Master’s Thesis entitled

Acoustical Monitoring of Model System for Vascular Access in Haemodialysis

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25th August 2014
Date submitted

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# Abbreviations and Symbols

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<th>Meaning</th>
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</thead>
<tbody>
<tr>
<td>a.u.</td>
<td>Arbitrary unit</td>
</tr>
<tr>
<td>AVF</td>
<td>Arteriovenous Fistula</td>
</tr>
<tr>
<td>BVM</td>
<td>Blood Volume Monitor</td>
</tr>
<tr>
<td>CGS</td>
<td>Centimeter-gram-second system of units</td>
</tr>
<tr>
<td>Co</td>
<td>Company</td>
</tr>
<tr>
<td>D(^{97%}_{\setminus \text{exc}})</td>
<td>All the data with removing of the points with a degree of stenosis equal to 97%</td>
</tr>
<tr>
<td>D(_{\text{phy}})</td>
<td>All the data with removing of the points with a degree of stenosis equal to 97% and a ΔP greater than 100mmHg</td>
</tr>
<tr>
<td>DOS</td>
<td>Degree of Stenosis</td>
</tr>
<tr>
<td>DS</td>
<td>Dry Substance</td>
</tr>
<tr>
<td>ESRD</td>
<td>End Stage Renal Disease</td>
</tr>
<tr>
<td>FFT</td>
<td>Fast Fourier Transform</td>
</tr>
<tr>
<td>GmbH</td>
<td>Gesellschaft mit beschränkter Haftung (company with limited liability)</td>
</tr>
<tr>
<td>HD</td>
<td>Haemodialysis</td>
</tr>
<tr>
<td>KDOQI</td>
<td>Kidney Disease Outcomes Quality Initiative</td>
</tr>
<tr>
<td>N.A.</td>
<td>Not Available</td>
</tr>
<tr>
<td>NI</td>
<td>National Instruments</td>
</tr>
<tr>
<td>PD</td>
<td>Peritoneal Dialysis</td>
</tr>
<tr>
<td>PTFE</td>
<td>Polytetrafluoroethylene</td>
</tr>
<tr>
<td>PVC</td>
<td>Polyvinylchlorid</td>
</tr>
<tr>
<td>PVDF</td>
<td>Polyvinylidene difluoride</td>
</tr>
<tr>
<td>RO</td>
<td>Reverse Osmosis</td>
</tr>
<tr>
<td>SF / SFs</td>
<td>Spectral Feature / Spectral Features</td>
</tr>
<tr>
<td>SI</td>
<td>International System of Units</td>
</tr>
<tr>
<td>SN</td>
<td>Single-Needle</td>
</tr>
<tr>
<td>STD</td>
<td>Standard deviation</td>
</tr>
<tr>
<td>USB</td>
<td>Universal Serial Bus</td>
</tr>
<tr>
<td>VA</td>
<td>Vascular Access</td>
</tr>
</tbody>
</table>

Table 1: Table of abbreviations and their meaning
## Symbols:

<table>
<thead>
<tr>
<th>Symbols</th>
<th>Definitions</th>
<th>Units used</th>
</tr>
</thead>
<tbody>
<tr>
<td>a</td>
<td>Semi-major axis of ellipse</td>
<td>(m)</td>
</tr>
<tr>
<td>b</td>
<td>Semi-minor axis of ellipse</td>
<td>(m)</td>
</tr>
<tr>
<td>C</td>
<td>Circumference</td>
<td></td>
</tr>
<tr>
<td>∆P</td>
<td>Pressure Drop</td>
<td>(mmHg) or (Pa)</td>
</tr>
<tr>
<td>∆P&lt;sub&gt;fit&lt;/sub&gt;</td>
<td>Difference of pressure that should normally exist between the two pressure sensors in absence of stenosis</td>
<td>(mmHg) or (Pa)</td>
</tr>
<tr>
<td>∆P&lt;sub&gt;experimental&lt;/sub&gt;</td>
<td>Difference of pressure between the pressure sensors situated before and after the stenosis</td>
<td>(mmHg) or (Pa)</td>
</tr>
<tr>
<td>D&lt;sub&gt;H&lt;/sub&gt;</td>
<td>Hydraulic diameter</td>
<td>(m)</td>
</tr>
<tr>
<td>DOS</td>
<td>Degree of Stenosis</td>
<td>(%)</td>
</tr>
<tr>
<td>dv</td>
<td>Difference of velocity</td>
<td>(m.s&lt;sup&gt;-1&lt;/sup&gt;)</td>
</tr>
<tr>
<td>F</td>
<td>Force of friction</td>
<td>(N) or (kg.m.s&lt;sup&gt;-1&lt;/sup&gt;)</td>
</tr>
<tr>
<td>f&lt;sub&gt;D&lt;/sub&gt;</td>
<td>Darcy friction factor</td>
<td>No unit</td>
</tr>
<tr>
<td>g</td>
<td>Acceleration due to gravity</td>
<td>(m.s&lt;sup&gt;-2&lt;/sup&gt;)</td>
</tr>
<tr>
<td>G</td>
<td>Needle gauge</td>
<td>(G)</td>
</tr>
<tr>
<td>I(t)</td>
<td>Current through a component</td>
<td>(amperes)</td>
</tr>
<tr>
<td>L</td>
<td>Characteristic linear dimension</td>
<td>(m)</td>
</tr>
<tr>
<td>λ</td>
<td>Darcy-Weisbach friction coefficient</td>
<td>No unit</td>
</tr>
<tr>
<td>m</td>
<td>Mass</td>
<td>(kg)</td>
</tr>
<tr>
<td>MAP</td>
<td>Mean Arterial Pressure</td>
<td>(mmHg)</td>
</tr>
<tr>
<td>P</td>
<td>Pressure</td>
<td>(mmHg) or (Pa) or (kg.m&lt;sup&gt;-1&lt;/sup&gt;.s&lt;sup&gt;-2&lt;/sup&gt;)</td>
</tr>
<tr>
<td>P&lt;sub&gt;inst&lt;/sub&gt;</td>
<td>Instantaneous electrical power</td>
<td>(W) or</td>
</tr>
<tr>
<td>ρ</td>
<td>Density</td>
<td>(kg.m&lt;sup&gt;-3&lt;/sup&gt;)</td>
</tr>
<tr>
<td>Q</td>
<td>Flow (in fact volumetric flow rate)</td>
<td>(m&lt;sup&gt;3&lt;/sup&gt;.s&lt;sup&gt;-1&lt;/sup&gt;) or (ml.min&lt;sup&gt;-1&lt;/sup&gt;)</td>
</tr>
<tr>
<td>q&lt;sub&gt;m&lt;/sub&gt;</td>
<td>Mass flow rate</td>
<td>(kg.s&lt;sup&gt;-1&lt;/sup&gt;)</td>
</tr>
<tr>
<td>q&lt;sub&gt;v&lt;/sub&gt;</td>
<td>Volumetric flow rate</td>
<td>(m&lt;sup&gt;3&lt;/sup&gt;.s&lt;sup&gt;-1&lt;/sup&gt;)</td>
</tr>
<tr>
<td>Re</td>
<td>Reynolds Number</td>
<td>No unit</td>
</tr>
<tr>
<td>R&lt;sub&gt;H&lt;/sub&gt;</td>
<td>Hydraulic radius</td>
<td>(m)</td>
</tr>
<tr>
<td>S</td>
<td>Cross-sectional Area</td>
<td>(m&lt;sup&gt;2&lt;/sup&gt;) or (pixels&lt;sup&gt;2&lt;/sup&gt;)</td>
</tr>
<tr>
<td>t</td>
<td>Time</td>
<td>(s)</td>
</tr>
<tr>
<td>T</td>
<td>Temperature</td>
<td>(°C)</td>
</tr>
<tr>
<td>µ</td>
<td>Dynamic viscosity</td>
<td>(Pa.s) or (Pl) or (kg.m&lt;sup&gt;-1&lt;/sup&gt;.s&lt;sup&gt;-2&lt;/sup&gt;) or (P) or (Po)</td>
</tr>
<tr>
<td>V</td>
<td>Volume</td>
<td>(m&lt;sup&gt;3&lt;/sup&gt;)</td>
</tr>
<tr>
<td>V(t)</td>
<td>Potential difference (or voltage drop) across a component</td>
<td>(volts)</td>
</tr>
<tr>
<td>v or v&lt;sub&gt;st&lt;/sub&gt;</td>
<td>Velocity at the stenosis</td>
<td>(m.s&lt;sup&gt;-1&lt;/sup&gt;)</td>
</tr>
<tr>
<td>v&lt;sub&gt;mean&lt;/sub&gt;</td>
<td>Mean velocity</td>
<td>(m.s&lt;sup&gt;-1&lt;/sup&gt;)</td>
</tr>
<tr>
<td>v</td>
<td>Kinematic viscosity</td>
<td>(m&lt;sup&gt;2&lt;/sup&gt;.s&lt;sup&gt;-1&lt;/sup&gt;) or (St)</td>
</tr>
<tr>
<td>z / dz</td>
<td>Height / distance in the vertical axis</td>
<td>(m)</td>
</tr>
</tbody>
</table>

Table 2: Table of symbols with their definition and units
ABSTRACT:

Stenosis is the main reason of the failure of a vascular access in haemodialysis. Its presence engenders an increase of the morbidity and an increase of the hospitalization for hemodialysed patients and its early detection consists thus in an important issue. Digital phonoangiography or digital acoustical analysis is an alternative to the current techniques combining the advantage of its low-cost, its easy implementation as well as its user- and skill-independency. This technique, automated version of the auscultatory technique used by the practitioners with their stethoscope, is based on the idea that the stenosis engenders modifications of the hemodynamic in the vascular access at the origin of sounds or “bruits”. This study proposed to assess the influence of different parameters on the acoustics by mean of an in vitro model system that allows controlling independently each of these parameters. Assessed parameters included the severity or degree of the stenosis, the flow, the pressures, the viscosity and the velocity. Results indicated that the essential parameter was the velocity at the stenosis which determines the appearance of spectral features, starting from a value of about 1.4 m/s while a value around 2.6 m/s could be almost always associated with certitude to their presence. Spectral features were found in the frequency bandwidth from 70 to 800Hz with three main regions located at 180-300Hz, 310-390Hz and 440-700Hz. Moreover results indicated that a minimum severity of the stenosis was required, corresponding to an obstruction of the lumen of the vessel of at least 44%. These results suggested that the underlying reason was the modification of the type of flow from the transitional or laminar to the turbulent state confirmed by the Reynolds number. This study also further investigated the possibility of detection of sounds directly on the extracorporeal blood circuit by transmission through the needle.
1. **INTRODUCTION:**

About 70% of patients suffering from end-stage renal disease are periodically treated by haemodialysis (1) representing about 2.25 millions of patients in 2013. The treatment is performed using a dialysis machine which consists in an extracorporeal circuit where the blood is cleansed from the waste but also from the excess of water. Cleansing is done by means of exchanges through a semi permeable membrane in a dialyzer. In order to assure this extracorporeal circulation, an access to the blood of the patient is necessary, called a vascular access. Different types of vascular accesses exist but the most commonly used is the arteriovenous fistula, which consists in the surgical anastomosis of an artery and a vein. If the fistula cannot be proceed (e.g. vessels too weak), an alternative consists in the graft which uses an artificial tubing to establish the connection between the artery and the vein (2). First intention should be the fistula due to the lower patency rate (3) (4). The purpose of this anastomosis is to provide a sufficient blood flow in the vessel for the practise of the cannulation by means of a shortcut between the high pressure arterial side and the low pressure venous side. The vascular access remains a primordial aspect of the dialysis, its state influencing directly the efficiency of the haemodialysis treatment. Even if some patients might not encountered any problems with their vascular access for a very long period (30 years for some patients), problems might arise also very quickly and/or frequently for another patients. The most frequent and important complication of a vascular access is a stenosis, corresponding to a narrowing of the lumen of the vessel. This narrowing has for main consequence to engender a reduction of the flow through the vascular access and could eventually lead to a complete obstruction of the vessel, provoking thus the failure of the vascular access. Furthermore, stenosis is generally an underlying cause of thrombosis (5) (6). Moreover the KDOQI guidelines state that a reduction of the lumen of the vessel by 50% starts to be the critical point at which the blood flow starts to decrease dramatically, encouraging thus the earliest detection possible of the stenosis (7). Different techniques exist such as for example Duplex Ultrasound, angiography, physical examination or auscultation of the vascular access. However these techniques have their own drawbacks including cost, user skill dependency, invasiveness, the need of special devices or the difficulty to implement in a routine protocol. Recently the technique called phonoangiography described in 1970 (8) or sometimes referred more simply as the acoustical analysis of the vascular access has been investigated. This technique which is in fact an optimized automated version of the current auscultation done by the practitioners with their stethoscope should bring the advantage to be non-invasive, a low cost technique, easily implemented in routine as well as limiting the effect of the user’s skills on the interpretation of results.

