Application of the Doppler Effect to the Diagnosis of Arterial and Venous Network Disorders: The Case of Stenoses

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Abstract

Each year in France, approximately 150,000 people suffer a cerebrovascular accident (stroke). As a public health issue, ischemic strokes occur due to interrupted blood flow to or within the brain. Prevention is thus a major priority. Doppler ultrasound has emerged as a rapid, non-invasive imaging method for exploring blood flow and serves as a key diagnostic tool for vascular system issues. Cardiovascular problems often stem from arterial narrowing, as is the case with stenosis, which is the focus of this study.

Research Question: What is the impact of blood vessel narrowing in stenosis on flow resistance and Doppler signal characteristics?

Contents

1 Introduction

1.1 Principles of Doppler Ultrasound

The Doppler effect describes a frequency shift between an emitted wave (ν_i) and a received wave (ν_r) due to relative motion between the source and receiver. In Doppler ultrasound, ultrasonic waves are reflected off red blood cells.

Given that the receiver and emitter are on the same probe and the speed of sound in human tissue is approximately 1500 m/s (with blood flow velocities around 1 m/s), the relationship simplifies to:

$$\Delta F = 2F_i \frac{v\cos(\theta)}{c}$$

After electronic processing, the received signal provides the velocity of red blood cells derived from the frequency shift. Typical ultrasound frequencies (ν_0) range from 2 to 10 MHz, producing Doppler shifts in the kHz range—audible to experienced physicians, enabling anomaly detection via sound characteristics.

2 Experimental Setup: Gampt Device

The experimental system for simulating Doppler ultrasound diagnostics comprises:

- A 1 MHz emitter-receiver probe
- Gel and prism to facilitate ultrasound transmission
- A fluid with suspended solid particles simulating red blood cells
- A pump providing variable flow rates
- Rigid tubes (300 mm long) with varying diameters ($D_1 = 7$ mm, $D_2 = 10$ mm, $D_3 = 16$ mm)
- Flexible tubes (10 mm diameter) connecting rigid tubes and pressure columns

In clinical practice, Doppler devices are coupled with conventional ultrasound imaging to examine blood flow within vessels.

