed to determine the most accurate method for estimating gestational age (GA) via fetal ultrasound in women presenting late in pregnancy with uncertain menstrual dates. Using data from the INTERGROWTH-21st project, involving over 4,000 women, ultrasound measurements of fetal head circumference (HC) and femur length (FL) were found to provide the best prediction of GA, with an estimated uncertainty of 6-7 days in the second trimester and ¿14 days in the third trimester. Incorporating FL alongside HC improved prediction intervals, while other measurements such as abdominal circumference, biparietal diameter, and occipitofrontal diameter did not enhance accuracy. This approach offers a valuable tool for estimating GA in populations lacking early antenatal care access, though efforts to improve timely initiation of care are still crucial.

15) **Self-Supervised Ultrasound to MRI Fetal Brain Image Synthesis**

    This article [7] proposes a novel technique for transforming clinical ultrasound (US) images into MRI-like images, aiming to combine the accessibility of ultrasound with the detailed insights provided by MRI, particularly for second-trimester fetal brain anomaly screening. The method utilizes a self-supervised, end-to-end trainable model that synthesizes MR images by extracting shared latent features from US images, assuming a common anatomical space between US and MRI data. This approach addresses the challenge of the lack of paired US-MRI data by employing adversarial learning to match the statistical distributions of synthesized and actual MRI images, without relying on external annotations.

    To enhance the synthesis quality and ensure anatomical accuracy, the model incorporates an adversarial structural constraint and introduces a cross-modal attention mechanism that uses non-local spatial information for multi-modal knowledge fusion. It also benefits from incorporating 3D auxiliary information from volumetric data, showing improved performance in generating realistic MR-like images. The technique's effectiveness is demonstrated through quantitative and qualitative evaluations against real fetal MR images and other synthesis approaches, highlighting its potential in improving the diagnostic utility of ultrasound images for fetal brain development monitoring.

16) **Frequency Regularization for Improving Adversarial Robustness**

    The paper [6] investigates DNN vulnerability to adversarial attacks despite their strong performance. It discusses the trade-off between standard and robust accuracy in adversarial training (AT) and proposes a frequency-based analysis to understand this phenomenon. By filtering inputs, the authors find robust models heavily rely on low-frequency content, resulting in lower standard accuracy. They introduce a frequency regularization (FR) method to align outputs and improve robust accuracy, along with Stochastic Weight Averaging (SWA) to further enhance robustness. Overall, the paper offers insights into DNN vulnerabilities and proposes methods to boost robust accuracy.

17) **Fourier Sensitivity and Regularization of Computer Vision Models**

    This paper [9] investigates the frequency sensitivity of deep neural networks, revealing that these models have heightened sensitivity to specific Fourier-basis directions in the input data, influenced by the dataset, training method, and architecture. The authors introduce a basis trick that leverages unitary transformations of the input-gradient to analyze a model's Fourier sensitivity. They then develop a Fourier-regularization framework aimed at adjusting the model's frequency sensitivities and biases. This regularization approach has been shown to enhance deep neural networks' robustness and classification accuracy across different evaluations.

18) **Fourier Sensitivity and Regularization of Computer Vision Models**

    This paper [2] addresses the challenge of balancing model complexity and data fit in system identification through kernel regularization, a method that has gained significant attention for its ability to incorporate a priori knowledge, such as stability and DC gain, into the model. Despite previous advances in kernel design and hyperparameter tuning, issues with high frequency decay in estimated impulse responses have emerged. To address this, the paper proposes a novel approach combining time-domain and frequency-domain regularization to enhance identification accuracy. This combined regularization approach is shown to effectively improve the system's impulse response by ensuring both exponential convergence and satisfactory high frequency decay. The paper's key contributions include detailing the method for integrating time and frequency regularization and providing a numerical example to demonstrate the enhanced identification accuracy.

