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CONTINUOUS NON-INVASIVE BLOOD PRESSURE MONITORING: A REVIEW OF MEASUREMENT CHALLENGES AND DEVICE MODELLING

C. Hymavathi, Raghu Akkapaka, Ch. Venkatesh,
Government College of Nursing, Kurnool.

ABSTRACT:

Healthy living is closely associated with balanced nutrition, regular physical activity, avoiding smoking, and managing stress—factors that directly influence arterial health. Continuous arterial blood pressure can be monitored non-invasively using two major technologies: The Finapres™ volume-clamp device and the Colin® CBM-7000 radial artery tonometer. This study examines the discrepancies reported in the output of these two systems. By analysing their operating principles and modelling their mechanical and vascular responses under provocation, potential explanations for the conflicting measurements are explored

Keywords: Arterial tonometry, Hemodynamic modelling, peripheral vasoconstriction, Viscoelastic tissue modelling, Cardiovascular monitoring.

INTRODUCTION:

Arterial health plays a vital role in maintaining physiological stability. The arterial network is not merely a passive system of vessels; it is an actively regulated distribution mechanism capable of adapting to changes in posture, flow demand, and stress within seconds. With increasing interest in assessing rapid arterial dynamics, the need for accurate, continuous, and non-invasive blood-pressure measurement has grown significantly.

Two commonly used continuous measurement systems are:

- Finapres™ volume-clamp finger monitor
- Colin® CBM-7000 radial artery tonometer

However, several studies have reported significant disagreement between the readings produced by these two devices during physiological stress. The primary goal of this article is to analyse these inconsistencies using mathematical and mechanical modelling of both devices and their interaction with vascular tissues.

The Finapres™ Technique

The Finapres employs the photoelectric volume-clamp principle, using infrared light transmission to monitor blood volume changes in the finger. Since infrared light is strongly absorbed by haemoglobin, fluctuations in transmitted intensity reveal variations in the blood-filled cross-sectional area of the finger.

A finger cuff applies external pressure (pext) that is continuously adjusted to maintain a constant light intensity. This pressure is interpreted as the arterial blood pressure.

Calibration Procedure

1. Inflate cuff to a pressure lower than expected arterial pressure.

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2. Measure light-intensity oscillations over multiple cardiac cycles.
3. Incrementally increase cuff pressure and repeat measurements.
4. Identify the pressure (p*) at which oscillation amplitude is maximal.
5. Record the corresponding steady-state intensity (I*).

The device then continuously modifies pext to keep light intensity stable at I*. The measured cuff pressure is assumed to equal the arterial pressure. This assumption, however, may introduce errors due to tissue transmission, venous filling, and non-uniform pressure distribution.

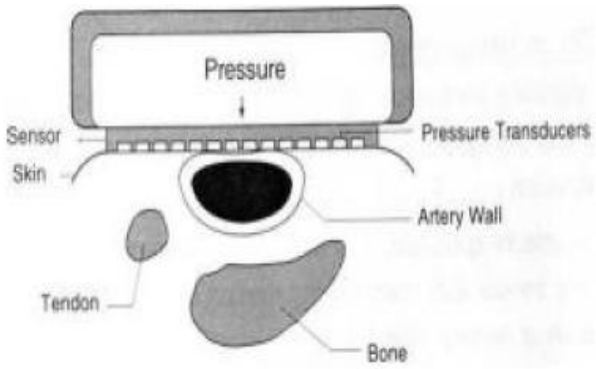
The Colin® Radial Artery Tonometer

The tonometer measures arterial pressure by pressing a row of piezoelectric sensors against the radial artery at the wrist. The sensors detect oscillatory displacement linked to arterial pulsations.

Fig 1:

Sensor Frame

Fig 2:



Before continuous monitoring begins, an oscillometric upper-arm cuff determines systolic and diastolic pressures. These values are used to calibrate the tonometer's subsequent readings.

Key considerations:

- Sensor displacement signals are mapped to pressure values, usually through linear interpolation.
- Recalibration was disabled in the experiments reviewed, which may influence accuracy over time.
- Changes in tissue stiffness or arterial wall properties can alter the sensor's response, affecting measurement validity.

Experimental Discrepancies

Two experiments highlight major differences between the systems:

Thigh-Cuff Occlusion Study (Birch & Morris, 2003)

Inflating thigh cuffs induced vasodilation, followed by a rapid pressure drop upon deflation. Both devices recorded responses, but Finapres

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consistently showed lower pressure than the tonometer.