Previous works done in this among divergences about the optimum frequency band(s) demonstrated that the bandwidth from 0 to 1000Hz is specific to the presence of a stenosis. More specifically, the optimum frequency bands were generally found at the higher frequencies: 300 – 600Hz (9), 625 – 700Hz and 875 – 1000Hz (10) or 700 – 800Hz (11). Other important conclusions were: an increased sound intensity, the presence of extra sounds and a redistribution of acoustic energy among different frequencies. Some of the studies underlined that the underlying reason for the generation of sounds is the local perturbation of the flow downstream the stenosis and an association to a modification of the type of flow to a turbulent flow (12) (13). Most of these studies were performed in vivo, mainly by comparing results with an electronic stethoscope of an acoustical analysis before and after an interventional surgery (generally angioplasty) underlying thus the differences between both events (14) (15). However, even if two patents have been published (16) and (17) and algorithms were developed to classify samples into stenotic or non-stenotic states (10) (13) (18), these studies cannot point out clearly the impact of the anatomical properties of the vascular access to the acoustical signal, limited thus to the suggestion that the mean flow may influence the characteristics of the generation of sounds. As a consequence, in this study, it was studied more in details the impact of different parameters on the acoustical signal, their influence on the acoustical signal and were determined which parameters are the most important. Moreover a study of the underlying reason of the apparition of spectral features is proposed. To be able to control easily various parameters, a simple in vitro model of a vascular access was designed and main parameters including the flow, the degree of stenosis, the pressure as well as the viscosity were modified in order to assess their impact on the acoustical analysis. Acoustical analysis was performed by means of the Fast Fourier Transform (FFT) with a special focus on the bandwidth from 70 to 800Hz. Additionally was evaluated the possibility of an acoustical detection system based on the extracorporeal circuit instead of directly on the patient as proposed in the other works ((16) and (17)).
2. **THEORY:**

### 2.1. Physiological and medical background of haemodialysis and vascular access

#### 2.1.1. Epidemiology

In order for the human body to work properly, there is a necessity of maintaining the homeostasis of the organism by different functions. One of these main functions is assumed by the kidneys which are responsible for the elimination of the nitrogenous waste and also the maintaining of the hydro-electrolytic and the pH balance in the blood as well as a proper water balance. Moreover, the kidneys provide a very important endocrinological function (especially erythropoietin, etc.). When the kidneys are no longer able to carry out these functions; vital diagnosis of the patient is at stake in the absence of treatment.

Patients suffering of chronic disease are called ESRD-patients (standing for End Stage Renal Disease). The main cause of chronic disease is diabetes. The incidence and the prevalence of ESRD continue to increase with a growth rate of about 6% in 2013 and represent a large problem for the society, the number of patients being treated for ESRD globally estimated to 3,200,000 for the year 2013 (1). This increase is linked to the aging of the population (more vascular problems) as well as the increase of the number of diabetic patients. For example in USA in 2006, the average age of patients at the start of dialysis was 62 years (19). Current treatments available are: the kidney transplantation (about 21%), the peritoneal dialysis (about 9%) and the haemodialysis (about 70%).

#### 2.1.2. Basic principles of dialysis and haemodialysis

The basic principle of the dialysis corresponds to exchanges through a semipermeable membrane. The first medium is the blood while the second medium is the dialysis solution with a composition similar to the normal extra-cellular liquid. The solute and water transfer are based on three main principles which are (see Figure 1):

- The transmembrane diffusion: a tendency for substances to move from the medium of higher concentration to the medium of lower concentration.
- The transmembrane convection also sometimes referred as ultrafiltration corresponding to the transport of water under a pressure difference.
- The osmosis which is the net movement of water across a selectively permeable membrane driven by a difference in the amounts of solute on the two sides of the membrane.

![Diagram](Figure 1: the three types of exchanges in dialysis)

The general principle of the haemodialysis is illustrated in Figure 2 and corresponds to an extracorporeal circuit. The blood is pumped outside the body of the patient through the arterial needle and the arterial line, and then goes through the dialyzer where the exchanges are taking place and is finally given back to the patient through the venous line and the venous needle. Anticoagulation (e.g. by automated Heparin infusion) is necessary to avoid the coagulation of the blood in the extracorporeal circuit. The arterial and the venous pressures can be measured. The dialysis generator can be roughly separated into two main parts: the extracorporeal circuit for the blood and the dialysis solution circuit. The dialysis solution contains the most important ions for the body (sodium, potassium, calcium, magnesium, bicarbonate). The dialysis solution is circulating at counter current of the blood circuit for efficiency. The dialyzer contains a semi permeable membrane where the exchanges between the blood and the dialysis solution are processed following the principles described above.
2.1.3. Vascular access and its complications

The vascular access is one of the most important aspects of the dialysis as it corresponds to the access to the blood of the patient and the quality of this vascular access has a direct impact on the quality of the dialysis. It is for example necessary to have a flow in the vascular access greater than the flow in the extracorporeal circuit, otherwise recirculation will occur. History of the vascular access is long and can be estimated starting in 1896 with Jaboulay and Briau who were practicing suturing of an artery-end-to-end-anastomosis with dogs (21). Modern haemodialysis therapy is associated to Willem Kolff in Netherlands who evidenced the need of a permanent vascular access (22). Nowadays, the state of the art (2) in this field is based on two types of vascular accesses: one permanent and one temporary. The permanent owns two main types which are the autologous arteriovenous fistula (also referred as autogenous fistulas) and the arteriovenous graft (also referred as non-autogenous fistulas). The fistulas correspond roughly to the subcutaneous anastomosis of an artery and a vein; idea being to furnish a sufficient flow rate for the cannulation by means of a shortcut between the high pressure arterial side and the low pressure venous side. The graft should be investigated when a fistula is surgically not achievable (e.g. quality of the vessels in diabetic patients). In this case a synthetic or biological tube is used to achieve the connection between both vessels, grafts being mostly done in polytetrafluoroethylene (PTFE). Nevertheless the grafts suffer of a worse patency rate and leading thus to more interventions compared to the fistulas (3) and (4). The temporary types of vascular accesses are the catheter and other vascular port access devices. Figure 3 presents illustrations of the two permanent types of vascular accesses (tribute to (23)).

Figure 2: general principle of haemodialysis (tribute to Fresenius Medical Care database of images)
An ideal vascular access should satisfy the three following conditions:
- To be able to deliver a sufficient blood flow rate
- Provide a long longevity of use
- Have a low complication rate, especially for stenosis, thrombosis and infection.

However the vascular access remains a leading cause for hospitalization and morbidity for the hemodialysed patients (24), the most common problems encountered being:
- Thrombosis: is the formation of a blood clot inside a blood vessel leading to an obstruction of the flow of the blood though the vessel
- Stenosis: a constriction or a narrowing of the lumen of the vessel (see Figure 4) that might lead to a reduction of the blood flow
- Infection: local and systemic infections are common
- Aneurysm: an abnormal blood-filled dilation of a blood vessel wall

Consequences of these complications are important and especially consequences of the stenosis. The failure of the vascular access limits the delivered dose of dialysis, effect which has a direct consequence on the survival rate of dialyzed patients (25). Moreover the KDOQI\(^1\) (Kidney Disease Outcomes Quality Initiative)

\(^1\) The KDOQI Guidelines corresponds to a huge overview and summary of the literature available in Dialysis and considered as the main important support.
Guidelines state that a reduction of the diameter of the vessel induced by a stenosis of 50% starts to be the critical point at which the blood flow start to decrease dramatically (7). Additionally stenosis is generally the underlying reason of the thrombosis (stenosis is over 85% of the cases responsible for thrombosed arteriovenous grafts (5) (6) (26) (27). The KDOQI stated that over 90% of the graft loss was caused acutely by thrombotic events (7). Studies furthermore revealed that the anastomosis was a common site of stenotic lesions in relation to the geometry of the anastomosis and especially to the angle (27) (28) (29). Associated to these, the costs due to vascular access complications are a leading problem for the Health System, evaluated for example to $1 billion annually in the US (30). The anastomosis geometry and especially the angle of the anastomosis have also an impact on the creation of stenosis. These complications of the vascular access are even more important due to the aging of dialysis patients and also the elongation of the dialysis period (31) (32). Consequently the KDOQI guidelines recommend highly the earliest detection of complications of the vascular access and also the development of monitoring and surveillance techniques. Nevertheless it remains important to mention that all stenotic lesions do not have a medical implication.

2.1.4. Surveillance and monitoring of the vascular access

It exists many different ways of investigating if a stenosis is present or not in a vascular access, each approach having its own drawbacks and advantages. Advantages can be summarized as non-invasiveness, the efficiency and accuracy of the technique used, its eventual low-cost character, the possibility of implementation in routine, a user- and skills-independency and not time-consuming.

The physical examination is the simplest technique, presenting the advantage to be cheap without the need of any specific materials or devices. However this technique is also highly user- and skills-dependent and results and interpretation might differ from one practitioner to another. The technique involves inspection, palpation and can be sometimes associated to the auscultation using a stethoscope. Moreover physical characteristics of the access during the practise of the treatment might be an indication of a stenosis (33). Parameters such as prolonged bleeding from the needle sites, oedema or changes in the pulse can be characteristics (34). The Doppler ultrasound is considered as the gold standard method to detect venous stenosis. This technique presents the advantage to be non-invasive and extremely accurate, mainly because of the peak systolic velocity (35). Another medical imaging technique is the angiography (Digital Subtraction Angiography) which is also very accurate but with the drawbacks of the necessity of special devices, a high cost and the use of a contrast medium. Another techniques use e.g. the measurement of the venous pressure, blood flow measurements or blood flow recirculation.

2.2. Fluid dynamics

2.2.1. Definitions

2.2.1.1. Fluids

A fluid can be considered as formed of a very large number of particles, very small and free to move. A fluid is consequently a continuous medium, deformable without rigidity and which can flow. Liquids, gas and plasmas are often distinguished. Studied liquids are often isotropic, mobile and viscous. Isotropic character assumes that the properties are identical in all directions of the space. Mobility is due to the fact that they do not own any specific form and they get the form of the recipient that contains them. Viscosity characterizes the fact that any modification of form induces resistance due to friction.

2.2.1.2. Compressible or incompressible

All fluids are compressible, including water, as their density is a function of the pressure modifications. Under steady conditions and considering that the changes in pressure are negligible, it is generally possible to simply the equations and the analysis of the flow by assuming that the fluids are incompressible and have a constant density.

2.2.1.3. Steadiness and uniformity

A uniform flow is a flow for which the flow velocity has the same magnitude and direction at every point in the fluid. A non-uniform, in the contrary, is when at a given moment the velocity is not the same at every point of the flow.

A steady flow is a flow for which the parameters (velocity, pressure and cross-section) might be different from one point to another but they do not change in the time. In the contrary, a steady flow is said when at any point in the fluid these parameters change.


2.2.2. **Physical parameters:**

2.2.2.1. **Density**

The density (volumetric mass density) $\rho$ of a fluid is its mass per unit of volume. The density $\rho$ (kg.m$^{-3}$) is defined as:

$$\rho = \frac{dm}{dV} \quad \text{Equation 1}$$

with $dm$ the mass (kg) and $dV$ the volume (m$^3$).

2.2.2.2. **Viscosity, dynamic and kinematic viscosities and types of fluids (Newtonian and non-Newtonian)**

The viscosity is a parameter that describes the internal friction of a fluid and its capacity to flow. The viscosity characterizes thus the resistance of the fluid to its flow when it is subjected to a force. The higher the viscosity and the less easily it flows. Under the effect of the interaction forces between the molecules of the fluid and interaction forces between the molecules of the fluid and the ones of the wall of the tube, each molecule of the fluid does not flow at the same velocity. Consequently there is a velocity profile. If the velocity of each particle of the fluid situated in a right section perpendicular to the flow, the velocity profile can be represented as in Figure 5. The movement of the fluid can be considered as many layers of fluid sliding on top of each other at different velocities. The velocity of each layer is function of its distance $z$ to the fixe plan: $v = v(z)$. A mean velocity $v_{\text{mean}}$ (m.s$^{-1}$) is defined as:

$$v_{\text{mean}} = \frac{q_v}{S} \quad \text{Equation 2}$$

where $q_v$ is the volumetric flow rate (m$^3$.s$^{-1}$) and $S$ the cross-sectional area (m$^2$).

![Figure 5: profile velocity in a pipe (z indicating a distance and $v$ the velocity)](image)

In viscosity are distinguished two types of viscosities. Firstly the dynamic viscosity: considering 2 adjacent layers separated by a distance $dz$. The force of friction $F$ which is applied at the surface of separation of the two layers is opposed to the sliding of one layer to another. This force $F$ (N or kg.m.s$^{-2}$) is proportional to the difference of velocity $dv$ (m.s$^{-1}$) of the two layers, but also to the area $S$ (m$^2$) and inversely proportional to the distance $dz$ (m) as:

$$F = -\mu S \frac{dv}{dz} \quad \text{Equation 3}$$

with $\mu$ is the coefficient of dynamic viscosity of the fluid. The unit from the international system of units is the Pa.s or Poiseuille (PI) considering that 1 PI = 1 kg.m$^{-1}$.s$^{-1}$. However it is still possible to find tables using the ancient system of units (CGS for centimeter-gram-second) with the use of the Poise (P or Po) and 1 PI = 10$^6$ P = 10 cP.

