Automated Analysis of Fetal Heart Rate from VSI-Based Ultrasound Using Segmentation-Guided Optical Flow

Emilio J. Ochoa*, Luis C. Revilla*, Stefano E. Romero†, Anna Jarvis‡, Abigail Chew ‡, Madeleine Peterson§, Marika Toscano‡, Thomas Marini¶, Maria Helguera*, and Benjamin Castaneda*
*Department of Biomedical Engineering, University of Rochester, New York, USA
†Laboratorio de Procesamiento Digital de Señales, Pontificia Universidad Católica del Perú, Lima, Perú
‡Department of Ginecology and Obstetrics, Division of Maternal Fetal Medicine, John Hopkins University, Baltimore, USA
§Eastern Virginia Medical School, Old Dominion University, Norfolk, Virginia, USA
¶Department of Imaging Sciences, University of Rochester Medical Center, Rochester, New York, USA

***Abstract*—Volume Sweep Imaging (VSI) enables standardized obstetric ultrasound acquisition by non-experts in low-resource settings; helping to the assessment of diverse fetal variables. While Doppler is used to detect fetal heart changes; due to the limited constraints is not possible to apply this method, and VSI has not yet been applied for fetal heart rate (FHR) measurement without Doppler capability. This study proposes a segmentation-guided optical flow method to estimate FHR from VSI-based B-mode cine-loops. Third-trimester VSI sweeps where fetal heart was visible were manually segmented frame-by-frame by a physician. Dense optical flow was computed within the heart mask, and the mean motion angle over time was bandpass-filtered (90–200 BPM) with variable Butterworth order. A confidence score (1–5) was proposed based on the filter order that was correlated to the quantity of frames with visible heart. Out of 114 cine-loops analyzed, all clips with confidence score ≤ 3 (n=49) were non-measurable by both the algorithm and physicians. Among high-confidence clips (≥ 4; n=65), 18 were excluded due to incomplete heart visualization, leaving 47 for Bland–Altman analysis. The mean bias was -8.63 BPM with 95% limits of agreement $[-52.26, 69.52]$ BPM and no statistically significant difference ($p > 0.05$). These findings demonstrate the feasibility of integrating automated FHR estimation into existing VSI obstetric protocols without Doppler, enabling functional cardiac assessment in settings with limited access to specialized sonography.**

***Index Terms*—Fetal heart rate, volume sweep imaging, optical flow, obstetric ultrasound, low-resource settings.**

I. Introduction

Fetal heart rate (FHR) monitoring is a cornerstone of prenatal care, providing essential indicators of fetal well-being and enabling early detection of conditions such as hypoxia, arrhythmia, or intrauterine growth restriction [1]. In standard obstetric practice, FHR assessment is typically performed using Doppler ultrasound or cardiotocography, modalities that require specialized hardware, trained personnel, and continuous access to electrical resources that are often scarce in rural or low-income regions [2]. As a result, millions of pregnancies worldwide go without adequate fetal monitoring, contributing to preventable perinatal morbidity and mortality, as evidenced by the large number of intrapartum stillbirths that could be avoided with routine FHR surveillance [3,4].

Volume Sweep Imaging (VSI) has emerged as an accessible acquisition protocol that enables non-specialist healthcare workers to collect diagnostically useful ultrasound data. In VSI, the operator performs systematic sweeps of the transducer based on anatomical landmarks, following a standardized sequence that does not require detailed anatomical or ultrasound knowledge [5]. By leveraging cine-loops acquired in a reproducible manner this approach has been shown to be useful in various obstetric tasks, including fetal presentation assessment, placental localization, and biometric measurements. However, extending VSI to functional cardiac assessment presents unique challenges [6]. Unlike static anatomical measurements, FHR estimation requires precise temporal analysis of moving cardiac structures, which is complicated by the dynamic, freehand sweep motion inherent to VSI.

Conventional FHR estimation methods rely on either M-mode echocardiography or Doppler spectral analysis, both of which require targeted imaging of the fetal heart by a skilled operator [7]. In contrast, VSI acquisitions capture the heart transiently, overlapped with motion from other anatomical regions. This intermittent visualization makes it impractical to apply traditional frame-by-frame intensity tracking or frequency-domain analysis directly. Additionally, in low-resource settings, where Doppler capability and trained sonographers are often unavailable, there is an urgent need for a robust, automated method to extract FHR from VSI data [8].

