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Phonocardiography: Revival of Cardiac Auscultation in the Digital Era: A Clinician-Oriented Review

Keywords: Phonocardiography; Cardiac Auscultation; Digital Stethoscope; Heart Murmurs; Cardiovascular Screening; Artificial Intelligence

Abstract

Cardiac auscultation remains a fundamental component of bedside cardiovascular examination. However, traditional auscultation using an acoustic stethoscope is highly dependent on clinician expertise and subjective interpretation. Phonocardiography (PCG), the graphical recording of heart sounds and murmurs, provides an objective method for analyzing cardiac acoustic signals. With the emergence of digital stethoscopes, advanced signal processing, and artificial intelligence (AI)-based sound analysis, PCG has significantly regained attention as a diagnostic adjunct in contemporary cardiology.

Recent studies have demonstrated promising diagnostic performance of PCG-based algorithms, with reported sensitivities ranging from 80–92% and specificities of 75–90% for detecting pathological heart murmurs and certain valvular heart diseases. While echocardiography remains the gold standard for structural cardiac evaluation, PCG offers advantages in screening, documentation, and remote monitoring, particularly in primary care and resource-limited settings.

This review discusses the principles of phonocardiography, current clinical applications, diagnostic performance, integration with artificial intelligence, and its potential role alongside echocardiography in modern clinical practice.

Introduction

Cardiac auscultation has been a cornerstone of bedside diagnosis since the invention of the stethoscope by René Laennec in 1816. Despite remarkable advances in cardiovascular imaging such as echocardiography and cardiac magnetic resonance imaging, auscultation continues to play an essential role in initial cardiovascular evaluation.

However, conventional auscultation has important limitations. Several studies have demonstrated significant variability in the diagnostic accuracy of cardiac auscultation among clinicians. In a classic study published in JAMA, only 20–40% of trainees were able to correctly identify common cardiac murmurs during auscultation.

Phonocardiography (PCG) was introduced to address these limitations by providing an objective visual representation of heart sounds. Early PCG systems gained popularity during the mid-20th century but were gradually replaced by echocardiography due to the latter's ability to visualize cardiac anatomy directly.

In recent years, the development of digital stethoscopes, advanced signal processing, and machine learning-based acoustic analysis has renewed interest in PCG. Contemporary PCG systems can detect

abnormal heart sounds with diagnostic accuracies approaching those of expert clinicians, making them potentially valuable tools for cardiovascular screening and education.

Principles of Phonocardiography

Phonocardiography refers to the recording of heart sounds and murmurs using sensitive microphones or electronic sensors placed on the chest wall. These sounds are converted into electrical signals and displayed graphically as waveforms.

Heart sounds primarily originate from vibrations produced during cardiac valve closure and blood flow turbulence. The two fundamental heart sounds are:

- **First heart sound (S1):** produced by closure of the atrioventricular valves.
- **Second heart sound (S2):** produced by closure of the semilunar valves.

Additional sounds such as **S3** and **S4**, as well as systolic and diastolic murmurs, can also be recorded using PCG.

The phonocardiogram is usually synchronized with an electrocardiographic (ECG) tracing to correlate acoustic events with electrical cardiac activity.

Evolution of Phonocardiography

Early phonocardiography systems were bulky and required specialized equipment. As a result, their use remained largely confined to research laboratories. The advent of portable electronic sensors and digital stethoscopes has significantly simplified the recording process.

Modern PCG systems allow:

- Digital recording of heart sounds
- Noise filtering
- Waveform visualization
- Storage and remote sharing of recordings

These innovations have facilitated the integration of PCG into routine clinical practice.

Clinical Applications of Phonocardiography

1. Detection of Heart Murmurs

PCG provides an objective method to document systolic and diastolic murmurs. It allows clinicians to determine:

- Timing of murmurs
- Intensity
- Duration
- Frequency characteristics

This is particularly useful for differentiating pathological murmurs from innocent murmurs in clinical settings.

2. Valvular Heart Disease

Phonocardiography plays a significant role in the evaluation of valvular disorders. Characteristic phonocardiography patterns help identify the timing and acoustic features of murmurs associated with these conditions. While echocardiography remains the gold standard for diagnosis, PCG can serve as a useful screening tool.