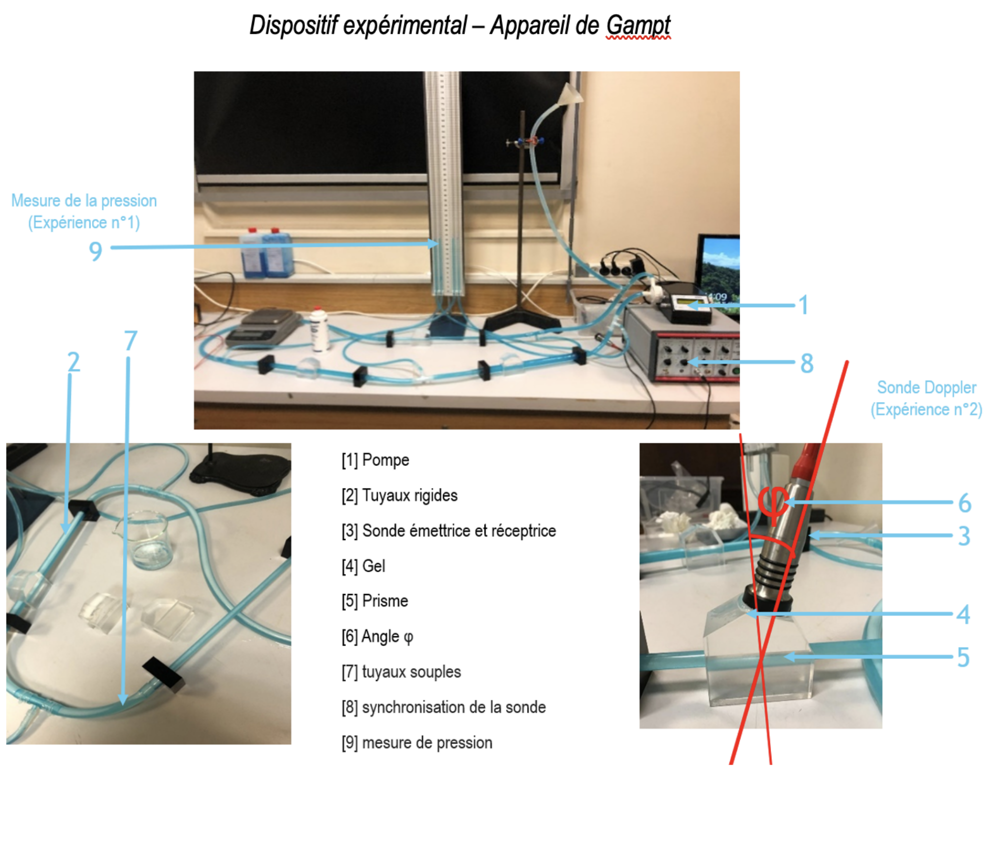


Figure 1: Experimental Setup

3 Experimental Findings

3.1 Experiment 1: Effect of Vessel Diameter Reduction on Doppler Signal

3.1.1 Objective

To experimentally demonstrate how reduced vessel cross-section affects the Doppler spectrum and to explore adjustable parameters for optimizing medical diagnostics.

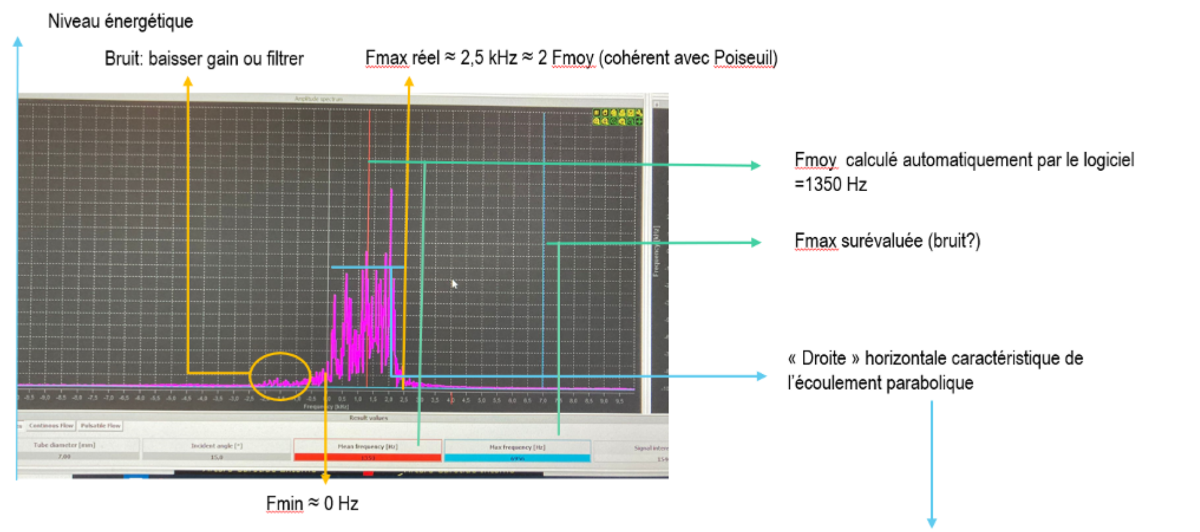


Figure 2: amplitude spectrum ($D = 7$ mm, angle $= 15°$)

3.1.2 Protocol and Hypothesis

A steady, incompressible laminar flow was imposed using the pump. The rigid tubes with diameters $D_1 = 7$ mm and $D_2 = 10$ mm were studied. After optimizing probe parameters (angles/gain), the Doppler spectrum evolution was observed for different flow rates and angles.

3.1.3 Results

- The method performed better for smaller sections ($D = 7$ mm) and grazing angles ($\phi_{\max}$). In practice, physicians optimize the incidence visually using ultrasound images.

A representative amplitude spectrum ($D = 7$ mm, angle $= 15°$) revealed:

- Visual estimation showed a frequency maximum of ~ 2500 kHz, consistent with Poiseuille flow characteristics. Automated frequency maximum detection may be imprecise.
- Nonparabolic profiles indicated turbulence, particularly at junctions.