Secondly the kinematic viscosity: the kinematic viscosity $\nu$ is the ratio of the dynamic viscosity $\mu$ (Pa.s) to the density of the fluid $\rho$ (kg.m$^{-3}$, Equation 1) as:

$$\nu = \frac{\mu}{\rho} \quad \text{Equation 4}$$

In the international system units, this unity of viscosity does not have a particular name (m$^2$.s$^{-1}$) but in the CGS system the unity was the Stoke (St) and 1 m$^2$.s$^{-1}$ = 10$^4$ St.

Fluids can be distinguished into two families according to their viscosity. Newtonian fluids have a coefficient of viscosity independent of the velocity gradient or the shear stress. It is the case of the gases, vapours and pure liquids with a weak molar mass. The other fluids are called non-Newtonian fluids which have their viscosity changing as function of the velocity and the constraints applied on them when they flow.
2.2.2.3. **Flow rates**

The flow rate corresponds to the quantity of matter which goes through a cross-sectional area during a period of time. Are distinguished the mass and the volumetric flow rates. If \( dm \) (kg) corresponds to the elementary mass of fluid which goes through a right section of pipe during an interval of time \( dt \) (s), the mass flow rate (kg.s\(^{-1}\)) is equal to:

\[
q_m = \frac{dm}{dt}
\]

Equation 5

If \( dV \) (m\(^3\)) corresponds to the elementary volume of fluid which goes through a right section of pipe during an interval of time \( dt \) (s), the volumetric flow rate (m\(^3\).s\(^{-1}\)) is equal to:

\[
q_v = \frac{dV}{dt}
\]

Equation 6

Relation between \( q_m \) and \( q_v \) is given as:

\[
q_m = \rho q_v
\]

Equation 7

where \( \rho \) (kg/m\(^3\)) is the density previously defined in Equation 1.

The liquids being incompressible and a little dilatable (density constant), the term of iso-volumetric flow can be used. As the flow expressed in the section 2.1 is a volumetric flow rate, the term of \( Q \) instead of \( q_v \) will be used for the rest of the report. Thus:

\[
Q = q_v = \frac{dV}{dt}
\]

Equation 8

2.2.3. **Law of mass conversation or principle of continuity**

During a very short interval of time \( dt \), the mass \( dm_1 \) of fluid which went through the section \( dS_1 \) at the point \( M_1 \) (or \( M'_1 \)) is the same as the mass \( dm_2 \) going through the section \( dS_2 \) at the point \( M_2 \) (or \( M'_2 \))(see Figure 6).

Considering volumes equal to \( M_1M'_1 \cdot dS_1 \) and \( M_2M'_2 \cdot dS_2 \), the law of mass conservation can be written as:

\[
\rho_1M_1M'_1dS_1 = \rho_2M_2M'_2dS_2
\]

Equation 9

or also as:

\[
dq_{m1} = dq_{m2}
\]

Equation 10

And for a steady flow the mass flow rate remains the same all along the right sections of a same streamtube.

Equation 9 can be also expressed as function of the velocity. In this case the distance \( MM' \) as function of the velocity is expressed as \( v \cdot dt \) and consequently Equation 9 can be rewritten as (36):

\[
\rho_1v_1dS_1 = \rho_2v_2dS_2
\]

Equation 11

2.2.4. **Bernoulli’s principle**

It is considered an ideal fluid of mass \( m \) between the sections \( dS_1 \) and \( dS_2 \) at a time \( t \). At the time \( t+dt \) the fluid is between \( dS_1' \) and \( dS_2' \) (see Figure 7). By application of the principle of the energy conservation applied to the mass \( m \) between the instants \( t \) and \( t+dt \), it can be written (36):
For conservative force fields, Bernoulli’s equation can be generalized as:

\[
\frac{\rho v_2^2}{2} + \rho g z + P_2 = \frac{\rho v_1^2}{2} + \rho g z + P_1 = \text{cst}
\]

Equation 12

where \( \rho \) is the density of the fluid (kg.m\(^{-3}\)) at all points in the fluid, \( v \) the fluid velocity (m.s\(^{-1}\)) at a point on a streamline, \( g \) the acceleration due to gravity (m.s\(^{-2}\)), \( z \) the height (m) or elevation of the point (\( z \)-direction is pointing upward, in the opposite direction to the gravitational acceleration) and \( P \) the pressure at a chosen point (Pa or kg.m\(^{-1}\).s\(^{-2}\)). Conditions for the application of Equation 12 and Equation 13 are that the fluid must be incompressible and the friction by viscous forces should be negligible. Equation 13 has consequently 3 components:

- \( P \) the static pressure
- \( \rho g z \) the pressure due to gravity, hydrostatic pressure
- \( \rho \frac{v^2}{2} \) the dynamic pressure

\[\text{Figure 7: Bernoulli’s principle representation}\]

### 2.2.5. Venturi effect

The Venturi effect (37) corresponds to the reduction of fluid pressure as consequence of a fluid flowing through a constricted section of a pipe (see Figure 8). This effect corresponds in fact to a jet effect: the velocity of the fluid increases as the cross sectional area of the pipe decreases and the static pressure at the narrowed part is lower than the pressure in the normal section of the pipe. The increase of the velocity is the consequence of the principle of continuity described in section 2.2.3. The velocity must increase while the pressure must decrease to satisfy the principle of conservation of mechanical energy. In Figure 8 the pressure \( P_1 \) is greater than pressure \( P_2 \) but the flow velocity \( v_2 \) is greater than \( v_1 \).

\[\text{Figure 8: representation of the Venturi effect (A is the cross-sectional area, another notation of S, v the velocity, P the pressure and h the height)}\]
The pressure drop due to the Venturi effect can be derived from the Bernoulli’s principle (section 2.2.4) and the continuity equation (section 2.2.3) in the special application to incompressible fluids as:

\[ \Delta P = \rho \left( P_1 - P_2 \right) = \frac{\rho}{2}(v_2^2 - v_1^2) \]  

Equation 14

where \( \rho \) is the density (kg.m\(^{-3}\)), \( P \) the pressure (Pa or kg.m\(^{-1}\).s\(^{-2}\)) and \( v \) the fluid velocity (m.s\(^{-1}\)).

### 2.2.6. Reynolds number and types of flows (laminar, transient and turbulent)

The Reynolds number (38) is a dimensionless quantity used in fluids mechanics used is order to characterize different flow regimes within a similar fluid, as particularly the laminar, the turbulent or the transient flow. This number is defined as the ratio of the inertial forces to the viscous forces, quantifying consequently the relative importance of both types of forces for given flow conditions. The Reynolds number is defined as:

\[ Re = \frac{\text{inertial forces}}{\text{viscous forces}} = \frac{\rho v L}{\mu} = \frac{vL}{\nu} \]  

Equation 15

where:
- \( v \) is the mean velocity of the object relative to the fluid (m/s)
- \( L \) is the characteristic linear dimension (travelled length of the fluid or hydraulic diameter in case of pipes system) (m)
- \( \mu \) is the dynamic viscosity of the fluid (Pa.s or N.s.m\(^{-2}\) or kg.m\(^{-1}\).s\(^{-1}\))
- \( \nu \) is the kinematic viscosity of the fluid (m\(^2\).s\(^{-1}\)) also defined as \( \nu = \frac{\mu}{\rho} \)
- \( \rho \) is the density of the fluid (kg.m\(^{-3}\))

For the flow in a pipe or a tube, the Reynolds number is generally defined as:

\[ Re = \frac{\rho v D_H}{\mu} = \frac{v D_H}{\nu S} = \frac{Q D_H}{\nu S} \]  

Equation 16

where:
- \( D_H \) is the hydraulic diameter of the pipe or tube (m)
- \( Q \) is the volumetric flow rate (m\(^3\).s\(^{-1}\))
- \( S \) is the pipe or tube cross-sectional area (m\(^2\))

According to the value of the Reynolds number three different kinds of flow can be described (see Figure 9)
- A laminar flow
- A transient or transitional flow
- A turbulent flow

![Figure 9: laminar and turbulent flow representations](image)

Values defining the transition for one type of flow to another vary largely depending on the sources but it can be considered that for a flow in a pipe of section \( S \), the laminar flow occurs for a Reynolds Number less than 2300 and turbulent flow for a Reynolds number greater than 4000 (39). These numbers are called critical Reynolds numbers and critical Reynolds numbers differ according to the geometry.

### 2.2.7. Hagen-Poiseuille equation/law and Darcy-Weisbach equation

The Hagen-Poiseuille equation (36) (or law) gives the pressure drop for a fluid flowing through a long cylindrical pipe. Assumptions are that the fluid is incompressible and Newtonian but also that the flow is laminar. The length of the pipe must be largely superior to its diameter and no acceleration of the fluid should happen. The equation is given as:
\[ \Delta P = \frac{8\mu LQ}{\pi R_H^4} = \frac{128\mu LQ}{\pi D_H^4} \]

Equation 17

where:

- \( \Delta P \) the pressure drop (Pa or kg.m\(^{-1}\).s\(^{-2}\))
- \( L \) the length of the pipe (m)
- \( \mu \) is the dynamic viscosity of the fluid (Pa.s or N.s.m\(^{-2}\) or kg.m\(^{-1}\).s\(^{-1}\))
- \( Q \) is the volumetric flow rate (m\(^3\).s\(^{-1}\))
- \( R_H \) the hydraulic radius (m)
- \( D_H \) the hydraulic diameter (m)

In the case of a turbulent flow, the flow is more complex and the determination of the pressure drop more complicated. The state of the surface of the pipe is important for turbulent flow and its influence is even greater that the Reynolds number is greater. The Darcy-Weisbach equation (36) relates the pressure loss \( \Delta P \) (Pa) due to the friction along a given length of pipe to the average velocity of the fluid flow:

\[ \Delta P = f_D \frac{L \rho v^2}{D} \]

Equation 18

where

- \( \Delta P \) the pressure drop (Pa or kg.m\(^{-1}\).s\(^{-2}\))
- \( f_D \) is called the Darcy friction factor (no unit)
- \( L \) the length of the pipe (m)
- \( D_H \) the hydraulic diameter (m)
- \( \rho \) the density of the fluid (kg.m\(^{-3}\))
- \( v \) is the mean velocity (m/s)

**2.3. Description and physiological values of the main parameters for patients in haemodialysis**

To put in relation the sections 2.1 and 2.2, the main parameters used to describe the vascular access of a patient in haemodialysis are described and presented in terms of physiological values.

**2.3.1. Blood rheology or hemorheology**

The blood is composed of two main compartments: the plasma which represents approximately 55% of the total blood volume and the cellular compartment. The plasma contains 91% of water, 7% of blood proteins (fibrinogen, albumin, and globulin) and 2% of nutrients, hormones and electrolytes. In case of a separation (e.g. centrifugal), the cellular components represent the remaining 45% of the total blood volume with two parts: the buffy coat (correspond to the white blood cells and the platelets) and the red blood cells (40). The haematocrit corresponds to the volume percentage of red blood cells in the blood. It is normally about 45% for men and 40% for women (41). However in the case of hemodialysed patients, a value of about 35% is often considered as normal (42).

Viscosity was previously defined in section 2.2.2.2 and in the case of the blood its viscosity is function of its composition (haematocrit), but also function of the shear and function of the vessel diameter. However, it can be considered that the blood viscosity is 3 to 4 times higher than the one of water. Figure 10 presents the relation existing between the viscosity and the haematocrit. Normal range of the blood viscosity is about 2.5 to 4cP. As previously described in section 2.2.2.2 the unit cP is generally still used. However it is common to find in the literature greater values as for example in (43) where the blood viscosities are situated at 4.5 +/- 0.7 and 6.1 +/- 1cP in their selected patients.
2.3.2. Flow

The flow in the vascular access varies largely between the different patients due to the anatomical differences (diameter of vessels …), differences in the types of anastomosis (fistulas or grafts) as well as the vessels which are used in order to perform the anastomosis. However flow through a mature and functional arteriovenous fistula averages about 500 to 800mL/min while it is generally higher than 1L/min for a graft (while some patients can reach some extremes with a flow greater than 3L/min). Studies suggest that a flow between 600 and 800 mL/min for a graft corresponds to the zone for which there is an increased risk for thrombosis (45), (46), (47) and (48). In terms of fistulas, it has been shown that a flow less than 500mL/min is associated with stenosis (49), visible in Figure 11 which presents the relationship of the ratio of the intra-access pressure ($P_{IA}$) to the Mean Arterial Pressure (MAP) with the flow in permanent vascular access. Consequently physiological values of flow in a graft are possible from about 300 to more than 2000mL/min while for a fistula it starts about 200mL/min. The KDOQI Guidelines mentions that the region of good function is situated around 1L to 2L/min.

2.3.3. Pressures

Pressure profiles (Figure 12) are different between the two vascular access types described in section 2.1.3. In a graft the pressure progressively decreases along the length of the graft. At the arterial and venous
anastomoses pressure gradients are present even in the absence of stenosis. Within the body itself of the graft, there is a pressure difference of about 30mmHg due to the effective driving force ((50), (51) and (52)).