19) **Absum: Simple Regularization Method for Reducing Structural Sensitivity of Convolutional Neural Networks**

    Absum [8] is a novel regularization technique designed to enhance the adversarial robustness of convolutional neural networks (CNNs) by addressing their inherent structural sensitivity to specific noise patterns, notably the vulnerability exploited by the simple yet effective Single Fourier attack. Unlike traditional regularization methods that may hinder loss function minimization through stringent constraints, Absum adopts a more flexible approach by penalizing the absolute sum of parameters in convolution layers, thereby reducing structural sensitivity without compromising performance. Experimental results show that Absum not only outperforms standard regularization techniques in defending against Single Fourier and transferred attacks but also increases resistance to high-frequency noise and gradient-based adversarial tactics like projected gradient descent, especially when combined with adversarial training.

20) **Fourier frequency adaptive regularization for smoothing data**

    The study [1] explores an advanced approach to data smoothing through Fourier domain transformation, addressing the limitations of traditional methods that apply a uniform smoothing law across all Fourier coefficients. By introducing a frequency adaptive regularization method, this technique assigns a unique regularization parameter to each coefficient, allowing for tailored smoothing that considers both the underlying function and noise levels. The research presents convergence proofs for this method and outlines an optimal strategy for selecting regularization parameters based on minimizing the L2 risk. Through numerical experiments with various test functions, the effectiveness of this frequency adaptive approach is demonstrated, showcasing superior performance compared to both standard wavelet regularization and wavelet adaptive regularization methods. This innovation promises enhanced precision in data smoothing by dynamically adjusting to the frequency characteristics of the data and noise.

21) **Comparison studies of 2D and 3D ultrasound biparietal diameter for gestational age estimation**

    This study [19] investigates the accuracy of predicting fetal gestational age using conventional two-dimensional (2D) ultrasonography (US) measurement compared to a proposed three-dimensional (3D) visualization toolkit, VTK. By acquiring data in the form of video clips and DICOM files, the research demonstrates that 3D volume acquisition offers higher accuracy and consistency in structural surveys compared to 2D methods. Ten trial measurements were conducted for each method, revealing mean BPD(biparietal diameter) measurements of 47.326 ± 0.643345mm (UTV 380) and 47.099 ± 0.377343mm (DICOM), with 2D measurements yielding a mean of 46.290 ± 0.455705mm. While limitations include the necessity for standardized volume acquisition and considerations for fetal cranial shape, the study concludes that the proposed 3D approach outperforms traditional 2D ultrasound in accuracy, flexibility, and consistency, thus offering significant advantages in fetal growth assessment and gestational age prediction.

22) **The risk of intrauterine fetal death in the small-for-gestational-age fetuses**

    This study [14] examined the risk of intrauterine fetal death (IUFD) in small-for-gestational-age (SGA) fetuses compared to non-SGA fetuses using a retrospective cohort analysis of births in the United States in 2005. The risk of IUFD(intrauterine fetal death) increased with gestational age and was inversely proportional to birth weight percentile for gestational age, with the highest risk of fetal death by cohorts of fetuses less than 3rd percentile, 3rd – 5th percentile, and 5th – 10th percentile compared to non-SGA pregnancies. The findings suggest that SGA fetuses face an elevated risk of IUFD across all gestational ages, highlighting the importance of assessing fetal growth for clinical decision-making and patient counseling in managing pregnancies with growth restriction.

C. Existing Approach & Challenges

The existing study showcases the potential of AI, particularly the VNet model, in segmenting fetal rs-fMRI brain images, emphasizing the balance between training time and performance. The application of Optuna for hyperparameter optimization enhanced model efficiency, highlighting the benefits of automated tuning. The research calls for further exploration to tackle fetal brain imaging challenges and to improve models like HighResNet. Notably, the study discovered a correlation between gestational age and segmentation accuracy, suggesting models perform better with older fetuses due to more distinct brain features.Addressing image quality and motion artifacts remains a critical challenge, with the potential solution of integrating advanced motion-correction techniques.

The computational efficiency, especially with GPU use, indicates the feasibility of these AI models for large-scale applications. Additionally, optimizing reprocessing steps like censoring thresholds could further improve model performance. The study concludes with a positive outlook on AI's role in fetal brain fMRI segmentation, offering significant reductions in manual labor and paving the way for advances in understanding prenatal brain development.