In this work, we present a method for FHR analysis directly from VSI-based B-mode ultrasound sequences, without requiring Doppler modes or expert acquisition. Our method employs segmentation masks to delineate the fetal heart, followed by dense optical flow computation within the segmented ROI to capture periodic cardiac motion. Temporal smoothing and peak detection algorithms are applied to estimate heart rate, with a confidence score reflecting the reliability of the measurement.

By validating against expert physician measurements, we demonstrate that this approach achieves clinically acceptable agreement and offers a scalable solution for prenatal cardiac assessment in underserved regions. This represents a step toward integrating functional cardiac evaluation into VSI-based obstetric telemedicine workflows, bridging a critical gap in global maternal-fetal healthcare.

II. Methods

A. VSI-OB Acquisition Protocol

Ultrasound data were acquired with the standardized *Volume Sweep Imaging* protocol for obstetrics (VSI-OB). Each examination comprises eight sequential B-mode cine-loops ("clips"), each corresponding to a predefined sweep over easily identifiable abdominal landmarks. This protocol reduces operator dependence and enforces consistent coverage across subjects. A schematic of the eight-clip sequence and anatomical coverage is be presented in Figure 1.

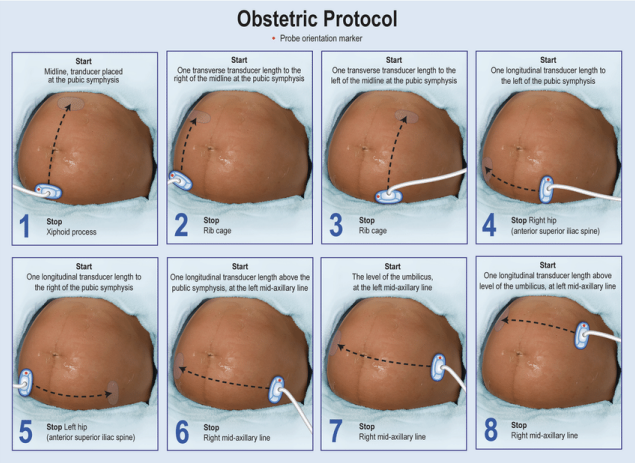


Fig. 1: Volume Sweep Imaging obstetric protocol.

B. Dataset and Manual Annotations

We enrolled 47 third-trimester patients for VSI-OB acquisition with an IRB approval at University of Rochester Medical Center. The acquisition device was a Butterfly Iq+ ultrasound (Butterfly Inc, MA). From all recorded clips, those with visible fetal heart were retained, yielding 114 B-mode clips for analysis. An experienced physician provided frame-wise binary masks delineating the fetal heart for each retained clip and reported a reference fetal heart rate (BPM) per clip (figure 3). Clips without visible heart were excluded from labeling and analysis.

C. Processing Pipeline Overview

The pipeline estimates fetal heart rate by restricting motion analysis to the physician-labeled heart region, extracting frame-to-frame optical flow, tracking the mean flow *angle* over time, band-pass filtering that 1D signal within the physiologic fetal range, and identifying the dominant frequency via FFT. Figure 2 summarizes the steps.

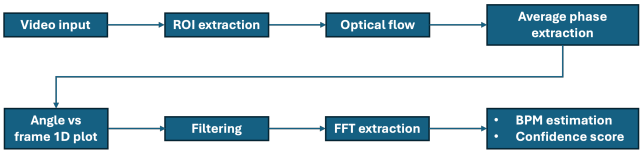


Fig. 2: Processing workflow for fetal heart rate detection.

a) ROI extraction and dense optical flow: Based only in labelled masks, a extraction of pixels inside the labels were performed to define them as the region of interest for analysis. Following that, Dense Farnebäck optical flow [11] is computed between consecutive frames using OpenCV library with tuned parameters (pyr_scale $= 0.5$, levels $= 3$, winsize $= 25$, iterations $= 5$, poly_n $= 7$, poly_sigma $= 1.5$). The flow is masked by the heart ROI and support mask.