Aortic Stenosis

Aortic stenosis results from obstruction to left ventricular outflow due to narrowing of the aortic valve. Common causes include degenerative calcification, congenital bicuspid valve, and rheumatic disease.

Phonocardiography features:

- Harsh crescendo–decrescendo systolic murmur
- Begins shortly after S1 and peaks in mid-systole
- Terminates before S2
- Often associated with reduced or delayed A2 component of S2
- Possible ejection clicks in congenital cases

Aortic Regurgitation

Aortic regurgitation occurs when the aortic valve fails to close completely, allowing retrograde blood flow into the left ventricle during diastole.

Phonocardiography features:

- High-pitched early diastolic decrescendo murmur
- Begins immediately after A2
- Best recorded along the left sternal border
- May be accompanied by Austin Flint murmur, a mid-diastolic rumble caused by regurgitant jet interference with the mitral valve

Mitral Stenosis

Mitral stenosis is most caused by rheumatic heart disease, leading to obstruction of blood flow from the left atrium to the left ventricle.

Phonocardiography features

- Loud S1 due to stiff valve closure
- Opening snap (OS) shortly after S2

- Low-frequency diastolic rumbling murmur
- Presystolic accentuation in patients with sinus rhythm
- Shorter S2–OS interval correlates with increased severity

Mitral Regurgitation

Mitral regurgitation occurs when the mitral valve fails to close properly during systole, allowing backward flow into the left atrium.

Phonocardiography features:

- Holosystolic (pansystolic) murmur
- Begins with S1 and extends to S2
- Usually uniform intensity
- Often associated with soft or absent S1
- May show S3 due to volume overload

Mitral Valve Prolapse

Mitral valve prolapses results from systolic displacement of the mitral leaflets into the left atrium.

Phonocardiography features

- Mid-systolic click
- Followed by a late systolic murmur
- Murmur duration varies with ventricular volume

Tricuspid Regurgitation

Tricuspid regurgitation involves backflow of blood from the right ventricle to the right atrium during systole.

Phonocardiography features

- Holosystolic murmur
- Best heard at the lower left sternal border
- Murmur intensity increases during inspiration (Carvallo's sign)
- Possible right-sided S3

Tricuspid Stenosis

Tricuspid stenosis is a relatively rare condition, most commonly of rheumatic origin.

Phonocardiography features

- Diastolic rumbling murmur
- Occurs after an opening snap
- Intensifies with inspiration
- Associated with prominent jugular venous pulsations

Pulmonary Stenosis

Pulmonary stenosis is commonly congenital, leading to obstruction of right ventricular outflow.

Phonocardiography features

- Systolic crescendo–decrescendo murmur
- Best recorded at the left upper sternal border
- May include an ejection click
- Delayed P2 component of S2

Pulmonary Regurgitation

Pulmonary regurgitation occurs when the pulmonary valve fails to close completely.

Phonocardiography features

- Early diastolic decrescendo murmur
- Best heard at the left upper sternal border
- In pulmonary hypertension, produces the Graham Steell murmur

3. Congenital Heart Disease

Phonocardiography can assist in the early detection of congenital cardiac anomalies, including:

- Ventricular Septal Defect
- Patent Ductus Arteriosus
- Atrial Septal Defect

Early recognition of abnormal heart sounds may prompt timely referral for definitive imaging.

4. Heart Failure Evaluation

The presence of a third heart sound (S3) is commonly associated with ventricular dysfunction and volume overload, particularly in patients with systolic heart failure. PCG can detect low-frequency sounds that may be difficult to appreciate with conventional auscultation.

5. Cardiovascular Screening

In primary care and community health settings, PCG may serve as a cost-effective screening tool for cardiovascular disease, especially in regions where access to advanced imaging is limited.

Integration with Artificial Intelligence

Recent advances in machine learning have significantly expanded the diagnostic potential of phonocardiography. Artificial intelligence algorithms can analyze large datasets of heart sound recordings to detect abnormal patterns.

