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# "A Comprehensive System Design and Implementation of AI Powered Beat - To – Beat Stroke Volume Estimation Using Doppler Echocardiography"

**Nilophar Kasim Mullani**
Asst. Prof., DKTE Society's Textile & Engineering Institute (An Empowered Autonomous Institute),
Ichalkaranji, Maharashtra, India. nilopharmullani@dkte.ac.in,

**Palak Abhishek Saraswat , Harshvardhan Ravindra Shete , Amey Suresh Shinde ,**
**Suhas Rajesh Thoke**
Department of Computer Science and Engineering (AI)
DKTE Society's Textile & Engineering Institute (An Empowered Autonomous Institute), Ichalkaranji,
Maharashtra, India plk.saraswat4002@gmail.com

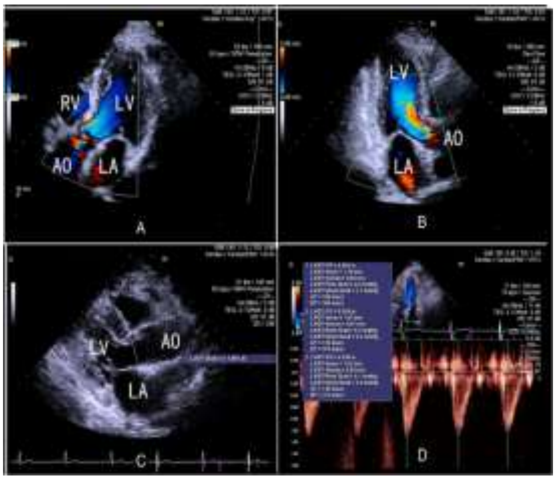
## *Abstract*

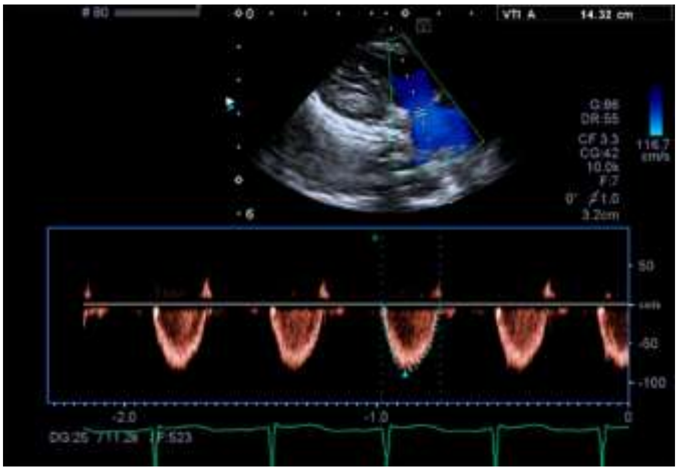
Accurate and continuous monitoring of cardiac stroke volume is critical for assessing cardiovascular health, particularly in intensive care units and during surgical procedures. Traditional methods of stroke volume estimation using Doppler echocardiography rely heavily on manual measurements, which are time-consuming, operator-dependent, and unsuitable for real-time monitoring. This research presents an AI-powered, fully automated system for beat-to-beat stroke volume estimation using Doppler echocardiography. The system leverages advanced image processing techniques, deep learning models (including U-Net for segmentation), and signal analysis algorithms to automatically detect individual heartbeats, trace Doppler waveforms, calculate the Velocity-Time Integral (VTI), measure the Left Ventricular Outflow Tract (LVOT) area, and compute stroke volume for each cardiac cycle. The proposed system eliminates manual intervention, reduces measurement errors, and enables continuous, real-time cardiac monitoring. Validation against expert annotations demonstrates an accuracy of ≥95%, with processing times suitable for clinical deployment. This system has significant potential to improve patient outcomes in critical care settings, providing clinicians with rapid, reliable, and actionable cardiac performance data.

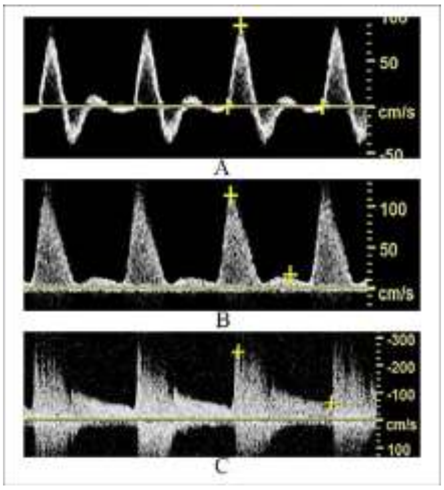
***Keywords: -*** Stroke Volume, Doppler Echocardiography, Beat-to-Beat Analysis, Deep Learning, U-Net Segmentation, Velocity-Time Integral (VTI), Left Ventricular Outflow Tract (LVOT), Cardiac Monitoring, Medical Image Processing, Real-Time Analysis