The existing approach is good enough, but it can be more robust because in real life scenario time is critical in emergency childbirth situation by improving the speed of the detection. By incorporating the frequency regularization with the existing approach not only improves the dice score but also combines diverse domain like medical field with computer vision to open further roads to explore this topic.

D. Research Milestones

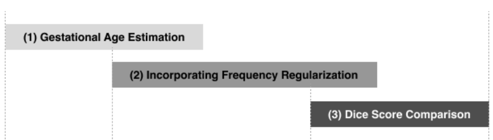

Fig. 1. Milestones

Initially, the gestational age is estimated using the current methods, using fMRI images from the dataset, which included 164 participants. Within this dataset, each 4D fMRI image comprises several 3D image volumes, leading to a grand total of 925 volumes following decomposition.

Then for frequency regularization, network parameters are manipulated at the tensor level across different architectures, keeping them in the frequency domain to selectively remove high-frequency elements through a zigzag pattern. Utilizing inverse discrete cosine transform (IDCT), it reconstructs the spatial tensors necessary for network training, leveraging the dispensability of high-frequency components to significantly reduce the number of active parameters through frequency regularization.

As the evaluation metrics to measure the success of this project, dice score comparison between existing approach and the enhanced method with incorporating frequency regularization will be measured.

II. Our Approach

The proposed resources and work plan for this project are as follows.

- Utilizing the established methodology for gestational age estimation, the study [17] employs an open-source fetal functional MRI (fMRI) dataset containing 160 cases (sourced from fetal-fMRI - OpenNeuro).
- We will utilize the pretrained model from the previous paper as the base model and employ monai.io to detect the fetal brain image and create the ground truth.
- The Frequency Regularization technique from a study [23] will be incorporated to restrict non-zero elements of network parameters in the frequency domain.
- A comparative analysis will be conducted between the Dice scores obtained from the prevailing gestational age prediction methodologies and those achieved through the integration of frequency regularization.
- The remaining steps will adhere to the reviewed paper's protocol for estimating gestational age. Additionally, the study will incorporate a delivery date calculation based on the estimated gestational age and experimenting to enhance its robustness by incorporating frequency regularization.

Calculation of Gestational Age (GA):

$$GA = f(HC)$$

Calculation of Expected Delivery Date (EDD):

$$GA_{\text{total\_days}} = GA_{\text{weeks}} \times 7 + GA_{\text{days}}$$
$$EDD = \text{Current Date} + GA_{\text{total\_days}}$$

Where:

- HC : The head circumference.
- GA_{weeks} : The gestational age in weeks.
- GA_{days} : The gestational age in days.
- EDD : The estimated delivery date.

This comparative assessment holds potential benefits for both primary and secondary references, serving to evaluate the efficacy of frequency regularization across diverse domains and augment the resilience of existing gestational age estimation methodologies.

III. Result and Analysis

Utilizing the open-source fetal functional MRI (fMRI) dataset from fetal-fMRI OpenNeuro and the monai.io medical imaging framework, as depicted in Figure 2, we have successfully detected the fetal brain in the fMRI scans, generated the ground truth, detected the fetal brain diameter, including the FOD (Fronto-occipital diameter), BPD (Biparietal diameter), and HC (Head circumference), and calculated the Gestational Age as well as the Expected Delivery Date, as shown in Figure 3 and table 1.

Additionally, we have experimented with frequency regularization to enhance the robustness of the previous approach.