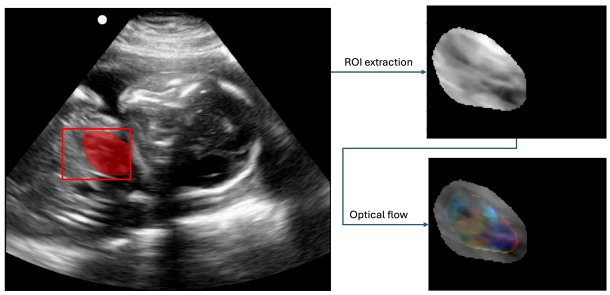


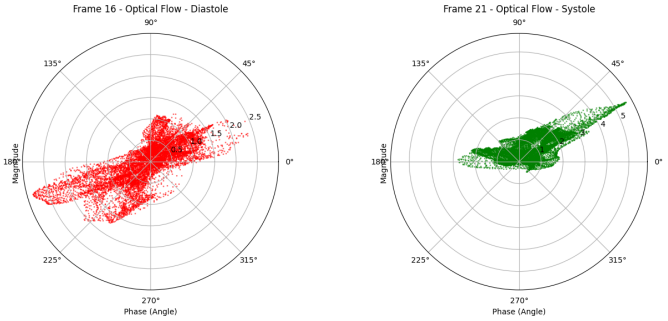
Fig. 3: Heart ROI extraction and optical flow estimation.

b) Angle tracking: Flow vectors are converted to polar form; only the *angle* image is retained. Non-zero pixels inside the ROI are pooled by their arithmetic mean, yielding a scalar angle (degrees) per time step. The resulting angle-change sequence is mean-centered to remove DC bias.

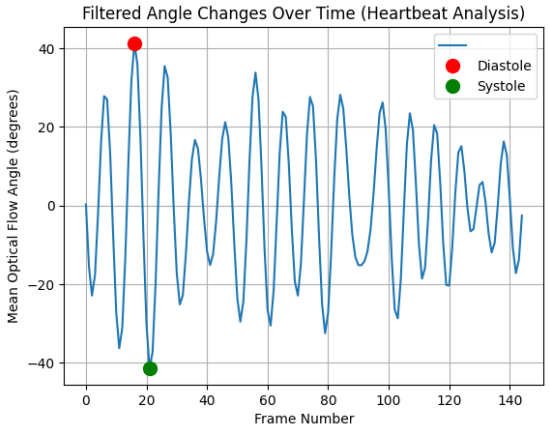
c) Band-pass filtering (physiologic range): Let $x[n]$ be the mean angle sequence sampled at video frame rate f_s (FPS). A zero-phase Butterworth band-pass filter is applied to filter between 100 and 200Hz with initial order 5. If the design is unstable for the given f_s and clip length, the order is reduced iteratively ($5 \to 4 \to \cdots \to 1$). If all orders fail, the unfiltered $x[n]$ is used and the clip is flagged as low confidence.

d) Frequency estimation and BPM: The dominant frequency is extracted from the single-sided FFT of $x_f[n]$. Let $\hat{f}$ be the frequency bin with maximum amplitude within $[100, 200]$ BPM due to physiological literature(i.e., $[1.67, 3.33]$ Hz). The heart rate estimate is $\widehat{\text{BPM}} = 60\,\hat{f}$. If no salient peak is present, $\widehat{\text{BPM}}$ is set to zero and the clip is deemed non-measurable.

e) Confidence scoring: Following the schematic in Figure 2, a discrete confidence score $\in [1, 5]$ was assigned to each cine-loop to reflect the stability of the band-pass filtering stage. The score was defined as the *final Butterworth filter order* (1–5) that could be sustained without instability. Achieving the maximum order of 5 required a sufficient number of frames to maintain a well-defined passband; when the available frame count was lower, the order had to be reduced to avoid

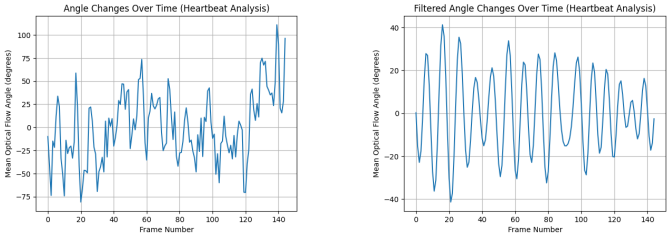


(a) (b)



(c)

Fig. 4: Angle tracking of optical flow vectors within the heart ROI. (a) Polar representation of flow angles during diastole. (b) Polar representation of flow angles during systole. (c) Temporal sequence of mean optical flow angle changes across frames, highlighting systolic and diastolic phases.