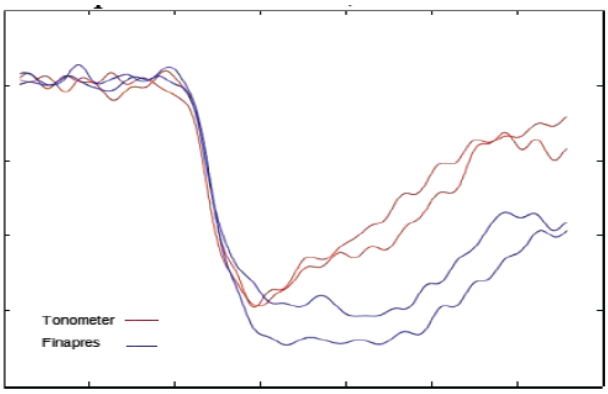

Fig: 3 Average blood-pressure

Lower-Body Negative Pressure Study (Birch, 2007)

Sinusoidally varying negative pressure caused further divergence in readings.

Possible explanations include:

For Finapres

- Cuff pressure may not directly transmit to arterial pressure.
- Maximum light-oscillation amplitude may not correspond precisely to mean arterial pressure.
- Capillary and venous filling under the cuff may distort readings over time.

For Tonometer

- Oscillometric calibration errors (~15%) limit overall accuracy.
- Interpolation methods may not account for physiological variations outside the calibration range.
- Tissue or arterial stiffening alters sensor response, producing drift.

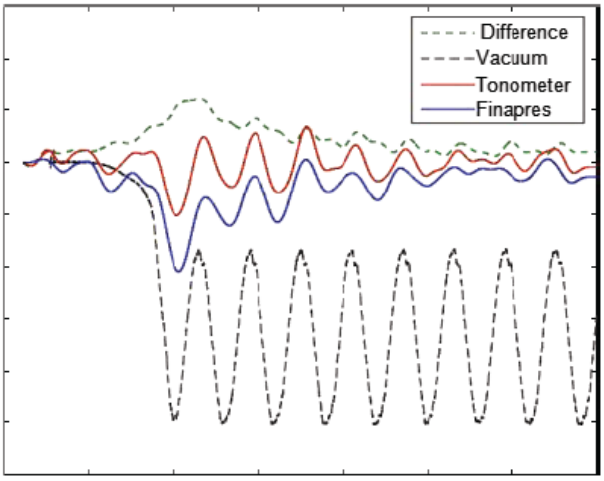

Fig 4: Average blood-pressure measurements from the tonometer and Finapres

Physiological Differences

Peripheral vasoconstriction during stress may lower finger pressure relative to radial artery pressure meaning both devices could be correct but measuring different conditions.

MECHANICAL MODELLING OF THE TONOMETER

Spring-and-Dashpot Representation

A simplified mechanical model represents:

- Pulsatile blood pressure as a driving spring (S1).
- Arterial wall and tissue as a viscoelastic combination of a spring (S2) and dashpot (D3).
- Tonometer transducers as a stiff spring (S4).

This model evaluates whether the transducer output accurately follows true arterial pressure

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and how sensitive readings are to changes in arterial stiffness.

Viscoelastic Slab Model

A more sophisticated model treats the wrist tissues (skin, arterial wall, fat, muscle) as a single viscoelastic slab of thickness h subjected to time-varying internal arterial pressure p(t). The tonometer measures normal stress at the slab's surface.

This model improves understanding of:

- How tissue deformation affects sensor readings
- The influence of arterial geometry
- How changes in stiffness modify the pressure–displacement relationship

MODELLING THE FINAPRES

Simplified Cuffed-Artery System

A basic model includes:

- An artery supplying blood
- A vein providing drainage
- A cuff applying uniform pressure

In the simplest version, the capillary network is replaced by a pressure-jump boundary condition.

A further reduced model examines only a compliant artery subjected to external cuff pressure pext, focusing on the relationship between transmitted light, internal pressure, and vessel cross-section.

