

## Abstract

**Objective:** Cine fluoroscopy (CF)-based routine checkup is the established method for mechanical prosthetic heart valve (MPHV) assessment to detect a condition called prosthetic valve dysfunction (PVD), which is a serious complication of valve replacement surgery (VRS). The current clinical practices involve extensive manual interventions for MPHV assessment, which are likely to suffer from intra and inter-observer variability. In addition, given the clinical burden, there is a need for automating CF-based PVD detection and making it deployable. MPHV localization in CF is a crucial pre-requisite for its automated assessment. Since CF involves Xray exposure and may not be available to a large population, a wearable modality like phonocardiography (PCG) seems to be a promising alternative. Despite the state-of-the-art performance of PCG-based methods, they are not deployable in clinical settings for early detection, which is crucial for improved survivability and patient management. **Problem statement:** To the best of the knowledge, PVD detection has not been automated yet and it is still carried out manually by the clinicians. The proposed work aims to automate CF and PCG-based PVD detection and then deploy the PCG-based PVD detection scheme in clinical settings. **Methodology:** CF-based PVD detection involves automated MPHV localization followed by PVD detection of CF videos. 38 participants with MPHV implant (20 functional MPHV and 18 PVD) were recruited and their CF was recorded. For automated localization, a novel, knowledge-based, physiologically constrained, method was developed. The key physiological knowledges utilized for the measurement of spatiotemporal prior were: difference in the radio-opacity of MPHV and native tissues in the thoracic region enables edge-detection-based spatial saliency determination. Second, MPHV, being implanted inside the heart is subjected to cardiac motion, which is temporally salient with respect to other objects in the thoracic region. For the automated CF-based PVD detection, a novel lightweight 3D convolutional neural network (CNN) framework was explored to perform binary classification (normal vs abnormal) of MPHV functioning and the results were compared with three existing lightweight 3D-CNN frameworks. The first and second frameworks accepted single input volumes, unprocessed CF and CF with localized MPHV respectively. Framework 3 accepted both the inputs, concatenated channel-by-channel. A novel multi-input fusion scheme was proposed (framework 4), which performed weighted-addition of the two inputs without increasing its dimension. The novelty of the framework is that the input weights are tuned during training. The frameworks were trained and tested on a dataset of 1150 CF samples (544 normal, 606 abnormal) and were made interpretable using gradient attribution maps. A customized and extended method was developed to obtain gradient attribution maps for novel framework. For the automated PCG-based classification of valvular heart diseases (VHD, pre-VRS), analytic continuous wavelet transform (CWT) scalograms were utilized as the time–frequency representations (TFRs) of the PCG signals. A 2-D CNN was designed for the multiclass classification (aortic stenosis, mitral regurgitation, mitral stenosis, mitral valve prolapse, and normal) of PCG signal’s TFR. For the automated PCG-based PVD detection, a 2-D CNN was explored towards the automated classification of persistence spectrum images of the PCG. Persistence spectrum, a TFR, displays the duration for which a particular frequency is present. It enables the identification of the hidden components of a signal.

This work explored persistence spectrum for PCG analysis. In all, 4215 PCG samples (2127 normal and 2088 PVD) were used for training and testing the CNN. Two AI interpretation techniques, occlusion maps and deep dream images, were used to introduce interpretability in the DL models' decision-making for both, VHD classification (pre-VRS) and PVD detection (post-VRS). The proposed work also aims to develop an internet of medical things (IoMT)-based automated PVD detection method for deployment in clinical settings. A standalone container was developed for carrying out PVD detection, which was then pushed to a virtual machine (VM). The VM, being a portable and interoperable system, was deployed on a server. An electronic stethoscope, for the collection of PCG, was connected to a smartphone, which was then used to stream the PCG data to the VM. **Results:** The proposed localization task generated an average precision (AP) of 97.87(5.38)%. MPHV was accurately detected in all the frames of all 38 CF videos. Wilcoxon rank sum test ( $\alpha=0.05$ ), performed on AP for PVD and functional-MPHV, generated the p-value, 0.8358, indicating that the proposed localization framework's performance was not affected by MPHV functioning. For the automated CF-based PVD detection, proposed framework 4 outperformed other frameworks with an overall accuracy of mean(SD)=97.34(5.89)% obtained during fivefold cross-validation (CV). Gradient attribution maps provided class-specific spatial features making the frameworks interpretable. The 3D-CNN in framework 4 "looked at" MPHV leaflets for the detection of abnormal class. For the automated PCG-based VHD classification, the highest accuracy achieved during fivefold CV was 99.6%, and the overall accuracy was 98.32(1.02)% for a publicly available PCG database. The overall accuracy of the proposed method for binary classification tested on the PhysioNet database was 93.07%. For the automated PCG-based PVD detection, the overall accuracy of 95.73(7.62)% was achieved during fivefold CV with the highest accuracy of 100% for three folds. Through AI interpretation, novel findings of native valve and MPHV's PCG characteristics in the spectral domain, corresponding to cardiac events were revealed, making the CNN decision transparent. The IoMT pipeline was successfully deployed and tested in clinical settings, generating correct classifications in a time-efficient manner (processing time=13.80(0.72)seconds, and communication time=6.99(0.80)seconds). **Significance:** The novel localization framework achieves state-of-the-art performance even in the presence of other non-biological objects. Automation is achieved for MPHV localization in CF frames. Clinical translation of the state-of-the-art interpretable and lightweight automated CF-based PVD detection framework has the potential to address the clinical burden imposed by PVD and address the inter and intra observer variability. The novel explainable PCG-based DL model potentially addresses PVD-induced clinical burden in resource-constrained settings with no radiation exposure and can be used for screening. Finally, the proposed IoMT framework for the deployment of PCG-based PVD detection is made scalable, interoperable and portable using commonly available gadgets like smartphones and PC. This ensures prevention of post-deployment failures in clinical settings.

**Keywords:** Mechanical prosthetic heart valve, Automated prosthetic valve dysfunction detection, Cine fluoroscopy, Phonocardiography, IoT-enabled deployment