The Mean Arterial Pressure (MAP) is defined as:

$$MAP = \frac{2}{3}DP + \frac{1}{3}SP$$

where DP and SP are the diastolic and systolic pressures. MAP in case of hemodialysed patients can be estimated around 100 mmHg (53) due to their higher age and rigidity of the vascular access.

![Resistances in Graft](image1)

![Resistances in AVF](image2)

Figure 12: pressure profiles in the two access types (AVF meaning arteriovenous fistula) (tribute to (7))

2.3.4. Dimensions of vessels

Different types of grafts exist but commonly the diameter of a graft is about 6mm at the venous and at the arterial anastomoses. However it is also possible to find a diameter increasing from 6 to 8mm. Smaller diameters can be found, e.g. in the case of the forearm loop graft between the brachial artery and the antecubital or the basilica vein, the arterial anastomosis is generally about 4mm and the venous anastomosis 6mm. Unrevised grafts have generally a length of 30cm to 40cm while revised grafts can be up to 60cm (54). Arteriovenous fistula is considered adequate when the diameter is greater than 0.6cm and 0.6cm from the skin surface (7).

2.4. Phonoangiography

2.4.1. Definition and history

The term of phonoangiography was firstly used by Robert S. Lees and C. Forbes Dewez in 1970 and was defined as “the quantitative analysis of sounds produced by blood flow” (8). The technique was initially not intended specifically to the arteriovenous fistula or grafts of hemodialysed patients until D. John Doyle et al. suggested it (55). The idea was first taken over in 2005 by H.A. Mansy and R.H. Sandler in (9) and then actively by M. Mungúa Mena and P. Vásquez Obando at the origin of many articles on the topic (56), (57), (58), (18) and (13)). They are both the main contributors to the application of the phonoangiography to the field and are also at the origin of two patents (16) and (17).
2.4.2. **State of the art**

Intentions of previous works in the field can be generalized into two categories. Firstly the determination of the specific spectral features due to the presence of a stenosis including also the determination of the optimum frequency band(s) as well as the positioning for the sensor (9) (57) (18). Secondly the development of algorithms or screening techniques to allow the classification of sounds into a non-stenotic or a stenotic case; the classification might be simply distinguished into “stenotic” and “non-stenotic” or might involve sub-classes according to the severity of the stenosis (10) (13) (18) (59). Some authors also investigated the sounds due to the anastomosis (58) (12); indeed Munguía concluded that the special features produced by the anastomoses are relatively close to the special features due to the presence of a stenosis leading thus to the possibility of misinterpretation, this results was also underlined by Gram (10). Underlying reason could be that the thrill also appears in case of venous stenosis (60). The studies were mainly performed using an (electronic) stethoscope (the 3M Littmann recurrently used) directly at the patient’s arm, generally without any distinction between the arteriovenous fistulae (AVF) or the grafts at the exception of T. Sato who separated clearly his results according to the type of vascular access (12). The studies are generally suffering of a limited number of samples, mainly due a limited number of the stenotic samples (57). Signal processing was mainly involving wavelets (12) (10), generally justified by the authors (14) as offering the possibility to establish a link between the time and the frequency domains whereas the Fast Fourier Transform (FFT) cannot (nevertheless used e.g. by (61) or (9)). Other methodologies were also investigated as for example the Burg method (14) (15). Most of the studies were involving a comparison of recordings from patients before and after treatment of the stenosis (by angioplasty or another surgical methodology) (9) (14). Other studies were performed using the comparison of recordings from stenotic segments against reference segments (10). Different positioning of the sensors was used according to the sources, involving often the positioning on the anastomoses or even eventually directly at the stenosis itself (10). However some authors underlined the direct impact on the results of how the sensor is attached as well as the condition of the skin or changes due to the movement of patient (12) (61). Mansy mentioned differences between pairs of recordings even if it was not a comparison before/after angioplasty, these results might be maybe affected by one of these above mentioned parameters (9).

Previous phonoangiographic works performed in another fields agreed to mention that the optimum frequency bands was situated between 20 and 1000Hz (62) (63) and also that the energy tended to decrease with increasing frequency (64) (65) (66) (67) (68) (69). In agreement with these postulates, all authors who applied the phonoangiography for vascular accesses agreed to mention that vessel stenosis changes were found to be associated with changes in amplitude and/or a redistribution of the signal energy with an increase of the energy within some frequency band(s) (Table 3), especially in the higher frequencies (> 200Hz). Indeed Mansy states that he got a very low correlation in the case of the frequencies below 200Hz (9). Gram further indicated that he got a significant drop in the blocks 125 – 250 and 275 – 500 when normalized in relation to intensity (10). Sato presented results of wavelets analysis for a fistula with a stenosis at different positions as well for a graft without stenosis (12). Results indicated differences at the systolic and diastolic part of the signals which was in agreement with results from other authors concerning the sounds associated with coronary stenoses more detectable during the diastole (66) (70) (71).

<table>
<thead>
<tr>
<th>Source</th>
<th>Investigated bandwidth (in Hz)</th>
<th>Optimum band (in Hz)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Gram (72) (10)</td>
<td>20 – 1000 by blocks of 125</td>
<td>625 – 700 875 – 1000</td>
</tr>
<tr>
<td>Malindretos (61) (73) (74)</td>
<td>0 – 10000</td>
<td>110 – 615</td>
</tr>
<tr>
<td>Mansy (9)</td>
<td>0 – 1000</td>
<td>300 – 600</td>
</tr>
<tr>
<td>Vásquez / Munguía (13) (58)</td>
<td>0 – 1000 with distinction of 62.5 – 125, 125 – 250, 250 – 500 and 500 - 1000</td>
<td>250 – 500 500 – 1000</td>
</tr>
<tr>
<td>Chen (14) (15)</td>
<td>25 – 800</td>
<td>246.6 ± 7.1 410.3 ±9.9 645.8 ± 12.2</td>
</tr>
<tr>
<td>Wang (11)</td>
<td>0 – 1000</td>
<td>700 – 800</td>
</tr>
<tr>
<td>Chien (75)</td>
<td>0 – 1000 with distinction of 1-10, 10-100, 100-200, 200-300, 300-600, 600-800 and 800-1000</td>
<td>300 – 600 600 – 800 800 – 1000</td>
</tr>
</tbody>
</table>

Table 3: optimum frequency bands for the detection of stenosis according to the different authors

Authors managed more or less successfully the classification of the recordings using their algorithm: Gram obtained 100% sensitivity and 94% specificity with 1279 murmurs correctly detected against 20 murmurs incorrectly detected and 17 murmurs not detected (72). Wang (59) obtained a positive predictive value of 87.84% and a sensitivity of 89.24%. Vasquez and Munguía in (13) got 83% of correct detection; results might be
explained by the training of their classifier from data coming from only one patient with a stenosis. Using another methodology they got this time 85% of correct classification (18). Results were also found associated to the severity of the stenosis or the importance of modification of the stenosis before and after angioplasty with results poorer for the smallest stenoses or small changes in diameter (9) (14).

2.4.3. Underlying reasons: acoustical aspects

The phonoangiography is in fact an ameliorated version of the auscultatory technique already used by the practitioners in practise. However as using digital signal processing techniques, this technique should avoid the drawbacks of the auscultatory method which are: an interpretation neither quantitative (no real assessment of the severity of the stenosis) nor objective (results might differ strongly from one practitioner to another based on his experience) but also the temporary character of the results (results are not stored on any support). Furthermore results might be highly user-skills dependent. Using signal processing processed by computers, the technique could remain inexpensive (when integrated to the dialysis generator), non-invasive and eventually portable allowing a continuous monitoring. Signal processing can use the Fast Fourier Transform or as often used in the literature, the wavelets. The phonoangiography is based on sounds created due to modifications in fluids dynamics that was described in section 2.2.

Sounds are produced when an object is in vibration or moving and is deforming a medium engendering the motion of its molecules. These deformations are propagating through this medium as waves of different pressure and these waves can be detected at the surface of the medium (skin in the case of the patient) using a pressure sensor (or acoustical sensor). Sounds can be characterized by their intensity (or amplitude), their duration in the time domain as well as their frequency content (reason why digital signal processing is applied in order to reveal the main frequencies). Sounds can be also characterized by their speed propagation in a medium (76). As a consequence, if the medium is modified (restriction of the area due to a stenosis) or if the moving or vibrating object is moving or vibrating differently, these will lead to a modification of the features of the sounds and able thus their detection. These sounds and vibrations in the case of the hemodialysed patients can be separated into three categories (60) as presented in Table 4. The source of the acoustical energy is believed to be related to the turbulence (77) (78) produced by a partially occluded vessel but also by the modification of the type of flow, from laminar to turbulent as described in section 2.2.6 (65) (62).

<table>
<thead>
<tr>
<th>Sounds and vibrations</th>
<th>Definitions</th>
<th>Normal conditions of the vascular access</th>
<th>Stenotic conditions of the vascular access</th>
</tr>
</thead>
<tbody>
<tr>
<td>Thrill</td>
<td>Due to the turbulences in the blood, described as low pitch, not audible but palpable frequency components. Buzzing sensation felt over the anastomosis</td>
<td>Low pitch and not audible but palpable Only present at the anastomosis Present as well as at the systolic and the diastolic part of the pulse cycle</td>
<td>Apparition of the thrill downstream the site of the stenosis Only present at the systolic part of the pulse cycle (in the most severe cases of stenosis)</td>
</tr>
<tr>
<td>Pulse</td>
<td>Due to the cardiac activity</td>
<td>Soft and compressible pulsation</td>
<td>Pulse becomes stronger and identical to water hammer effect</td>
</tr>
<tr>
<td>Bruit</td>
<td>A turbulent blood flow is at the origin of the vibration of the vessel’s wall</td>
<td>Low pitch, continuous and present at the systolic and diastolic part of the pulse cycle</td>
<td>High pitch, discontinuous and audible only at the systolic part of the cycle</td>
</tr>
</tbody>
</table>

*Water hammer effect is the result of a sudden change in the velocity of a liquid*

Table 4: Different sounds and vibrations of the vascular access, their definitions and their modifications between the normal and the stenotic states of the vascular access (60)
3. MATERIALS AND METHODS:

3.1. Flow experiments

3.1.1. Setup of the experiment

In order to study the influence of different parameters on the acoustics, a model of a vascular access with an adjustable stenosis has been built as represented in Figure 13. Three different media of different viscosities were used (reverse-osmosis water, sucrose- and glycerine-water solutions) using a total volume of 10L (1). The vascular access of the artificial patient was a silicon tube of inner diameter 5mm and an external diameter of 1cm (wall thickness 2.5mm). A continuous flow was generated by a centrifugal pump (External Pump Royal Nr. 02, Barwig BWV, Germany) controlled by a voltage source (2). The volumetric flow in mL/min was determined by a precision flow meter (Digmesa FHK article number 937-45XX/01) connected to a pulse counter (DFM 100 version 3.01 Nr. 47307, ELV Elektronik AG, Germany) (5). Different degrees of stenosis were performed by means of an external reduction of the cross-sectional area of the tube using a progressive clamp (4) controlled by a dedicated number of turns of the clamp. Pressure and temperature were determined by two sensors (Umed, Fresenius Medical Care, Germany) at equal distances on either side (3) of the point of the stenosis (4). Both sensors were connected to a computer using serial plugs. For the dimensions of the setup refer to Figure 13. The audio acquisition system was composed of a miniature pre-polarized condenser transducer microphone (6) (AKG C411L, AKG Acoustics GmbH, Austria) connected to a battery supply device B29L (AKG B29L, AKG Acoustics GmbH, Austria) with a battery 9V, itself connected to an external soundcard Creative SoundBlaster X-Fi Surround 5.1 Pro USB (6). The frequency range of the microphone was from 10 Hz to 18 kHz. The microphone was placed and fixed directly on the silicon tube 15cm downstream the stenosis using double face adhesive tape with a ring holder of appropriate diameter to avoid the squeezing of the tube (and thus a local stenosis). Audio acquisition was performed with the freeware Audacity version 2.0.1. Post signal processing of audio files was performed with Matlab R2012a. Datasheets of the material are provided in appendices, section 7.1.

Figure 13: Artificial patient model

(1) Reservoir (2) Pump (3) Pressure and temperature sensors (4) Progressive clamp for generation of the stenosis (5) Flow meter (6) Audio acquisition system

The following rules have been respected during the different recordings:
- All the devices including computer have been used working on battery (except the pump). This was done in order to restrict the effect of the 50Hz and its harmonics from the power supplies on the recordings. The voltage source alimenting the pump was placed as far as possible from the experiment and particularly from the microphone. The experiment was kept at the maximum distance possible from other sources of 50Hz present in the room.
- The battery of the microphone was changed every day to conserve the same quality of recording.
- The microphone has never been moved during the process of all the different experiments.
- For each experiment, an audio track (duration 30 seconds, sampling rate 48 kHz, wav format) was recorded. In a databank, each experiment was associated to the medium used and the corresponding degree of stenosis (DOS, definition in section 3.1.3.1). Each experiment was also associated to a flow, pressures (before and after the stenosis) and temperature which were averaged over the interval of the recording.

