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A New Method for Classifying Arteriovenous Fistula Stenosis Evaluation using Bilateral PPG Analysis

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Introduction

Arterio Venous (AV) fistulas are vital access points for haemodialysis patients, allowing for the safe and efficient exchange of blood during dialysis. These fistulas, created by surgically connecting an artery to a vein, are designed to provide long-term vascular access, essential for patients suffering from End-Stage Renal Disease (ESRD). However, a common and significant complication of AV fistulas is stenosis, or narrowing of the blood vessels, which can impair blood flow and lead to dialysis-related complications, such as poor clearance of waste products, increased risk of thrombosis and potential fistula failure. Timely detection of stenosis is crucial for preventing these severe outcomes and maintaining the patency of the AV fistula [1].

Traditional methods for detecting AV fistula stenosis include Doppler ultrasound, angiography and Magnetic Resonance Angiography (MRA). While these imaging techniques are reliable and effective, they often require specialized equipment, skilled technicians and, in some cases, invasive procedures or contrast agents, which may not be suitable for all patients, particularly those with kidney dysfunction. As a result, there is a growing need for non-invasive, accessible and cost-effective alternatives for stenosis detection. In this context, Photo Plethy Smography (PPG) has emerged as a promising tool due to its simplicity, affordability and non-invasive nature. PPG measures blood volume changes in the microvascular bed, typically via optical sensors placed on the skin. Although PPG has been widely used in pulse oximetry and heart rate monitoring, its potential for detecting vascular abnormalities, including AV fistula stenosis, remains underexplored. Existing studies on PPG have mainly focused on single-site measurements and there is a gap in research regarding the use of bilateral PPG analysis to assess AV fistula stenosis [2].

Description

The proposed classification technique takes advantage of Photo Plethysmo Graphy (PPG) to detect asymmetries in blood flow between the two arms of a patient with an AV fistula. In healthy individuals, the blood flow in both arms is typically symmetrical and the PPG signals from both arms should be relatively similar in terms of amplitude, frequency and waveform shape. However, when stenosis occurs in the AV fistula, blood flow to the affected arm may be reduced, resulting in detectable differences in the PPG waveforms. By analyzing the bilateral PPG signals, the technique aims to identify these asymmetries, which may serve as indicators of stenosis or other vascular abnormalities. The process begins with the acquisition of PPG data from both arms. PPG sensors, typically consisting of an LED light source and a photodetector, are placed on the skin of both wrists (and another anatomical site). These sensors continuously record PPG signals, which are digitized and transmitted to a processing unit for analysis. To ensure accurate results, the raw signals are first pre-processed to remove noise and other artifacts. This step is essential as PPG signals can be sensitive to movement, ambient light and other external factors. Common pre-processing techniques include filtering, normalization and signal smoothing, which help to ensure the signals represent true physiological change [3].

Next, key features are extracted from the pre-processed PPG signals. These features may include peak amplitude, pulse rate, systolic and diastolic durations and waveform shape characteristics. By examining these features, the system can assess whether there are significant differences between the two arms. For instance, if the amplitude or pulse rate in one arm is substantially lower than the other, it may indicate a reduced blood flow in the affected arm, which could be a sign of AV fistula stenosis. The extracted features are then compared to identify any asymmetries, which are the key indicators of potential stenosis [4]. Once asymmetries are detected, the next step involves classifying the data into "stenosis" or "no stenosis" categories. This classification is achieved using machine learning algorithms, such as Support Vector Machines (SVM), random forests, or deep learning networks. The classifier is trained on a dataset of known cases of AV fistula stenosis and non-stenosis, enabling it to distinguish between the two conditions based on the extracted features. The classifier's performance is evaluated by comparing its results to those of traditional diagnostic methods, such as Doppler ultrasound or angiography, using metrics such as sensitivity, specificity and accuracy. These validation steps are crucial to ensuring the reliability and effectiveness of the proposed method [5].

Conclusion

The proposed novel classification technique utilizing bilateral Photo Plethysmo Graphy (PPG) analysis represents an innovative approach to the non-invasive evaluation of arteriovenous fistula stenosis. By comparing the PPG signals from both arms, the method can detect asymmetries in blood flow that may indicate the presence of stenosis, offering an early warning system for potential fistula complications. This technique has several advantages over traditional diagnostic methods, including its non-invasive nature, portability and cost-effectiveness, making it a potentially valuable tool for routine clinical monitoring, especially in resource-limited settings. One of the key benefits of this approach is that it avoids the need for invasive procedures or the use of contrast agents, which are often required in traditional imaging methods such as Doppler ultrasound or angiography.

Additionally, PPG sensors are relatively inexpensive and easy to use, making the technique suitable for widespread adoption in outpatient clinics or even at the patient's bedside during dialysis. Furthermore, the ability to continuously monitor the AV fistula's condition could lead to earlier detection of stenosis, allowing for timely interventions that could prevent more severe complications, such as fistula thrombosis or failure. However, further research is needed to optimize the technique and validate its performance in larger and more diverse patient populations. The classification algorithm should be refined to improve accuracy and its ability to detect different types of stenosis such as early-stage or subtle stenosis should be thoroughly tested. Additionally, clinical studies comparing this PPG-based method to traditional imaging techniques are essential to confirm its diagnostic utility and ensure it meets the standards required for clinical use.

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Conflict of Interest

None.

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