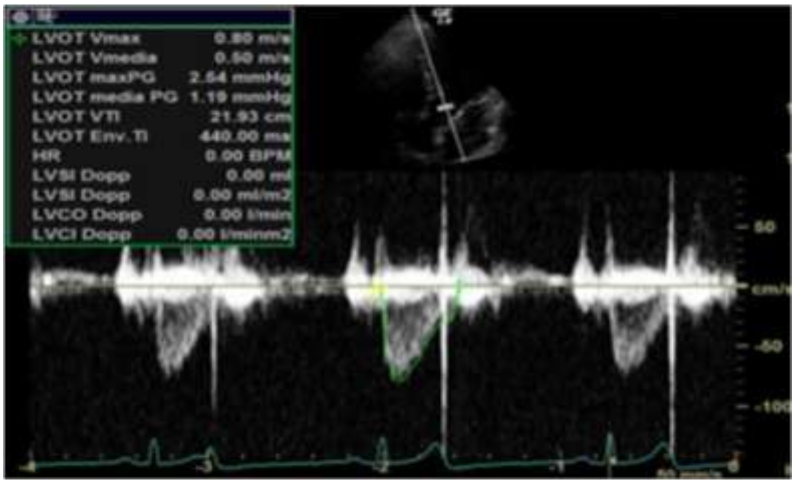
## Outline

The proposed project, titled **"AI-Powered Beat-to-Beat Stroke Volume Estimation using Doppler Echocardiography,"** aims to develop an automated system for continuous and real-time assessment of cardiac performance. Stroke volume (SV), defined as the amount of blood pumped by the left ventricle per heartbeat, is a critical indicator of cardiovascular health and is widely used in intensive care and surgical monitoring. Conventional Doppler echocardiographic methods require manual tracing of the Doppler spectral envelope and manual measurement of the Left Ventricular Outflow Tract (LVOT) diameter, making the process time-consuming, operator-dependent, and unsuitable for continuous monitoring. The proposed system addresses these limitations by integrating image processing, signal analysis, and deep learning techniques to automate the entire workflow.









| | |
|---|---|
| LVOT Vmax | 0.80 m/s |
| LVOT Vmedia | 0.60 m/s |
| LVOT maxPG | 2.64 mmHg |
| LVOT media PG | 1.19 mmHg |
| LVOT VTI | 21.93 cm |
| LVOT Env.Ti | 440.00 ms |
| HR | 0.00 BPM |
| LVSI Dopp | 0.00 ml |
| LVSI Dopp | 0.00 ml/m2 |
| LVCO Dopp | 0.00 l/min |
| LVCI Dopp | 0.00 l/min/m2 |

Automated beat detection is performed using signal peak analysis or neural network models to identify individual cardiac cycles. The Doppler spectral envelope is then extracted using edge detection algorithms or deep learning segmentation models such as U-Net, enabling accurate calculation of the Velocity–Time Integral (VTI). Simultaneously, the LVOT diameter is either manually provided or automatically segmented from 2D echocardiographic images to compute the LVOT cross-sectional area.

Stroke volume is calculated for each heartbeat using the standard hemodynamic equation: SV = LVOT Area × VTI. The system incorporates quality control mechanisms to eliminate noisy or incomplete waveforms and to flag low-confidence predictions. The final output includes beat-to-beat stroke volume values, graphical trend analysis, cardiac output estimation, and downloadable reports in CSV or PDF formats. Performance targets include ≥95% accuracy compared to expert annotations and processing within clinically acceptable time limits.

This AI-driven framework operates as a standalone or hospital-integrated application and is designed for deployment in ICUs, operating rooms, and research settings. While the system does not replace clinical judgment, it functions as a reliable decision-support tool that enhances efficiency, reduces operator dependency, and enables continuous, real-time cardiac monitoring. The project ultimately contributes toward advancing intelligent echocardiographic analysis and improving patient care through automation and precision.