3.1.2. Recording processes

Two different types of sequences of experimental settings were performed:

- **Sequence of type 1:**
  - The setting of the voltage of the pump remained constant and the degree of stenosis was progressively increased in 27 steps from the absence of stenosis to a maximal degree of stenosis of 97%.
  - Thus one sequence is equal to 27 audio tracks
  - This type of sequence was performed for different initial flows; these values being presented in the left part of Table 5 and as function of the medium used.

- **Sequence of type 2:**
  - The degree of stenosis remained constant and the flow was progressively increased using 14 different values of voltage from 3V to 9.5V by step of 0.5V.
  - Thus one sequence is equal to 14 audio tracks
  - This type of sequence was performed for different values of degree of stenosis (right part of Table 5):
    - Firstly without stenosis
    - And then from a degree of stenosis of 44% to 97% corresponding to a total of 14 different degrees of stenosis.

- Sequences of type 1 were performed before sequences of type 2. This allowed determining that the lower degrees of stenosis (4% to 40%) were not useful to be recorded for the sequences type 2 as they do not present any spectral interest.

- Both types of sequences were done for three different media: reverse osmosis water (RO-water), sucrose-water solution and glycerine-water solution. These media are further described in section 3.1.3.3.

- Between two measurements of a sequence, a minimum waiting time of 2 minutes for stabilisation of the system in the new configuration was used.

<table>
<thead>
<tr>
<th>Sequence types:</th>
<th>Type 1: Voltage constant and variation of the degree of stenosis (DOS)</th>
<th>Type 2: Degree of stenosis constant and variation of the voltage</th>
</tr>
</thead>
<tbody>
<tr>
<td>Definition of the sequence</td>
<td>DOS 0% to DOS 97% in 27 steps thus one sequence = 27 audio tracks</td>
<td>3V to 9.5V by step of 0.5V thus one sequence = 14 audio tracks</td>
</tr>
<tr>
<td>Each sequence being performed for:</td>
<td>Initial flows at DOS 0% (in mL/min)</td>
<td>n</td>
</tr>
<tr>
<td>Media used</td>
<td>Water</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
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<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td><strong>Total sequences:</strong></td>
</tr>
</tbody>
</table>

Equal to 1 for all
### Table 5: Repartition and description of the sequences and audio tracks (1264 audio tracks available for a total of 68 different sequences)

<table>
<thead>
<tr>
<th></th>
<th>Sequences: 68</th>
<th>Audio tracks: 1264</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Total audio tracks:</strong></td>
<td>(26 + 42)</td>
<td>(687 + 577)</td>
</tr>
<tr>
<td><strong>Intermediate totals of audio tracks, all media considered</strong></td>
<td>687 (390 + 135 + 162)</td>
<td>577 (196 * 3 – 11)**</td>
</tr>
<tr>
<td><strong>Total audio tracks:</strong></td>
<td>162 (6 * 27)</td>
<td>42 (14 * 3)</td>
</tr>
<tr>
<td><strong>Intermediate totals of sequences, all media considered</strong></td>
<td>26 (15 + 5 + 6)</td>
<td>42 (14 * 3)</td>
</tr>
<tr>
<td><strong>Total audio tracks:</strong></td>
<td>135 (5 * 27)</td>
<td>92 (12 + 14 * 27)</td>
</tr>
<tr>
<td><strong>Sucrose-water solution</strong></td>
<td>811 683 641 501 407</td>
<td>Equal to 1 for all</td>
</tr>
<tr>
<td><strong>Glycerine-water solution</strong></td>
<td>806 794 676 641 500 407</td>
<td>Equal to 1 for all</td>
</tr>
<tr>
<td><strong>Total sequences:</strong></td>
<td>5</td>
<td>14</td>
</tr>
<tr>
<td><strong>Total audio tracks:</strong></td>
<td>390 (1 * 12 + 14 * 27)</td>
<td>92 (97)</td>
</tr>
</tbody>
</table>

---

### 3.1.3. Controlled parameters

#### 3.1.3.1. Degree of stenosis (DOS)

A stenosis corresponds to a narrowing of a vessel (see section 2.1.3). The degree of stenosis (DOS, in %) is defined as the percentage of reduction of the cross-sectional area of the vessel. It is defined as:

\[ \text{DOS}_{\text{position } i} = 100 - \left( \frac{S_{\text{position } i}}{S_{\text{position } 1}} \right) \times 100 \]

where \( S_{\text{position } i} \) is the cross-sectional area of the vessel in absence of stenosis and \( S_{\text{position } 1} \), the cross-sectional area of a stenosis number \( i \). Consequently a DOS equal to 0% corresponds to an absence of stenosis and a DOS equal to 100% to a complete obstruction of the vessel. Figure 14 presents different degrees of stenosis.

![Figure 14: different degrees of stenosis](a) (b) (c)

The DOS was regulated by an external reduction of the cross-sectional area of the tube using a progressive clamp with an internal width equal to the external diameter of the silicon tube. Thus the tube was fixed horizontally (x axis) by the clamp and the DOS was mainly determined by the reduction of the vertical dimension of the stenosis (y axis). This allowed highly reproducible settings of the DOS (results of
reproducibility about the DOS available in section 4.1). The different configurations of the degree of stenosis were defined by the number of turns of the clamp using a visual mark and controlled with a numerical scale between two fixed points of the clamp such as represented in Figure 15.

![Figure 15: mechanical definition of the degree of stenosis](image)

(a) Numerical scale for verification of the configuration of the stenosis between two fixed points (b) Visual mark for the determination of number of turns

Conversion of the number of turns into cross-sectional areas for the determination of DOS using Equation 20 was processed using projections by means of photographs. A white lamp at one extremity was used to light up the tube. The clamp was placed 2cm from another extremity where the camera was standing on a tripod with a macro lens with fixed settings (Sony Alpha 55 with Sony 30mm F2.8 DT macro). This second extremity was held to stay at a fixed position (Figure 16). One photograph was taken for each of the 27 configurations of the stenosis. In order to assess the reproducibility of this system, 4 different series of 27 pictures were done starting again from the absence of stenosis configuration. Results are provided in section 4.1. Position no. 1 was considered as reference and corresponded to the absence of stenosis, thus DOS 0%. Variation of positioning between two positions was defined as a turn of 90 degrees of the visual mark. Position no. 27 corresponded to the maximum stenosis possible before a complete obstruction of the vessel.

![Figure 16: photographing system in order to perform the projections of the degree of stenosis](image)

Image processing was then performed for each picture available and included the following steps:
To facilitate the determination of the borders, the auto-determination of the different borders of the image was done based on local maxima of the gradient of the binary image with Matlab using the function `edge` with application of the Canny Method. Limits auto-detected by means of this function were underlined in red (Figure 17).

Then it was necessary to select by hand the correct border that delimitates the stenosis using Microsoft Paint by choosing the appropriate pixels and converting them into green (Figure 17).

![Figure 17: application of the edge function of Matlab with the Canny Method (here a DOS 53%) in order to auto-determine the borders of the image. Then selection by hand in green in Microsoft Paint of the correct border delimiting the stenosis](image)

The width (respectively height) of the green shape corresponded to the maximal horizontal (respectively vertical) dimension. The form was finally auto-filled in the inner part delimited by the border using the function `imfill` and the total number of pixels was counted (Figure 18).

![Figure 18: conservation of the border of the stenosis and determination of the width (x axis) and height (y axis) of the stenosis](image)

At the end of this process, the degree of stenosis $DOS_{position_i}$ (in %) was finally defined as:

$$
DOS_{position_i} = 100 - \text{mean} \left( \frac{\text{total number of pixels}_{position_i}}{\text{total number of pixels}_{position_1} + 100} \right)_{n=4}
$$

Equation 21

with position 1 being the absence of stenosis. For each stenosis, final values of width and height corresponded also to the means of the results from the 4 series. Width and height were converted from pixels into millimetres using distances in the pictures that were known in pixels as well as in millimetres enabling the assessment of a conversion coefficient. A coefficient to correct the effect of perspective was also applied in order to obtain the width of the stenosis at the position 1 equal to 5mm. Results about DOS are available in section 4.1.
3.1.3.2. Flow

Variation of the flow in the vessel was done by variation of the voltage of the pump. The volumetric flow (definition in section 2.2.2.3) was assessed using a precision flow meter connected to a pulse counter (datasheet indicating a precision of 2% for a range from 320mL/min to 8.50L/min, available in appendices in section 7.1.4). Calibration was performed by calculating the necessary time to fill reference volumetric flasks. Calibration curve (r=0.9994) used is presented in Figure 19 and defined the flow \( Q \) (mL/min) as:

\[
Q = 11.7205 \times x + 20.3517
\]

Equation 22

where \( x \) represents the value given by the flow meter (a.u.).

![Calibration curve of the flow meter](image)

Figure 19: calibration curve of the flow meter

3.1.3.3. Viscosity

Definitions and types of viscosity are given in section 2.2.2.2 and physiological values of the blood viscosity in section 2.3.1. In this part and in the rest of this report the term of viscosity refers in fact to the dynamic viscosity of a medium and the unit cP is used instead of the unit of the SI, the Pa.s.

Three different media were used with three different viscosities. The first medium used was reverse-osmosis water (RO water). The second medium used was a sucrose-water solution of weight percentage equal to 31.5%. The solution was obtained by mixing 2kg of pure-sugar with 4kg of water. The result of the mixing was also evaluated by measuring the weight (precision-scale with 4 digits precision, Kern ACJ/ACS 320-4M, Kern & Sohn GmbH, Germany) of 10 samples of 1mL (performed with pipette) at 20°C. Using the weight and the volume, the density could be determined and the composition was determined by reading the tables of composition in % in weight as function of the densities (79). The last medium was a glycerine-water solution with a percentage in weight of 51.5% of glycerol. The determination of the composition of the medium was determined by its density using the same principle as for sucrose (tables coming from (80)).

Experiments were generally performed between 25° and 28°C. For each medium, corresponding densities and viscosities at 25 and 28°C are determined in Table 6 (data were extrapolated when necessary). Results of the determination of the sounds velocity using the module BVM (Blood Volume Monitoring) of a 5008 dialysis generator of Fresenius Medical Care are also presented.

<table>
<thead>
<tr>
<th>Medium</th>
<th>Composition (% in weight)</th>
<th>Density (in kg/m³) at</th>
<th>Viscosity (in cP) at</th>
<th>Sounds velocity in medium (in m/s)^*</th>
<th>References</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>25°C</td>
<td>28°C</td>
<td>25°C</td>
<td>28°C</td>
</tr>
<tr>
<td>RO-water</td>
<td>not applicable</td>
<td>997.0</td>
<td>996.2</td>
<td>0.893</td>
<td>0.836</td>
</tr>
<tr>
<td>Sucrose-water</td>
<td>31.5</td>
<td>1132.4</td>
<td>1131.2</td>
<td>2.9931</td>
<td>2.7489</td>
</tr>
</tbody>
</table>
solution | 51.5 | 1127.9 | 1126.3 | 5.3373 | 4.7987 | 1706.84 at 24.57°C
---|---|---|---|---|---|---
Glycerine-water solution

*Reference for sounds velocity determination: isotonic sodium chloride solution NaCl 0.9% at 25.29°C gave 1507.12 m/s
** Data taken for tap water and not for reverse-osmosis water

Table 6: composition, densities and dynamic viscosities at 25°C and 28°C, sounds velocity and references for the three different media used

In appendices are presented on more details the tables and data about the viscosities and the densities used (see section 7.5).

3.1.3.4. Pressure drop

The pressure was measured using two sensors on either side of the stenosis (see section 3.1.1, Figure 13). In order to determine the pressure drop at the stenosis, $\Delta P_{\text{experimental}}$ (in mmHg) was defined as the pressure difference existing between these sensors:

$$\Delta P_{\text{experimental}} = P_{\text{before}} - P_{\text{after}}$$  \hspace{1cm} \text{Equation 23}

Secondly $\Delta P_{\text{fit}}$ was defined as the pressure difference which should exist in absence of stenosis between the two pressure sensors. This was performed by gathering all values of $\Delta P_{\text{experimental}}$ in the case of the absence of stenosis (DOS 0%) and expressing them as function of the flow $Q$ (in mL/min) and applying a regression; results of the equation obtained for each medium being presented in Figure 20.

Finally the difference of pressure (in mmHg) at the point of stenosis induced by the stenosis is determined as the difference between the experimental difference of pressure between the two sensors ($\Delta P_{\text{experimental}}$) and the difference of pressure which should exist between the two sensors in absence of stenosis ($\Delta P_{\text{fit}}$):

$$\Delta P = \Delta P_{\text{experimental}}(DOS, Q, \text{medium}) - \Delta P_{\text{fit}}(0, Q, \text{medium})$$  \hspace{1cm} \text{Equation 24}

Figure 20: determination of $\Delta P_{\text{fit}}$ by applying a regression of the $\Delta P_{\text{experimental}}$ as function of the flow for all measurements with a DOS equal to 0% and for each medium.