AI-assisted PCG systems are capable of:

- automated murmur detection
- classification of heart sounds
- prediction of valvular disease

These technologies may improve diagnostic accuracy and reduce dependence on subjective clinical interpretation. Modern PCG analysis systems utilize machine learning algorithms trained on large datasets of annotated heart sound recordings.

Common methodologies include:

1. Signal Processing Techniques

Heart sound recordings are first processed to remove background noise using techniques such as:

- band-pass filtering
- wavelet transformation
- adaptive noise cancellation

2. Feature Extraction

Important acoustic features are extracted from the phonocardiogram, including:

- frequency spectrum
- temporal features (S1–S2 intervals)
- amplitude variation
- spectral entropy

3. Machine Learning Models

Extracted features are then analyzed using algorithms such as:

- Convolutional Neural Networks (CNN)
- Recurrent Neural Networks (RNN)
- Vision Transformers
- Support Vector Machines (SVM)

Deep learning models are particularly effective because they can automatically identify complex patterns in heart sound recordings.

Diagnostic Accuracy and Quantitative Evidence

Several recent studies have evaluated the diagnostic performance of AI-assisted phonocardiography systems.

AI-assisted PCG systems have demonstrated encouraging results in murmur detection and classification:

- Sensitivity for pathological murmur detection: 80–92%
- Specificity: 75–90%
- Overall classification accuracy: approximately 85–90%

Deep learning models trained on large heart sound datasets have achieved particularly strong performance. In a study published in IEEE Journal of Biomedical and Health Informatics, transformer-based neural networks identified congenital valvular murmurs with an accuracy exceeding 88%.

Similarly, research in Computers in Biology and Medicine reported that AI-assisted PCG could distinguish normal from abnormal heart sounds with over 90% sensitivity in controlled datasets.

Despite these promising findings, real-world diagnostic performance may be lower due to background noise, patient variability, and recording conditions. Consequently, PCG is currently best regarded as a screening or triage tool rather than a definitive diagnostic modality.

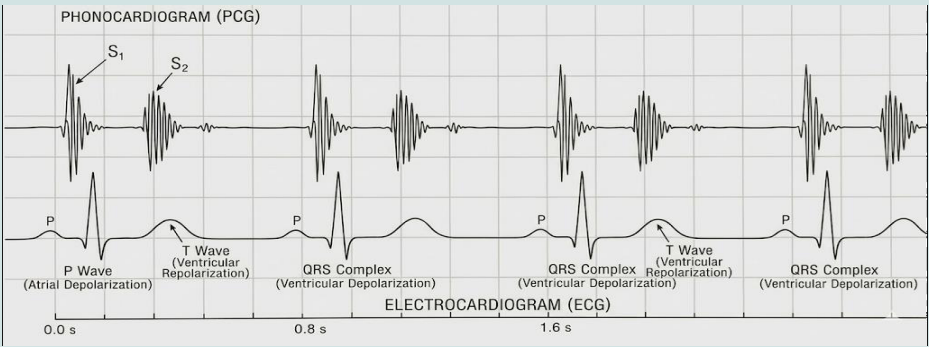


Figure 1: Simultaneous recording of phonocardiography (PCG) and electrocardiography (ECG) demonstrate correlation between electrical and acoustic cardiac events.

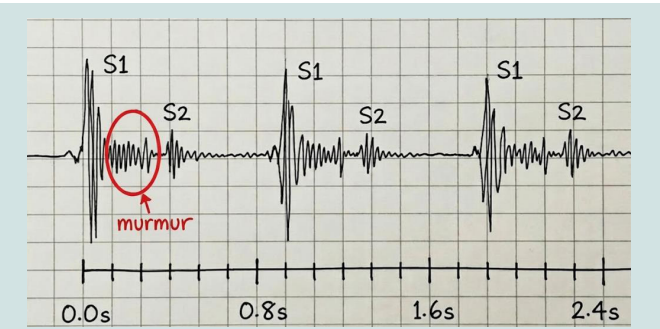


Figure 2: Systolic murmurs occur during heart muscle contraction (between S1 and S2 sounds) due to heart valve stenosis or regurgitation. While diastolic murmurs (between S2 and S1) are noticed in cases of mitral or tricuspid stenosis.