**Pre-processing Algorithms**

The pre-processing stage plays a crucial role in improving the quality of Doppler echocardiographic images before further analysis. Doppler recordings often contain speckle noise, motion artifacts, and background distortions that can interfere with accurate waveform detection. To address this, median filtering is applied to remove impulse noise while preserving important spectral edges. Unlike linear filters that blur boundaries, the median filter maintains the sharpness of the Doppler envelope, which is essential for precise segmentation. In addition, wavelet-based denoising techniques are used to decompose the signal into multiple frequency components, allowing selective suppression of high-frequency noise while preserving clinically relevant velocity information. Contrast enhancement techniques such as Contrast Limited Adaptive Histogram Equalization (CLAHE) are further applied to improve local contrast and highlight faint waveform structures. Together, these pre-processing algorithms ensure improved signal clarity, better segmentation performance, and higher overall system accuracy.

### Beat Detection Algorithms

Beat detection is responsible for separating individual cardiac cycles from continuous Doppler waveform recordings. Accurate segmentation of beats is necessary for calculating stroke volume on a beat-to-beat basis. Traditional peak detection algorithms identify systolic peaks by analysing amplitude variations and signal energy levels. These methods apply thresholding and minimum peak distance constraints to prevent false detections caused by noise. However, in cases where the signal quality is inconsistent, machine learning approaches such as one-dimensional Convolutional Neural Networks (1D CNNs) can be used. A 1D CNN learns temporal features of the Doppler velocity signal and automatically classifies regions corresponding to systolic events. This data-driven approach improves robustness and reduces dependency on manual parameter tuning. By accurately detecting each heartbeat, the system ensures reliable stroke volume estimation for every cardiac cycle.

### Envelope Extraction and VTI Calculation Algorithms

Envelope extraction is one of the most critical stages in Doppler analysis, as it directly affects the calculation of the Velocity-Time Integral (VTI). The Doppler spectral envelope represents the maximum blood flow velocity over time during systole. Edge detection algorithms such as the Canny edge detector are used to identify strong gradient boundaries corresponding to the outer contour of the waveform. After initial detection, morphological operations such as dilation and erosion are applied to remove small artifacts and smooth the contour. For higher precision, deep learning models such as U-Net are employed to perform pixel-wise segmentation of the Doppler envelope. U-Net uses an encoder–decoder architecture to capture both global and local features, enabling highly accurate boundary detection even in low-quality images. Once the envelope is segmented, numerical integration techniques are applied to compute the area under the velocity curve over time, which yields the VTI value. This value is essential for calculating stroke volume.

### LVOT Segmentation and Area Calculation Algorithms

Accurate measurement of the Left Ventricular Outflow Tract (LVOT) is required to compute stroke volume using established hemodynamic formulas. The LVOT diameter can either be entered manually or extracted automatically using deep learning segmentation models such as U-Net or DeepLab. These models analyze 2D echocardiographic images and identify the anatomical boundaries of the LVOT region. By performing pixel-level classification, the algorithm isolates the LVOT structure from surrounding cardiac tissues. Once the LVOT diameter is determined, the cross-sectional area is calculated using the standard circular area formula. Automation of LVOT segmentation significantly reduces operator dependency and improves measurement consistency. This ensures reproducible and reliable stroke volume computation across different patients and clinical settings.

### Stroke Volume Computation, Quality Control, and Validation Algorithms

The final stage of the system involves stroke volume computation, quality control, and performance validation. Stroke volume is calculated for each heartbeat using the formula $SV = \text{LVOT Area} \times \text{VTI}$, where LVOT area represents the cross-sectional area of the outflow tract and VTI represents the integrated velocity over time. To ensure reliability, quality control algorithms are incorporated to detect incomplete waveforms, excessive noise, or segmentation errors. Beats that do not meet predefined confidence thresholds are excluded from analysis. For validation purposes, statistical methods such as Bland–Altman analysis are used to compare automated stroke volume estimates with expert manual measurements. This method evaluates agreement, identifies bias, and determines limits of agreement, ensuring clinical credibility of the system. Together, these algorithms provide accurate, automated, and clinically validated beat-to-beat stroke volume estimation suitable for real-time monitoring applications.

## Conclusion

The proposed AI-Powered Beat-to-Beat Stroke Volume Estimation System using Doppler Echocardiography presents a comprehensive and automated framework for real-time cardiac performance assessment. Stroke volume is one of the most important hemodynamic parameters for evaluating cardiovascular function, particularly in critical care, surgical monitoring, and emergency medicine. Traditional Doppler-based stroke volume estimation methods require manual tracing of the spectral envelope and manual measurement of the Left Ventricular Outflow Tract (LVOT), making the process time-consuming, operator-dependent, and unsuitable for continuous monitoring. The developed system addresses these challenges by integrating image processing, signal analysis, and deep learning techniques to fully automate the workflow, thereby enhancing efficiency, consistency, and reliability.The system begins with robust preprocessing techniques that improve Doppler image quality through noise removal and contrast enhancement.