3.1.3.5. Velocity at the stenosis

In order to compare results from different settings at flow and DOS, the parameter velocity at the point of the stenosis was used. Velocity was already defined in section 2.2.2.2. The averaged velocity $v_{\text{stenosis}}$ (in m/s) at the stenosis was defined as the ratio of the flow $Q$ (in m³/s) over the cross-sectional area $S_{\text{stenosis}}$ of the vessel in the stenosis (in m²) as:

$$v_{\text{stenosis}} = \frac{Q}{S_{\text{stenosis}}}$$  \hspace{1cm} \text{Equation 25}

If the term velocity is used afterwards, it refers in fact to the velocity at the point of the stenosis.
3.1.4. **Signal processing**

3.1.4.1. **Fast Fourier Transform (FFT)**

Information concerning the recording processes is provided in sections 3.1.1 and 3.1.2. The first second and the last second of an audio track were truncated, limiting thus the audio track to a time signal of 28 seconds. Afterwards, the FFT was applied to the time signal using the function `fft` from Matlab and using a number of points which corresponds to the nearest power of 2 of the length of the signal using the function `nextpow2`. Absolute value of the signal was used. As the main important spectral components were situated in the range from 0 to 1 kHz, only this range was further analysed. Code in Matlab is available in appendices section 7.3.1.

3.1.4.2. **Smoothing the signal**

In order to facilitate further analysis of the different properties and features of the spectra, only the general shape of the signal was conserved using a method of conservation of the local maxima of the signal. The spectrum was divided into many equal sub-portions and for each sub-portion the local maximum (defined by its amplitude and position) was conserved. The global shape of the signal was finally reconstructed by keeping only these values and not the intermediate values. The size of the sub-portions was chosen in such a way that the general shape represented the best the original spectrum. The final resolution obtained was approximately equal to 1 Hz. Figure 21 represents an example of an original spectrum compared to the final shape obtained using this method with a resolution equal of 1 Hz.

3.1.4.3. **Cleaning the signal**

Some signals suffering of the presence of very sharp and high peaks due to electronic interferences (mainly at 50Hz and its harmonics), the signal needed to be cleaned from these peaks. The cleaning process was performed by replacing the values of a peak by the average of the local signal just before and just after the peak. A progressive mean was used in order to conserve as much as possible the tendency of the signal. More detailed explanations about the methodology are provided in appendices section 7.3.2.

3.1.4.4. **Total signal intensity**

The total signal intensity was calculated using an integration of the signal limited from 70.5Hz to 800.5Hz, region where the spectral features were concentrated. Once the cleaning process performed, the integration was done using the function `trapz` from Matlab from 70.5 to 800.5Hz.

3.1.4.5. **Determination of the presence – or not – of spectral features (SF)**

In case of the absence of a stenosis, the general shape of the spectrum corresponded to the one presented in Figure 22.
“Spectral features detected” defined the fact that at least one part – or even more – of the spectrum was differentiating enough from this general shape, characterised by the appearance of greater amplitudes coming out of this line, leading thus to the appearance of peaks, more or less spread. In order to define if spectral features were present or not in a spectrum, a reference line was defined as:

\[
\text{Reference line} = \text{mean}_{\text{signal}} + 2 \times \text{std}_{\text{signal}}
\]  \hspace{1cm} \text{Equation 26}

For a sequence, the reference line was defined for the DOS 0% of the sequence and kept for the further degrees of stenosis of the same sequence. For the sequences of type 1 (see section 3.1.2 for the definition), the reference line was defined for the DOS 0% of the sequence. Then for each of the 26 remaining DOS of the same sequence, the spectrum of each of them was always compared to this reference line. For sequences of type 2, the reference line was defined for the DOS 0% for which the voltage setting was identical (explanations in appendices section 7.3.3). Mean and STD were obtained by segmentation of the bandwidth from 70.5 to 800.5Hz by blocks of 2Hz. Spectral features are defined as “detected” if at least one part of the signal is coming above the reference line in a significant way and coming out of the general shape defined in Figure 22; the determination being performed manually for the 68 experiments available. Figure 23 presents an example of a signal for which the spectral features were defined as “detected”.

Figure 22: general shape of a spectrum of a DOS 0%

Figure 23: example of a signal where spectral features were defined as detected as the signal is largely above the reference line
3.1.4.6. Graphical representations of the spectral features

In order to present graphically the results associated to the spectral features in order to know their number, positions and other characteristics, data were handled as following:

- Firstly all data were divided according to the medium used: RO-water, sucrose-water solution or glycerine-water solution.
- All the data available for one medium were separated according to their velocity at the stenosis in 10 groups for sucrose and glycerine and 11 groups for RO-water as defined in Table 7.

<table>
<thead>
<tr>
<th>Groups</th>
<th>Sucrose and glycerine</th>
<th>RO-water</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>$v_{st} \leq 1$</td>
<td></td>
</tr>
<tr>
<td>2</td>
<td>$1 &lt; v_{st} \leq 1.5$</td>
<td></td>
</tr>
<tr>
<td>3</td>
<td>$1.5 &lt; v_{st} \leq 2$</td>
<td></td>
</tr>
<tr>
<td>4</td>
<td>$2 &lt; v_{st} \leq 2.5$</td>
<td></td>
</tr>
<tr>
<td>5</td>
<td>$2.5 &lt; v_{st} \leq 3$</td>
<td></td>
</tr>
<tr>
<td>6</td>
<td>$3 &lt; v_{st} \leq 3.5$</td>
<td></td>
</tr>
<tr>
<td>7</td>
<td>$3.5 &lt; v_{st} \leq 4$</td>
<td></td>
</tr>
<tr>
<td>8</td>
<td>$4 &lt; v_{st} \leq 5$</td>
<td></td>
</tr>
<tr>
<td>9</td>
<td>$5 &lt; v_{st} \leq 6$</td>
<td></td>
</tr>
<tr>
<td>10</td>
<td>$v_{st} &gt; 6$</td>
<td>$6 &lt; v_{st} \leq 7$</td>
</tr>
<tr>
<td>11</td>
<td></td>
<td>$v_{st} &gt; 7$</td>
</tr>
</tbody>
</table>

Table 7: repartition of the groups of velocities at the stenosis for the graphical representations of the spectral features

- For one group of velocity at the stenosis, all the spectra available for this group were averaged to get only one final spectrum representative of the group.

3.1.5. Reynolds calculation

The equation for the calculation of the Reynolds Number (Equation 16) given in section 2.2.6 is only valid for a circular cross-sectional area. The generated stenoses having a form close to an ellipse, this equation could not be used directly. In case of a flow in a tube or a pipe with a non-circular cross-sectional area, the hydraulic diameter of the pipe can be replaced according to (83) and (84) by:

$$D_H = 4 \cdot \frac{S}{C}$$  \hspace{1cm} \text{Equation 27}

where $C$ is the circumference of the form (in m) and $S$ the cross-sectional area of the form (in m$^2$). Replacing $D_H$ in Equation 16, the Reynolds Number (no unit) can be finally expressed as:

$$Re = \frac{4\rho Q}{\mu C_{stenosis}}$$  \hspace{1cm} \text{Equation 28}

where:

- $\rho$: the density of the fluid (in kg.m$^{-3}$)
- $Q$: flow (in m$^3$/s)
- $C$: the circumference of the stenosis (in m)
- $\mu$: the dynamic viscosity of the fluid (in kg.m$^{-1}$.s$^{-1}$)

The density $\rho$ and the dynamic viscosity $\mu$ were determined as function of the temperature and for each medium using the same sources that were cited in section 3.1.3.3.

The circumference was the only parameter that was not assessed directly from the projections (see section 3.1.3.1) but approximated using an ideal ellipse of semi-major axis $a$ and of semi-minor axis $b$ as presented in Figure 24. $a$ corresponds thus to the half-width of the stenosis while $b$ corresponds to the half-height.
Using this ideal ellipse, the circumference could be calculated using the first approximation of the calculation of the circumference of an ellipse by Ramanujan (85) which is defined as:

$$C = \pi \cdot \left[ 3(a + b) - \sqrt{(3a + b)(a + 3b)} \right]$$  \hspace{1cm} \text{Equation 29}

where:
- $a$ is the semi-major axis of the ideal ellipse equal to the half-width $x$
- $b$ is the semi-minor axis of the ideal ellipse equal to the half-height $y$

### 3.1.6. Stability and reproducibility of the system

The reproducibility of the generation of stenosis can be assessed with the 4 different series of photographs that was taken as described in section 3.1.3.1.

In order to assess the stability of the system, that means when a configuration was settled and the same protocol was used, variations (in %) of the flow, of the pressure after, of the pressure before and of the total signal intensity value were also assessed. This was done by comparing these parameters for sequences with an $n$ equal to 2 or 3 in Table 5 by applying the Equation 30:

$$\text{Variation} = \frac{\text{std}}{\text{mean}} \times 100$$  \hspace{1cm} \text{Equation 30}

Finally to assess the reproducibility of the system, all data having at the same time a variation of the flow, of the pressure after and of the pressure before less or equal to 1% (using the Equation 30) were gathered. For each group satisfying these 3 conditions, the variation of the total signal intensity value was calculated using the Equation 30.

### 3.2. Transmission through the needle experiment

#### 3.2.1. Setup of the experiment

The main purpose was to study if whether sounds could be transmitted through a needle and through the tubing system to be directly recorded at the arterial line of the extracorporeal circuit. The analysis of the sound transmission through the needle was performed using the system represented schematically in Figure 25. The system consisted on one side of the emission part including a waterproof speaker (1) (model K28WP, 8Ohm, maximum power 2W, Visaton, Germany) inserted in an air trap (2) from a tubing system Fresenius (SN-Set ONLINEplus BVM 5008-R, Fresenius Medical Care) filled with RO-water. The speaker was in direct contact with the water and the system was totally free of air. The system was filled with reverse-osmosis from the bottom using the yellow needle (3). The speaker was connected using a jack plug to the line out of the external soundcard (same as used during the flow experiments, see section 3.1.1). This emission side was equivalent in a hemodialysed patient to the sound generation in the fistula of a patient (e.g. stenosis and/or anastomosis).

The acquisition part consisted of a piezoelectric sensor (4) (Polyvinylidene difluoride (PVDF) sensor, 28µm thick, 22x171mm laminate, PK10418, Sensing Technologies GmbH & Co. As it was not possible to fix the piezoelectric sensor directly on a tubing system due to the large size of the sensor and the bad adherence of the
sensor on the tubing system, the piezoelectric sensor was wrapped around a reservoir (5) from a tubing system Fresenius (single needle chamber of a SN-Set ONLINEplus BVM 5008-R, Fresenius Medical Care). The piezoelectric sensor was wrapped and fixed on the reservoir using an adhesive layer already present on the sensor and tightened with the holder to increase the contact of the piezoelectric sensor on the surface of the reservoir. The piezoelectric sensor was connected with a double shielded coaxial cable (8) to an amplifier (Piezo Film Lab Amplifier GP-BOX 200712010, Sensing Technologies GmbH & Co) working on battery (2 batteries of 9V) and to an Intro Sense™ AD-USB box using a National Instruments NI USB-6008 card. Acquisition of sounds data was performed using LabView (dedicated software, introSense Analog Signal Recording version 2.1.1.0, Sensing Technologies GmbH & Co). This side was an equivalent of the signal detection at the dialysis machine.

Connection between the two systems was assured by a needle and two different tubing systems. The violet needle (9) (dialysis fistula needle, type A-401G, reference 5077401, 14G, diameter needle 2mm and needle size 2cm, silicon tubing, total size including needle and tubing: 20.5cm, Fresenius Medical Care) was inserted in the audio emitting side at the top of the air-trap and fixed with strong glue. The tubing system of the needle was connected to PVC extra tubing using a Luer connector (10). This extra tubing system (7)(tubing system for 5008, Fresenius Medical Care) of length 10cm included a Luer connector on one side and a plastic tubing connector on other side. This plastic connector allowed the connection to the tubing system coming out of the reservoir (6). This connection part corresponded thus to the line of the extracorporeal circuit but shortened and with blood replaced by water.

The whole system was filled with RO-water and a particular attention was paid to avoid any presence of air bubbles, especially in the needle and the tubing part of the system. The two parts of the system were placed on different supports to avoid any direct transmission through vibrations. The needle and the tubing systems were consequently the only connection between the emitting and the acquisition sides. The speaker was used to play the audio files previously recorded during the flow experiments described in section 3.1. As reference, to be sure that no other transmission than through the needle itself existed, measurements were initially performed with disconnection of the needle to the tubing system at the level of the Luer connector (10) and also by locking the clamps of both respecting systems (11 and 12).

The total internal length through the system starting from the speaker to the position of the piezoelectric sensor was approximately equal to 60 centimetres. Other dimensions are provided in Figure 25. Datasheets of the material are provided in appendices, section 7.1.