(a) (b)

Fig. 5: Band-pass filtering of mean optical flow angle sequence. (a) Raw angle-change sequence over time before filtering. (b) Filtered sequence within the physiologic range using a Butterworth band-pass filter, highlighting the periodic heartbeat pattern.

distortion or filter failure. Consequently, a drop in filter order implicitly indicated limited temporal resolution for constructing a smooth, high-confidence heart rate curve.

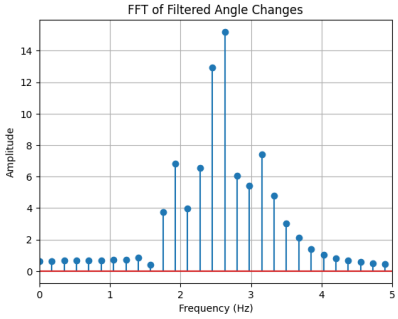


Fig. 6: Frequency estimation from filtered angle changes using FFT. The dominant frequency peak within the physiologic range is identified and converted into BPM.

D. Outcome Measures

For every analyzed clip we report: estimated heart rate $\widehat{\text{BPM}}$, number of analyzed frames, total frames, and effective filter order (confidence score 1–5). These are compared against physician-reported BPMs in the Results section.

III. Results

A. Confidence Score Distribution and Agreement

For videos with a confidence score ≤ 3 (n=49), both the algorithm and two independent expert physicians agreed that fetal heart rate could not be reliably measured (100% agreement). These clips were excluded from further quantitative evaluation.

B. Exclusion Due to Incomplete Heart Visualization

Among the remaining 65 clips (confidence scores 4 or 5), 18 were excluded because the heart was intermittently out of view due to sweep motion or acoustic shadowing, preventing the physician from establishing a continuous frame sequence for ground-truth BPM estimation.

C. Bland–Altman Analysis

The final Bland–Altman analysis was conducted on the 47 remaining clips, comparing algorithm-estimated heart rates against physician-reported BPMs. The mean difference between methods was -8.63 BPM, with 95% limits of agreement ranging from -52.26 BPM to 69.52 BPM. No statistically significant difference was observed ($p > 0.05$).

TABLE I: Confidence score distribution, exclusions, and agreement metrics for the final analysis set.

Stage	Count	Agreement w/ Doctors
Filtering by Confidence Score		
Total analyzed clips	114	–
Confidence score ≤ 3	49	100% (no possible)
Confidence score 4 or 5	65	–
Excluded (incomplete heart view)	18	–
Final Analysis Set (Bland–Altman)		
Final analysis set	47	Bias = -8.63 BPM
95% LoA (BPM)	–	$[-52.26,\ 69.52]$
p-value	–	NS

IV. Discussion

This study presents the first implementation of a fetal heart rate (FHR) estimation method directly from VSI-based B-mode ultrasound acquisitions without requiring Doppler imaging or specialized acquisition hardware. By combining physician-provided segmentation masks with dense optical flow analysis, the method was able to isolate periodic cardiac motion from freehand sweep artifacts—a long-standing limitation of VSI for functional cardiac assessment.

The confidence scoring mechanism proved useful for automatically identifying cine-loops unsuitable for reliable frequency estimation, with a threshold of ≤ 3 achieving complete agreement with expert physicians in flagging non-measurable cases. This step is critical in a telemedicine workflow, as it can prevent the reporting of unreliable results without human review [9]. The majority of exclusions among high-confidence clips were due to transient loss of the heart in the imaging plane, underscoring the importance of acquisition quality even when standardized VSI sweeps are followed. Is important to note that this is not a limitation of the algorithm, but due to the acquisition speed in VSI protocol [10].

In the final analysis set, Bland–Altman comparison showed a small difference of 8.63 BPM with the expert measurements. While the absence of systematic error is encouraging, the wide variability indicates that occasional large deviations still occur. These outliers may be attributable to residual motion contamination, limited temporal resolution in shorter clips, or physiological variability between measurement moments.