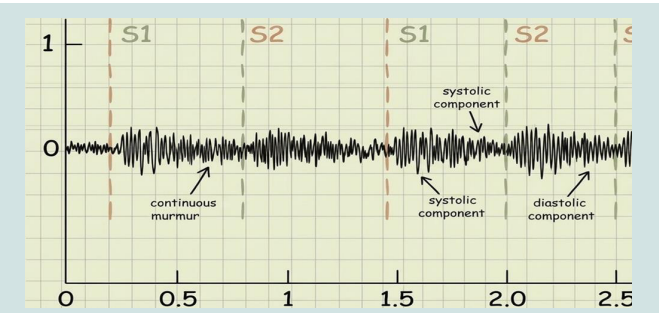


Figure 3: Continuous murmurs are classically associated with Patent Ductus Arteriosus. Ventricular septal defects typically produce holosystolic murmurs.



Figure 4: Abnormal S3 which may often indicate systolic heart failure, volume overload, or mitral regurgitation.

Phonocardiography versus Echocardiography

Although PCG provides objective acoustic analysis of heart sounds, it cannot directly visualize cardiac anatomy. In contrast, echocardiography allows detailed assessment of:

- valve morphology
- chamber dimensions
- ventricular function
- blood flow patterns

Because of these capabilities, echocardiography remains the gold-standard imaging modality. However, PCG offers several complementary advantages:

Advantages of PCG

- Non-invasive and inexpensive
- Portable and easy to perform
- Suitable for mass screening
- Allows continuous monitoring
- Enables digital storage and telemedicine applications

Advantages of Echocardiography

- Direct visualization of cardiac structures
- Quantitative hemodynamic assessment
- Precise measurement of valve gradients and regurgitation severity

In practical clinical workflows, PCG may be particularly useful for:

- Primary care screening for heart murmurs
- Rural or resource-limited settings where echocardiography is unavailable
- Telemedicine-based cardiac evaluation
- Medical education and auscultation training

In such contexts, abnormal PCG findings can serve as a trigger for

referral for definitive imaging with echocardiography.

Clinical Scenarios Where PCG Adds Greatest Value

Based on current evidence, phonocardiography may be particularly useful in the following settings:

Primary Care Screening

PCG can assist general practitioners in identifying patients who require referral for echocardiography.

Pediatric Cardiology Screening

Digital PCG systems may help distinguish innocent murmurs from pathological murmurs in children.

Telemedicine and Remote Monitoring

Smartphone-connected digital stethoscopes allow transmission of heart sound recordings for remote expert interpretation.

Role in Medical Education

Declining exposure to classical cardiac auscultation has been reported among medical trainees. Phonocardiography provides a valuable educational tool by allowing learners to visualize heart sounds and correlate them with clinical findings.

Recorded phonocardiograms can be used in teaching sessions to demonstrate characteristic murmurs and improve auscultatory skills.

Real-World Limitations

Despite promising research results, several practical challenges remain:

- Dataset bias: Many models are trained on limited or curated datasets.
- Environmental noise: Clinical environments may reduce signal quality.
- Device variability: Different digital stethoscopes produce different signal characteristics.
- Regulatory approval: AI-based diagnostic tools require extensive validation before clinical deployment.

Therefore, AI-assisted PCG systems should currently be considered clinical decision-support tools rather than standalone diagnostic systems.

Future Directions

The future of phonocardiography lies in the integration of digital stethoscopes, wearable sensors, and artificial intelligence. Portable PCG devices linked to smartphone applications may enable remote cardiac screening and telemedicine-based diagnosis. With increasing emphasis on cost-effective healthcare, PCG has the potential to play a major role in cardiovascular screening programs worldwide.

Conclusion

Phonocardiography represents an objective extension of traditional cardiac auscultation. Advances in digital technology and artificial intelligence have renewed interest in this classical diagnostic method. For clinicians, PCG offers a valuable tool for documenting heart sounds, improving murmur detection, and enhancing medical education. While it cannot replace advanced imaging modalities, phonocardiography may serve as an important adjunct for early detection and screening of cardiovascular disease.

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