3.2 Experiment 2: Effect of Vessel Diameter Reduction on Resistance to Flow

3.2.1 Theoretical Background

For laminar incompressible flow in blood vessels, Poiseuille's law applies:

$$\Delta P = \frac{8 \cdot \eta \cdot L}{\pi \cdot R^4} \cdot D$$

where R depends on vessel geometry. Resistance increases with reduced vessel diameter.

3.2.2 Experiment 2.1: Section Influence on Pressure Drop

Using rigid tubes of $D_1 = 7$ mm and $D_2 = 10$ mm, pressure differences (ΔP) were measured with Capstone-linked pressure sensors.

Findings:

- A linear relationship (ΔP vs. Q) with high correlation coefficients ($R^2 = 0.9991$ for linear models).
- Turbulence was observed at junctions, consistent with non-linear pressure loss due to geometric transitions.

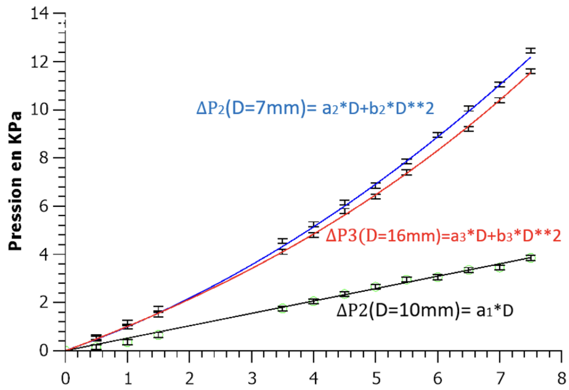


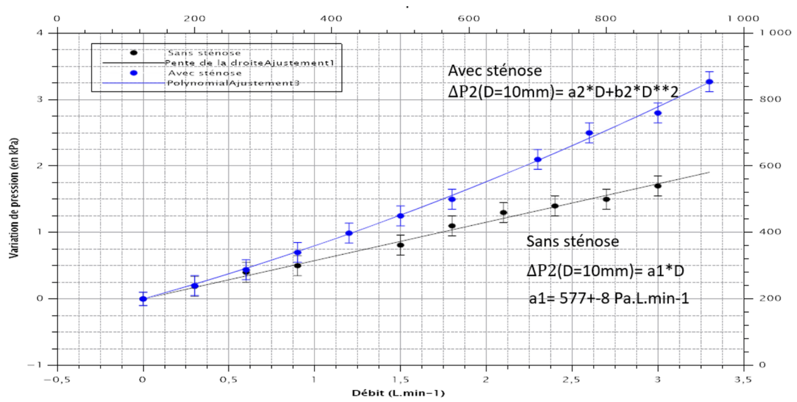
Figure 3:

3.2.3 Experiment 2.2: Stenosis Modeling

Modeling Approach:

- *Laminar Model:* Stenosis treated as a series of elemental tubes; resistance increase was negligible.
- *Turbulent Model:* Stenosis modeled as abrupt expansions/reductions causing significant nonlinear resistance.

Practical Implementation: A clamp created a 4 mm diameter stenosis in a 10 mm diameter tube. Pressure drops confirmed turbulence-induced non-linear effects.



Courbe obtenue - Qtiplot

Figure 4:

Results: Pressure drops confirmed turbulence-induced non-linear effects.

4 Discussion

- **Flow Resistance:** Linear increase in the absence of junctions; quadratic growth with turbulence.
- **Turbulence at Junctions:** Singular pressure losses consistent with Bernoulli's theorem.
- **Diagnostic Optimization:** Pulsed Doppler mode and grazing incidence improve stenosis detection.
- **Doppler Signal Analysis:** Parabolic flow spectra confirm laminar conditions; turbulence deforms spectra, aiding stenosis identification.

5 Conclusion

The study highlights:

- Increased flow resistance due to vessel narrowing, accentuated by turbulence.
- Challenges in stenosis diagnosis due to junction-induced turbulence.
- Diagnostic optimization through tailored Doppler settings.

Future Directions: Investigating stenosis-induced wall collapse in deep vessels and advanced flow resistance metrics like Pourcelot's index.

References

1. L. Pourcelot, *Application of Doppler Examination to Peripheral Circulation Studies* (Chap. I, p. 13).
2. C. Gautier, *Basics of Doppler Signal Interpretation in Arterial Networks* (2013, Slide 60).