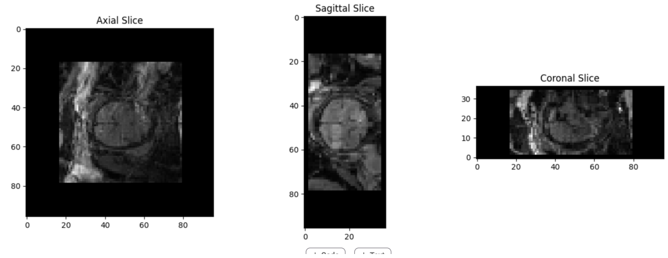

Fig. 2. fMRI Fetal Brain Image

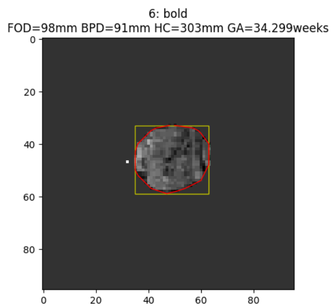

Fig. 3. Gestational Age Prediction

Our preliminary experiments showcase a significant enhancement, with a 181.95 percent increase in the dice score, as reflected in Table 2. However, due to time constraints during the implementation of this project, further code checks and enhancements need to be conducted to re-evaluate this result.

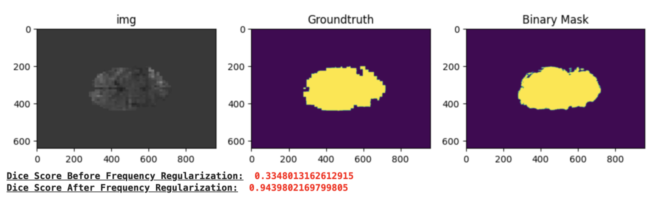

Fig. 4. Frequency Regularization and Dice Score Result

IV. Discussion

The Dice Score is a vital metric used to assess the accuracy of image segmentation algorithms, particularly in medical imaging applications such as gestational age detection from ultrasound images. This score quantifies the similarity between the segmented regions identified by the algorithm (predicted segmentation) and the actual anatomical regions (ground truth segmentation). A Dice Score ranges from 0 to 1, where a score of 1 denotes perfect agreement and 0 indicates no overlap.Initially, the Dice Score for the segmentation algorithm used in gestational age detection was 0.3348013162612915, suggesting a suboptimal performance with considerable discrepancies between the algorithm's output and the true anatomical structures. This low score indicated poor identification of key features necessary for accurate gestational age estimation, such as the crown-rump length or other fetal measurements.

Gestational Age	Estimated Delivery Date
32 weeks 6 days	2024-12-05 (According to the prediction dated April 20, 2024)

TABLE I
GESTATIONAL AGE AND ESTIMATED DELIVERY DATE RESULT

Dice Score Before	Dice Score After
0.3348013162612915	0.9439802169799805

TABLE II
EVALUATION METRICS

Upon implementing Frequency Regularization, the Dice Score improved dramatically to 0.9439802169799805. This significant increase reflects a much-improved alignment between the predicted segmentation and the ground truth, indicating that the segmentation algorithm now more accurately identifies and outlines the relevant fetal structures necessary for precise gestational age assessment. Such improvements are crucial for accurate medical diagnoses and monitoring of fetal development.

V. Conclusion

In this study focused on gestational age detection, we observed a marked improvement in the segmentation performance of fetal brain images following the implementation of Frequency Regularization. This notable advancement highlights the value and efficacy of Frequency Regularization in mitigating class imbalances and augmenting the precision of segmentation algorithms within the context of gestational age estimation.Despite these encouraging outcomes, there is still potential for enhancing the segmentation quality further. A primary limitation we identified is the size and diversity of our current dataset. To refine and optimize our segmentation algorithm effectively, a larger and more varied collection of fetal brain images is essential. Such an expanded dataset would expose the algorithm to a wider array of fetal brain structural variations and complexities, thereby bolstering its ability to generalize across different gestational stages and more accurately delineate various brain regions.

Consequently, to propel the segmentation accuracy and robustness of our algorithm for more precise gestational age detection, it is crucial to acquire an increased number of fetal brain images. These images should represent a wide spectrum of gestational ages and conditions. Expanding our dataset in this manner will not only enhance the performance of our algorithm but also ensure more reliable and precise analyses of fetal brain development for clinical assessments and research studies. This advancement will significantly contribute to improved outcomes in prenatal care and understanding of fetal development.

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