These models aim to clarify:

- When cuff pressure equals true arterial pressure
- How venous backflow and capillary filling influence readings
- The effect of cuff compression on tissue and vessel geometry

AIM AND OBJECTIVES

Aim

To analyse and compare the performance of two widely used non-invasive continuous blood-pressure monitoring systems—Finapres™ and the Colin® CBM-7000 radial artery tonometer—and to investigate the reasons behind the discrepancies observed in their measurements during physiological stress conditions.

Objectives

To review the operating principles of the Finapres™ volume-clamp method and the Colin® radial artery tonometry technique.

To evaluate experimental differences in blood-pressure outputs recorded by both devices under controlled provocations such as thigh-cuff occlusion and lower-body negative pressure.

To develop mechanical and mathematical models simulating device–tissue interactions in order to determine how accurately each system reflects true arterial pressure.

To identify potential physiological and technical factors that contribute to inconsistencies between the two measurement methods.

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CONTINUOUS NON-INVASIVE BLOOD PRESSURE MONITORING: A REVIEW OF MEASUREMENT CHALLENGES AND DEVICE MODELLING

To provide foundational insights that support the development of improved non-invasive continuous blood-pressure monitoring technologies

MATERIALS AND METHODS

Materials

- Finapres™ finger volume-clamp blood pressure monitor
- Colin® CBM-7000 radial artery tonometer
- Thigh-cuff occlusion equipment capable of applied pressure for several minutes
- Lower-body negative-pressure (LBNP) chamber
- Infrared sensing system (Finapres internal)
- Piezoelectric transducer array (Tonometer internal)
- Adult human participants as previously described in the referenced studies

Methods

Experimental Data Review

Data from two established studies were analysed:

Thigh-cuff occlusion experiment

Cuffs were inflated around both thighs for 3 minutes 20 seconds, followed by rapid deflation. Continuous blood-pressure readings were collected simultaneously using both devices.

Lower-body negative-pressure experiment

Participants were placed in a chamber applying sinusoidally varying negative pressure. Finapres and tonometer outputs were recorded throughout.

Device-Operation Analysis

- The Finapres™ was evaluated based on its light-intensity regulation mechanism and volume-clamp calibration steps.
- The Tonometer was assessed based on its transducer displacement signals and external oscillometric calibration.

Mechanical and Mathematical Modelling

Two modelling approaches were used for the tonometer:

- Spring-and-dashpot viscoelastic model simulating blood pulsation, arterial wall elasticity, and soft-tissue damping.
- Viscoelastic slab model representing layered tissues between the radial artery and sensor, enabling evaluation of pressure transmission.

For the Finapres:

- Cuffed-artery model describing how external cuff pressure interacts with arterial pressure, venous return, and capillary filling.
- Simplified artery-only model to test the conditions under which cuff pressure equals true arterial pressure.

Comparative Evaluation

Model outputs were compared with reported experimental results to identify:

- Agreement or disagreement between true and measured pressures
- Sensitivity of readings to arterial stiffness, tissue elasticity, venous congestion, and calibration accuracy

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- Physiological factors influencing peripheral pressure differences

RESULTS:

Consistent Discrepancies Observed

In both thigh-cuff and lower-body negative-pressure experiments, the Finapres consistently recorded lower blood pressures than the tonometer during induced hypotensive phases.

Physiological Explanation for Differences

Peripheral vasoconstriction triggered by low-pressure states can cause pressure in finger arteries (measured by Finapres) to drop more sharply than in the radial artery (measured by the tonometer). This indicates that both devices may be correct, but measure different vascular regions with different responses.

Finapres-Specific Limitations Identified

- Cuff pressure may not be uniformly transmitted through finger tissues.
- Calibration assumptions (peak oscillation = mean arterial pressure) may not always be valid.
- Capillary filling and venous backflow beneath the cuff can distort light-intensity readings over time.

Tonometer-Specific Limitations Identified

- Initial oscillometric calibration may introduce up to 15% error, which carries forward into continuous readings.
- Unknown interpolation methods may compromise accuracy when pressure amplitudes change significantly.
- Tissue elasticity and arterial stiffness alter sensor displacement signals, reducing reliability.

Modelling Results

- Spring-and-dashpot model showed that tonometer readings lag behind true pressure when tissue damping increases.
- Viscoelastic slab model demonstrated that arterial stiffening can significantly alter surface stress detected by the tonometer.
- Finapres models suggested that external cuff pressure equals arterial pressure only under specific conditions; venous expansion disrupts this relationship.