Figure 25: schematic representation with dimensions of the analysis system used for the study of sound transmission through a needle
3.2.2. **Signal processing**

Signal processing used the same steps of FFT, smoothing and cleaning as previously described for the system described in section 3.1 with the distinction that the sampling frequency was 10 kHz instead of 48 kHz (see sections 3.1.4.1 to 3.1.4.3).
4. RESULTS

4.1. Characteristics of the stenoses

After image processing of the projections of the different stenoses as described in Materials and Methods section 3.1.3.1, Figure 26 represents the evolution of the DOS as function of the position number $i$ of the stenosis after application of the Equation 21 and where the stenosis position number 1 represents the absence of stenosis. Figure 27 represents this time the evolution of the width $x$ and the height $y$ (in mm). Figure 28 is a representation of the geometrical evolution of the increasing stenoses. As mentioned in Materials and Methods section 3.1.3.1, the values used afterwards in the rest of the report correspond to the mean of the values from the 4 series of data. In appendices, section 7.4, are presented in more details all the values used associated to the characteristics of the DOS.

![Figure 26: variation of the DOS in % as function of the position number $i$ of the stenosis (reproducibility factor of n=4) and where 1 corresponds to the absence of stenosis](image)

![Figure 27: variation of the width $x$ (upper values) and height $y$ (bottom values) (in mm) of the stenosis as function of the position number $i$ of the stenosis (reproducibility factor of n=4) and where 1 corresponds to the absence of stenosis](image)
The averaged standard deviation (STD) over the 25 stenoses (DOS 0% being the reference, it was excluded and also DOS 97% as mentioned in section 4.2) was 0.4%, the minimum STD being 0.1% and the maximum 1.3%. Concerning the width x and the height y in millimetres:

- Results of the width x:
  - Small variations of the results up to the stenosis number 18 and larger variations afterwards
  - Averaged STD over the 25 stenoses: 0.07mm
  - Minimum STD: 0.01mm
  - Maximum STD: 0.27mm

- Results of the height y:
  - Results extremely good over the whole set
  - Averaged STD over the 25 stenoses: 0.02mm
  - Minimum STD: 0.006mm
  - Maximum STD: 0.04mm

Consequently the system used for the generation of the different degrees of stenosis (described in Materials and Methods section 3.1.3.1) is a well reproducible system.

4.2. Information relative to the data

From the whole set of data described in Materials and Methods section 3.1.2, data associated to a DOS equal to 97% were removed. The reason is double: most of these data had a flow which was extremely low and where consequently the precision of the flow meter was not appropriate. Secondly, most of these points induced a pressure drop ΔP which was extremely high (for example greater than 300mmHg). For these both reasons, these points (63 points) were removed from the whole set of data. Their distribution function of the medium and detection of spectral features (SF) are described in Table 8, middle part of the table. For the rest of this report, if nothing special is mentioned, it means that this set of data was used. The denomination D_{97%excl} can be also sometimes used.

For some parts of the report, only data in a physiological range (as described in theory section 2.3) were kept. These data are also presented in Table 8, right part of the table. This set of data involves the suppression of the data with a DOS 97% but also all points that had a ΔP greater than 100mmHg. This value was based on the value of the Mean Arterial Pressure (MAP) described in Equation 19. In the case of this set of data, the main parameters could be defined as the following:

- ΔP between 0 and 100mmHg.
- The maximum flow available was equal to 1450 mL/min and the minimum to 161 mL/min. Over the 1104 available points, 4 points had a flow lower than 200mL/min: 3 points with a flow of 161 mL/min and one point with a flow of 184 mL/min.
- The range of DOS was from 0 to 92%
- For the rest of this report, if the graphic or the text indicates “in physiological range’ or ‘D_{phy}”, the following set of data was used.
4.3. Stability and reproducibility of the flow experiments system:

4.3.1. Reproducibility of the parameter DOS

In section 4.1 were already presented the results of the reproducibility of the parameter DOS.

4.3.2. Stability of the system

From section 4.3.1, it is known that the parameter DOS was a well reproducible parameter. In order to assess the reproducibility of the other main parameters, especially the flow and pressures (before and after the stenosis), the stability of the system was firstly checked. This part had for intention to answer to the following question: if two experiments with exactly the same setting at the beginning of the experiment were compared and if the protocol used during the both experiments was strictly the same (corresponding to increase the DOS), would the values of flow and pressures (before and after the stenosis) be exactly the same or not? Consequently was the system acting exactly identically or not?

The methodology used is described in Materials and Methods section 3.1.6 and Table 9 presents the 3 groups of data used. For each group it is stated the values of the flow but also the pressures before and after the stenosis at the initial configuration (DOS 0%). During the recordings of the other stenoses, nothing except the degree of stenosis was changed, the configuration of the voltage of the pump remained the same. The viscosity is a parameter which did not change during the process of an experiment; the viscosity is consequently not studied.

The medium used for all data being the RO-water.

<table>
<thead>
<tr>
<th>Medium</th>
<th>Denominations</th>
<th>All data ***</th>
<th>All data with the suppression of points of DOS 97% (D_{phys})</th>
<th>Data in physiological range **** (D_{phys})</th>
</tr>
</thead>
<tbody>
<tr>
<td>RO-water</td>
<td>All points</td>
<td>586</td>
<td>558</td>
<td>518</td>
</tr>
<tr>
<td></td>
<td>Points with SF detected **</td>
<td>205</td>
<td>197</td>
<td>157</td>
</tr>
<tr>
<td>Sucrose-water solution</td>
<td>All points</td>
<td>329</td>
<td>312</td>
<td>287</td>
</tr>
<tr>
<td></td>
<td>Points with SF detected **</td>
<td>164</td>
<td>153</td>
<td>128</td>
</tr>
<tr>
<td>Glycerine-water solution</td>
<td>All points</td>
<td>349</td>
<td>331</td>
<td>299</td>
</tr>
<tr>
<td></td>
<td>Points with SF detected **</td>
<td>118</td>
<td>107</td>
<td>75</td>
</tr>
<tr>
<td>TOTAL</td>
<td>All points</td>
<td>1264</td>
<td>1201</td>
<td>1104</td>
</tr>
<tr>
<td></td>
<td>Points with SF detected **</td>
<td>487</td>
<td>457</td>
<td>360</td>
</tr>
</tbody>
</table>

** "SF" stands for "spectral features"

*** According to the principle defined in Materials and Methods section 3.1.4.5

**** "Data in physiological range" corresponds to "All data" minus the points of DOS 97% and minus the points where ΔP > 100 mmHg

Table 8: repartition of the data as function of the medium and the detection of spectral features

4.3. Stability and reproducibility of the flow experiments system:

4.3.1. Reproducibility of the parameter DOS

In section 4.1 were already presented the results of the reproducibility of the parameter DOS.

4.3.2. Stability of the system

From section 4.3.1, it is known that the parameter DOS was a well reproducible parameter. In order to assess the reproducibility of the other main parameters, especially the flow and pressures (before and after the stenosis), the stability of the system was firstly checked. This part had for intention to answer to the following question: if two experiments with exactly the same setting at the beginning of the experiment were compared and if the protocol used during the both experiments was strictly the same (corresponding to increase the DOS), would the values of flow and pressures (before and after the stenosis) be exactly the same or not? Consequently was the system acting exactly identically or not?

The methodology used is described in Materials and Methods section 3.1.6 and Table 9 presents the 3 groups of data used. For each group it is stated the values of the flow but also the pressures before and after the stenosis at the initial configuration (DOS 0%). During the recordings of the other stenoses, nothing except the degree of stenosis was changed, the configuration of the voltage of the pump remained the same. The viscosity is a parameter which did not change during the process of an experiment; the viscosity is consequently not studied. The medium used for all data being the RO-water.

<table>
<thead>
<tr>
<th>Groups</th>
<th>Initial flow at DOS 0% (in mL/min)</th>
<th>Initial P_{before} at DOS 0% (in mmHg)</th>
<th>Initial P_{after} at DOS 0% (in mmHg)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Signal 1: 630</td>
<td>107</td>
<td>59</td>
</tr>
<tr>
<td></td>
<td>Signal 2: 630</td>
<td>107</td>
<td>58</td>
</tr>
<tr>
<td>2</td>
<td>Signal 1: 864</td>
<td>160</td>
<td>78</td>
</tr>
<tr>
<td></td>
<td>Signal 2: 858</td>
<td>160</td>
<td>77</td>
</tr>
<tr>
<td>3</td>
<td>Signal 1: 642</td>
<td>114</td>
<td>66</td>
</tr>
<tr>
<td></td>
<td>Signal 2: 642</td>
<td>113</td>
<td>65</td>
</tr>
<tr>
<td></td>
<td>Signal 3: 642</td>
<td>115</td>
<td>67</td>
</tr>
</tbody>
</table>

All groups were RO-water

Table 9: information about flow and pressures for the data used in order to check the stability of the system

Figure 29, Figure 30 and Figure 31 represent respectively the variations in the flows, the pressures after and the pressures before for the 3 groups calculated by applying the Equation 30. In term of flows, it can be seen that the general variation is below 1% except for some points which are below 2%. Only the two last stenoses of the first group are more varying (below 6%). Concerning the pressures after, the variation is generally below 1.5% until the DOS 40%; afterwards the variation being below 3%. In terms of pressures before, the system remains below 1% until DOS 57%, from DOS 61% to DOS 79% below 2%. However in the last degrees of
stenosis, the variation increases to be below 8%. Consequently, when a configuration is settled and an experiment is processed exactly in the same manner, it can be said that the parameters flow, pressure before and pressure after remains relatively constant from one experiment to another.

Figure 29: stability of the system: variation of the flows for 3 groups as function of the DOS, medium: RO-water

Figure 30: stability of the system: variation of the pressures after for 3 groups as function of the DOS, medium: RO-water
Figure 31: stability of the system: variation of the pressures before for 3 groups as function of the DOS, medium: RO-water

Regarding this time the spectra and more specifically the variation of the total signal intensity (Figure 32), the variation remains generally below 3% at the exception of some values. These values correspond to the higher degrees of stenosis (greater than DOS 61%) with a variation mainly below 6%. This can be expected as the variations for the flow or the pressures were greater. However the system remains globally well reproducible.

Figure 32: stability of the system: variation of the total signal intensity for 3 groups as function of the DOS, medium: RO-water

4.3.3. Reproducibility of the system

To assess the reproducibility of the system, as mentioned in Materials and Methods section 3.1.6, this time were gathered only data for which the variations of the flow, of the pressure before the stenosis and of the pressure after the stenosis were less or equal to 1% (this was performed using the set of data D_{97%exc}). If these 3 conditions were satisfied, the variation of the total signal intensity was finally assessed using again the Equation 30. Results are presented in Figure 33 and it was distinguished if the group was composed of 2 points or 3 points.
A total number of 84 groups were found and only for the RO-water were found groups composed of 3 points. All media considered, the variation is for a large majority of the points below 4%. For the remaining points, the variation remains below 10%. The increase of the degree of stenosis cannot be related to an increase of the variation of the total signal intensity.

Figure 33: assessment of the reproducibility of the total signal intensity for points for which the variations of the flow and the pressures were less or equal to 1%, as function of the DOS and medium

4.4. Flow experiments: spectra and main characteristics

The audio recordings of the flow experiments were performed using two different types of sequences (see Materials and Methods, section 3.1.2). Figure 34 represents a sequence of type 1 meaning that the voltage was kept constant whereas the degree of stenosis was progressively increased. The FFT spectra of each of the different DOS are superimposed all together on a same graphic with a coloured codification of the different degrees of stenosis. This representation allows comparing more easily the results from the different settings as the DOS increases. The lowest DOS (4% to 40%) were not represented as they do not present any particular spectral features, remaining flat identically to DOS 0%. Identically, Figure 35 represents the superimposed spectra from an experiment where the DOS was kept constant (equal to 89%) and the voltage was progressively increased (sequence of type 2). Figure 34 and Figure 35 were cleaned from noise interferences according to the cleaning process described in the Materials and Methods section 3.1.4.3. For each spectrum, data concerning the DOS, the flow and the pressures are available in the legend.

Figure 34: comparison of spectra for an increasing value of the degree of stenosis and for a constant voltage (sequence of type 1), medium: RO-water
From Figure 34 and Figure 35, it can be noticed that when the DOS or the flow is increasing, there is also an increase in the amplitudes. This increase is not equally spread over the whole spectra and some frequencies are privileged compared to others and described as “spectral features” (SFs). For example, in Figure 34, amplitudes are greater for the region around 200Hz and another region spreading from 240-310Hz. In Figure 35, three main features can be underlined: from 150 to around 300Hz, another from 310 to 360Hz and a last one from 450 to 650Hz. In the case of the increasing DOS (sequence of type 1), it is also important to notice that the maximum of the amplitudes is for a DOS situated between 79 and 85% and afterwards, the amplitudes decrease. This can be explained by the fact that the flow falls down as the severity of the stenosis is progressively increasing. Nevertheless this effect was only observed for spectra with the medium RO-water. It is also important to notice that, in the case of the system used and described in Materials and Methods section 3.1.1, an increase of the severity of the stenosis induced a related decrease of the flow, both parameters being connected. Regarding the pressures, the pressure before the stenosis is increasing while the pressure after the stenosis is decreasing. Concerning the spectra with increasing voltage – or flow (sequence of type 2) – the maximum of amplitudes is located this time for the maximum flow available. The increase of the flow is also responsible for the increase of the pressures.