Compared to conventional Doppler- or M-mode-based methods, this approach offers the advantage of being fully compatible with low-cost, grayscale-only ultrasound devices and non-expert acquisition. This makes it particularly suited for rural or resource-limited settings where Doppler capability and continuous electricity are unavailable. Nonetheless, achieving consistent frame coverage of the fetal heart remains a challenge that will need to be addressed through improved training, acquisition feedback, or automated view selection.

Future work should focus on integrating automated heart segmentation in place of manual segmentation, expanding the dataset to improve statistical power, and exploring adaptive filtering strategies to handle clips with borderline frame counts. Incorporating real-time quality feedback to guide sweep execution could further increase the proportion of usable clips and improve measurement stability.

V. Conclusion

We developed and validated a segmentation-guided optical flow framework for estimating fetal heart rate from VSI-based ultrasound clips, demonstrating feasibility in a dataset of third-trimester pregnancies. The system reliably identified non-measurable cases and achieved clinically acceptable agreement with expert physician measurements in usable clips, despite wide limits of agreement. These findings suggest that functional cardiac assessment can be incorporated into existing VSI obstetric protocols without Doppler, enabling scalable prenatal monitoring in settings with limited access to specialized sonography. Further refinement of acquisition protocols and automated view selection will be essential to maximize reliability and clinical utility.

References

[1] C. E. Valderrama, F. Marzbanrad, L. Stroux, and G. D. Clifford, "Template-based quality assessment of the Doppler ultrasound signal for fetal monitoring," *Frontiers in Physiology*, vol. 8, Art. 511, 2017.

[2] M. Toscano, T. J. Marini, K. Drennan, T. M. Baran, J. Kan *et al*., "Testing telediagnostic obstetric ultrasound in Peru: a new horizon in expanding access to prenatal ultrasound," *BMC Pregnancy and Childbirth*, vol. 21, no. 1, Art. 328, 2021.

[3] C. E. Valderrama, N. Ketabi, F. Marzbanrad, P. Rohloff, and G. D. Clifford, "A review of fetal cardiac monitoring, with a focus on low- and middle-income countries," Physiological Measurement, vol. 41, no. 11, p. 11TR01, Nov. 2020

[4] World Health Organization, "Stillbirth." [Online]. Available: https://www.who.int/health-topics/stillbirth. [Accessed: Aug. 16, 2025].

[5] T. J. Marini, J. M. Weis, T. M. Baran, J. Kan, S. Meng *et al*., "Lung ultrasound volume sweep imaging for respiratory illness: a new horizon in expanding imaging access," *BMJ Open Respiratory Research*, vol. 8, no. 1, e000919, Nov. 2021.

[6] J. Arroyo, T. J. Marini, A. C. Saavedra *et al*., "No sonographer, no radiologist: new system for automatic prenatal detection of fetal biometry, fetal presentation, and placental location," *PLoS One*, vol. 17, e0262107, 2022.

[7] American Institute of Ultrasound in Medicine, "Prudent Use and Safety of Diagnostic Ultrasound in Pregnancy," AIUM Official Statement, May 2020.

[8] A. H. Khandoker, F. Marzbanrad, and Y. Kimura, "Editorial: Recent advances in Doppler signal processing and modeling techniques for fetal monitoring," *Frontiers in Physiology*, vol. 9, Art. 691, 2018.

[9] R. A. Tabaeeian, B. Hajrahimi, and A. Khoshfetrat, "A systematic review of telemedicine systems use barriers: primary health care providers' perspective," Journal of Science and Technology Policy Management, vol. 15, no. 3, pp. 610–635, 2024

[10] M. A. Erlick, T. J. Marini, T. Drennan, K. Drennan, A. Dozier, B. Castaneda, T. M. Baran, and M. Toscano, "Assessment of a brief standardized obstetric ultrasound training program for individuals without prior ultrasound experience," Ultrasound Quarterly, vol. 39, no. 3, pp. 124–128, Sept. 2023.

[11] Farnebäck, Gunnar. "Two-frame motion estimation based on polynomial expansion." Scandinavian conference on Image analysis. Berlin, Heidelberg: Springer Berlin Heidelberg, 2003.