Overall Interpretation

Discrepancies between the two devices arise from a combination of measurement-site physiology, device calibration, and tissue mechanics.

Neither system universally reflects true arterial pressure under all conditions.

DISCUSSION

The comparative evaluation of the Finapres™ and the Colin® radial artery tonometer reveals that discrepancies in continuous non-invasive blood pressure measurements arise from both methodological limitations and physiological factors inherent to each technique. Although both devices are widely used in research

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and clinical monitoring, their readings diverge significantly under conditions that challenge cardiovascular stability, such as thigh-cuff deflation and lower-body negative pressure. Understanding the underlying causes of these differences is essential for improving the accuracy and reliability of non-invasive monitoring tools.

A major observation across experiments is that the Finapres consistently records lower arterial pressures during acute hypotensive phases compared with the tonometer. One plausible explanation lies in the distinct anatomical measurement sites. The Finapres measures pressure in the digital arteries of the finger, whereas the tonometer captures pressure in the radial artery. Under stress, the body initiates peripheral vasoconstriction to preserve perfusion to vital organs. As a result, finger arteries may experience a more pronounced reduction in pressure than the radial artery. This implies that differences in readings may reflect true physiological variation rather than device malfunction.

However, device-specific limitations also contribute significantly to inconsistencies. The Finapres relies on the volume-clamp principle, assuming that the external cuff pressure required to maintain constant light transmission equals intra-arterial pressure. In practice, this assumption is sensitive to tissue structure, finger geometry, and venous blood accumulation beneath the cuff. Venous congestion during prolonged measurement can raise local pressure, altering the light-volume relationship and reducing measurement fidelity. Additionally, the calibration method, which identifies the cuff pressure that maximises pulsatile light fluctuations, may not consistently correspond to mean arterial pressure in all individuals.

The tonometer, although mechanically different, is not free from error. Its reliance on an oscillometric cuff for initial calibration introduces baseline inaccuracies of up to 15%, which persist throughout monitoring. Furthermore, the radial artery's interaction with surrounding soft tissues and the applied sensor force influences the transducer displacement signal. The modelling results show that changes in tissue stiffness or arterial wall properties can significantly distort the pressure transmitted to the sensor, particularly during physiological stress or in elderly individuals with stiffened arteries.

Mechanical modelling reinforces these conclusions. The spring-and-dashpot model highlights how viscoelastic damping of wrist tissues introduces phase delays and amplitude variations in the tonometer's pressure estimation. The more advanced viscoelastic slab model further demonstrates that the surface stress measured by the tonometer is highly dependent on the mechanical characteristics of the underlying tissues. These findings support concerns that the tonometer's accuracy may deteriorate when pressure amplitudes extend beyond the initially

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calibrated range or when tissue properties change during the course of an experiment.

In contrast, the Finapres models illustrate how external cuff pressure, venous return, and capillary expansion influence the stability of finger pressure measurements. As venous pressure gradually rises under the cuff, the relationship between external compression and true arterial pressure becomes increasingly non-linear. This effect may account for the downward shift in Finapres readings observed in both experiments.

Taken together, the findings demonstrate that neither device provides a universally accurate estimate of arterial pressure under all conditions. Instead, each system performs differently depending on measurement site physiology, device calibration, and tissue mechanical behaviour. The consistent divergence observed across experiments suggests that device outputs should be interpreted with caution, particularly during rapid hemodynamic changes. These insights highlight the importance of developing improved calibration protocols, enhanced modelling frameworks, and more robust sensor designs that can adapt to dynamic physiological environments.

Ultimately, the complementary strengths and limitations of the Finapres™ and radial artery tonometer underline the need for continued investigation into hybrid or multimodal approaches for non-invasive continuous blood pressure monitoring. Such advancements may help overcome current constraints and provide more accurate, reliable, and clinically meaningful hemodynamic assessments.

CONCLUSION

Differences between Finapres™ and radial artery tonometers arise from both device-specific limitations and physiological factors. Mechanical modelling suggests that:

Finapres readings can drift due to venous filling, non-uniform pressure transmission, and assumptions in its calibration method.

Tonometer accuracy is limited by initial calibrations, tissue mechanics, and sensor-pressure mapping.

Peripheral vascular responses during stress may cause genuine pressure differences between finger arteries and radial arteries.

Improved modelling and calibration strategies are essential to enhance the reliability of non-invasive continuous blood-pressure monitoring systems.

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