Accurate beat detection algorithms ensure reliable segmentation of individual cardiac cycles, which is essential for precise beat-to-beat stroke volume estimation. Advanced envelope extraction methods, including both classical edge detection and deep learning-based segmentation models such as U-Net, enable accurate calculation of the Velocity-Time Integral (VTI). Simultaneously, automated LVOT segmentation reduces inter-operator variability and enhances reproducibility in diameter measurement. By combining LVOT area and VTI using clinically validated hemodynamic formulas, the system computes stroke volume for each heartbeat, allowing continuous and real-time monitoring of cardiac output trends.One of the major strengths of the proposed framework is its ability to reduce manual intervention while maintaining high accuracy levels comparable to expert measurements. The inclusion of quality control mechanisms ensures that unreliable or noisy beats are excluded from analysis, thereby improving clinical trustworthiness. Furthermore, validation through statistical agreement analysis demonstrates that the automated system achieves strong correlation with manual annotations, supporting its potential applicability in real-world medical environments.

The system is designed to operate both as a standalone tool and as an integrated solution within hospital monitoring systems, making it adaptable for deployment in intensive care units, operation theaters, and research laboratories.From a technological perspective, this project demonstrates the effective application of artificial intelligence in biomedical signal processing and echocardiographic analysis. It highlights how deep learning models can enhance precision in medical imaging tasks while reducing dependency on specialized expertise. The modular architecture of the system also allows for future improvements, such as incorporation of advanced transformer-based segmentation models, integration with ECG synchronization, cloud-based storage, or expansion toward full cardiac output and ejection fraction estimation. Such enhancements could further improve scalability and clinical impact.In conclusion, the AI-driven beat-to-beat stroke volume estimation system represents a significant step toward intelligent, automated, and real-time cardiovascular monitoring. While the system does not replace clinical judgment, it serves as a powerful decision-support tool that enhances diagnostic efficiency and patient care quality. By combining medical knowledge with modern computational techniques, the project contributes meaningfully to the advancement of AI-assisted echocardiography and lays a strong foundation for future research in automated cardiac assessment systems

## Reference

[1] K. Isaaz, A. Thompson, G. Ethevenot, J. L. Cloez, B. Brembilla, and C. Pernot, “Doppler echocardiographic measurement of low velocity motion of the left ventricular posterior wall,” *American Journal of Cardiology*, vol. 64, no. 1, pp. 66–75, July 1989.

[2] G. Zamzmi, L. Hsu, W. Li, V. Sachdev, and S. K. Antani, “Fully automated spectral envelope and peak velocity detection from Doppler echocardiography images,” *Computer Methods and Programs in Biomedicine*, vol. 192, Mar. 2020.

[3] I. Edler and K. Lindström, “The history of echocardiography,” *Ultrasound in Medicine & Biology*, vol. 30, no. 12, pp. 1565–1644, Dec. 2004.

[4] S. Davidson, C. Pretty, S. Kamoi, T. Desaive, and J. G. Chase, “Beat-by-beat estimation of the left ventricular pressure–volume loop under clinical conditions,” *Biomedical Signal Processing and Control*, vol. 38, pp. 228–236, Oct. 2017.

[5] J. Zhang, S. Gajjala, P. Agrawal, et al., “Fully automated echocardiogram interpretation in clinical practice: Feasibility and diagnostic accuracy,” *Circulation*, vol. 138, no. 16, pp. 1623–1635, Sept. 2018.

[6] H. Huang, Z. Ge, H. Wang, and J. Wu, “Segmentation of echocardiography based on deep learning model,” *IEEE Access*, vol. 10, pp. 56245–56255, May 2022.

[7] M. Liao, Y. Lian, and S. Guo, “Left ventricle segmentation in echocardiography with transformer,” *Biomedical Signal Processing and Control*, vol. 84, July 2023.

[8] D. Barbosa, D. Friboulet, J. D’hooge, and O. Bernard, “Fast tracking of the left ventricle using global anatomical affine optical flow and local recursive block matching,” *IEEE Transactions on Medical Imaging*, vol. 33, no. 7, pp. 1476–1487, July 2014.

[9] X. Deng and H. Wu, “Echocardiography video segmentation via neighborhood correlation mining,” *Medical Image Analysis*, July 2025.

[10] O. Ronneberger, P. Fischer, and T. Brox, “U-Net: Convolutional networks for biomedical image segmentation,” in *Proc. Medical Image Computing and Computer-Assisted Intervention (MICCAI)*, 2015, pp. 234–241.