The system will be consequently firstly described in a “qualitative” way by describing the spectral features (the number of spectral features but also their positions, importance and behaviours). After that, the system will be described in a more “quantitative” way by describing the systems as function of different parameters and especially using the total signal intensity. The total signal intensity was calculated using an integration and is an important parameter that enables to get a numerical interpretation of the whole amplitudes of the spectra. By analysing the system in this way, it would be possible to assess the influence of the different parameters on the system and to understand which parameters are the most important for the apparition of sounds and thus of spectral features.

4.4.1. Distribution of the amplitudes: spectral features

In this section, the system is firstly described in a “qualitative” way. This consists in describing – when they are present – the different spectral features in term of numbers, positions, importance but also about their tendency when the velocity at the stenosis is increased. As mentioned above, the flow and the DOS cannot be considered independently and as described in section 3.1.3.5, the parameter velocity was used which is a parameter useful as it corresponds to the combination of both parameters. For this section was considered the set of data D_{F>97%}. In order to better assess the main spectral features without having to describe in details the spectra of the 64 sequences available as it was done for Figure 34 and Figure 35 above, the spectra were averaged according to the method described in Materials and Methods section 3.1.4.6 using different groups of velocities at the stenosis as presented in Table 7 in Materials and Methods. Each spectrum is thus a final averaged spectrum of many other spectra and the number of spectra included in this average is always mentioned in the legend (under the form n="x"). Table 10 presents an overview of these values. In the case of RO-water, 11 groups were selected while only 10 groups were selected for sucrose- and glycerine-water solutions. This difference is due to the remark mentioned above about the fact that in case of RO-water, the amplitudes are decreasing after reaching a certain maximum and a 11th group was selected in order to be able to show this effect in the spectra. To describe each
medium, a first graphic (Figure 36, Figure 38 and Figure 40) presents the averaged spectra using their amplitudes as function of the frequencies and a second graphic (Figure 37, Figure 39 and Figure 41) presents the spectra normalized to the spectrum of the first group (velocity at the stenosis \( \leq 1 \) m/s) as function of the frequencies.

<table>
<thead>
<tr>
<th>Groups</th>
<th>Velocities at the stenosis ( v_a ) (in m/s)</th>
<th>Number of spectra used for the average</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>RO-water</td>
</tr>
<tr>
<td>1</td>
<td>( v_a \leq 1 )</td>
<td>188</td>
</tr>
<tr>
<td>2</td>
<td>( 1 &lt; v_a \leq 1.5 )</td>
<td>117</td>
</tr>
<tr>
<td>3</td>
<td>( 1.5 &lt; v_a \leq 2 )</td>
<td>61</td>
</tr>
<tr>
<td>4</td>
<td>( 2 &lt; v_a \leq 2.5 )</td>
<td>53</td>
</tr>
<tr>
<td>5</td>
<td>( 2.5 &lt; v_a \leq 3 )</td>
<td>33</td>
</tr>
<tr>
<td>6</td>
<td>( 3 &lt; v_a \leq 3.5 )</td>
<td>26</td>
</tr>
<tr>
<td>7</td>
<td>( 3.5 &lt; v_a \leq 4 )</td>
<td>25</td>
</tr>
<tr>
<td>8</td>
<td>( 4 &lt; v_a \leq 5 )</td>
<td>22</td>
</tr>
<tr>
<td>9</td>
<td>( 5 &lt; v_a \leq 6 )</td>
<td>17</td>
</tr>
<tr>
<td>10</td>
<td>( v_a &gt; 6 )</td>
<td></td>
</tr>
<tr>
<td>11</td>
<td>( 6 &lt; v_a \leq 7 )</td>
<td>8</td>
</tr>
<tr>
<td></td>
<td>( v_a &gt; 7 )</td>
<td>8</td>
</tr>
</tbody>
</table>

Table 10: repartition of the number of spectra used for each average as function of the velocity at the stenosis group and the medium used.

4.4.1.1. Medium: RO Water:

Figure 36: averaged spectra for each of the 11 groups of velocity at the stenosis with the amplitudes as function of the frequencies (from 70.5 to 800.5Hz), medium: RO water \((n=558)\), data used: \( D_97\% \text{ excl} \)

Figure 36 represents the amplitudes of the averaged spectra for each of the 11 groups of velocities for the medium RO water as function of the frequencies for the bandwidth of 70.5 to 800.5Hz. Firstly, it can be observed that no spectral features can be detected for velocities at the stenosis below 1.5 m/s. The total number of spectral features can be estimated up to 7 when considering a velocity at the stenosis high enough. However the number of the spectral features varies as the velocity at the stenosis progressively increases. The first spectral feature to be detected is situated close to 300Hz, in the bandwidth from about 250 to 310Hz. This SF owns its maximum originally at 300Hz but will shift progressively to the lower frequencies to be situated around 255 to 295Hz, its maximum being spread almost equally as a plateau. Another SF is situated at 120Hz, this SF being extremely sharp compared to others and remaining for all velocities. From velocities at the stenosis greater than 2 m/s, two new SFs start to appear: a first one located around 190-240Hz and the second around 165Hz, also relatively sharp compared to the others. The SF of 165Hz does not shift. Concerning the SF around 190-240Hz, this one seems to fusion with the SF located from 250 to 310Hz to form only one very spread SF for the highest
velocities at the stenosis; distinction between the two groups being clear up to 6 m/s and afterwards it becomes difficult to distinguish them from each other.

For the higher frequencies, there are 3 distinct SFs. The first one to appear is located from 320 to 370 Hz and its maximum is situated around 340 Hz and becomes more and more sharp as the velocities at the stenosis increase. The two others SFs start from velocities greater than 3 m/s. The first one is from 380 to 440 Hz and the last one is largely spread in the high frequencies, going from around 440 Hz to almost 700 Hz. Except the SF from 250-310 Hz, the SFs generally do not shift. As mentioned already from Figure 34, the intensities fall down after reaching a maximum which is included in the group of velocities between 6 and 7 m/s.

In Figure 37, the same spectra are plotted but relatively to the first group of velocity to better assess the importance of the different spectral features and their evolution in time. In this case it can be observed that there is a progressive shift of the main amplitudes as the velocity at the stenosis increases. Up to velocities lower than 4 m/s, the main part of the main amplitudes is situated for the lower frequencies (before 320 Hz). Nevertheless, when the velocity increases, the groups of the higher frequencies, and more particularly the spectral feature situated between 440 and 700 Hz become more and more important relatively to the others. Whereas the most important feature was situated between 250 and 310 Hz for the groups of velocity up to 4 m/s, the SF 440-700 Hz becomes the main important for the highest velocities. When considering the moment from which the amplitudes fall down (comparison between red and medium blue groups), it can be observed that the relative importance of the SF 440-700 Hz remains the same while the importance of the SFs in the lower frequencies (before 320 Hz) falls down. This confirms the idea that the higher frequencies (more than 320 Hz) are the most important for the highest velocities at the stenosis.

![Figure 37: spectra normalized to the first group of velocity (velocity_{stenosis} ≤ 1 m/s) as function of the frequencies (from 70.5 to 800.5 Hz), medium: RO-water (n=558), data used: D_{97.5}, excl](image)

4.4.1.2. Medium: sucrose-water solution

Figure 38 is an equivalent of Figure 36 but for the sucrose-water solution. For this medium, it can be noticed that the distribution is different and less spectral features can be observed. However, contrary to the RO-water medium, the spectral features start to be detected from velocities at the stenosis greater than 1 m/s, with a spectral feature located around 130 Hz. Compared to other SFs, this SF is particularly sharp and the most important. As the velocity at the stenosis increases, it will spread more and more to be finally from around 100 Hz to 180 Hz for the highest velocities. Even if it spreads, this SF remains with its maximum always located at around 130 Hz. Another spectral feature starts to be drawn from velocities at the stenosis greater than 2 m/s situated around 300 to 390 Hz with its maximum located at 340 Hz.

For the lower frequencies (below 320 Hz), two last SFs are present: one around 180 to 220 Hz and another one around 220 to 290 Hz. This last one seems to be originally located around 275 Hz to progressively shift to get its maximum around 240 Hz.
Identically to water, a very broad spectral feature is located in the higher frequencies (greater than 320Hz), spreading from around 475Hz to about 700Hz. For the highest frequencies, a spectral feature also starts to come out around 425 to 470Hz. Comparing to RO-water, similarities are found:
- The SF 475-700Hz is clearly the same as for water from 440 to 700Hz.
- 425-470Hz of sucrose could be associated to 380-440Hz of water but more shifted to the higher frequencies.
- Identically, 300-390Hz of sucrose associated to 320-370Hz of water.
- The SF 220-290Hz of sucrose could be an equivalent to the 190-240 and 250-310Hz blocks of the water.
- The very sharp peak of 130Hz is an equivalent to the one of 120Hz of water.
- The SFs do not generally shift except the one located around 220 to 290Hz.

**Figure 38**: averaged spectra for each of the 10 groups of velocity at the stenosis with the amplitudes as function of the frequencies (from 70.5 to 800.5Hz), medium: sucrose-water solution (n=312), data used: D97% excl.

Regarding the relative amplitudes (Figure 39), the same tendency of shifting the major amplitudes to the higher frequencies as described for water can be announced. However, in case of sucrose-water solution, this shift effect starts sooner. For the lowest velocities at the stenosis (that means lower than 3.5 m/s), spectral features are located predominantly at 130Hz, around 340Hz and around 580Hz. Afterwards, the large SF spreading from 475 to 700Hz becomes the SF for which the evolution increases the most. For all velocities, the main spectral feature is the one located at 130Hz. Another spectral feature knowing a large increase is the one located around 240Hz.
4.4.1.3. Medium: glycerine-water solution

From Figure 40, it can be underlined that the apparition of the spectral features becomes more tardive compared to the previous media (from velocities at the stenosis greater than 2 m/s) and also that the number of spectral features continues to fall down (5 compared to 6 for sucrose and 7 for water). Again an important but very sharp spectral feature can be found at 130Hz. This SF is clearly the same as previously described for water and sucrose. Considering out this first SF of 130Hz, the first spectral feature starts to appear from velocities at the stenosis greater than 2 m/s but nevertheless with a very weak tendency. This first spectral features being located around 210 to 290Hz and being one of the most important features. This one shifts but weakly from around 260 to 240Hz as the velocities increase. It is necessary to wait velocities at the stenosis between 2.5 and 3 m/s to see appearing the next spectral feature situated around the 580Hz region. This spectral feature is again the largest feature which will progressively spread more and more to reach finally for the highest velocities a region going from about 440Hz to about 700Hz. Two last spectral features appear later on, one located around 160 to 205Hz and another around 310 to 370Hz.
Figure 40: averaged spectra for each of the 10 groups of velocity at the stenosis with the amplitudes as function of the frequencies (from 70.5 to 800.5Hz), medium: glycerine-water solution (n=331), data used: D

Considering relative amplitudes (Figure 41), this time it can be noticed that there are three main spectral features: 130Hz, 210-290 and the large 440-700 with its maximum around 580Hz. All of them remain equally relatively important up to the velocity group from 3.5 to 4m/s. From the next group of velocity (4 to 5 m/s), the two groups of the lower frequencies (130 and 210-290Hz) progressively lose their relative importance to the benefit of the group located around 580Hz.

Figure 41: spectra normalized to the first group of velocity (velocity < 1 m/s) as function of the frequencies (from 70.5 to 800.5Hz), medium: glycerine-water solution (n=331), data used: D

4.4.1.4. All media:

Table 11 presents a summary about the remarks done for the three different media. Similarities between the different media can be summarized as:
- When comparing the results of a same medium (intra-medium comparison):
  - The early detection of spectral features starts always in the lower frequencies (below 320Hz) while the detection in the higher frequencies (greater than 320Hz) starts later on.
However, there is a tendency that the amplitudes of the higher frequencies increase more than the amplitudes of the lower frequencies when the velocity at the stenosis increases to finally a more relative importance of the higher frequencies than the lower frequencies for the greatest velocities.

The maximum of a spectral feature does generally not shift but its area generally spreads more and more as the velocity increases.

Obviously, the amplitudes increase as the velocity at the stenosis increases except for water where the amplitudes decrease after a certain limit of velocity.

The number of spectral features increases as the velocity increases.

- When comparing the different media between them (inter-media comparison):
  - For the spectral features located in the higher frequencies (this concerns the region around 420 to 440 and the one around 440 to 700Hz), the maximum shifts to the higher frequencies as the viscosity increases (for example 440-700 owns its maximum at 520Hz for water, then at 570Hz for sucrose and finally at 580Hz for glycerine).
  - The number of spectral features decreases as the viscosity increases: 7 for RO-water, then 6 for sucrose and finally 5 for glycerine.
  - Nevertheless, all media keeps this tendency that the most important amplitudes shift to the higher frequencies when the velocity at the stenosis increases.

- In term of comparison of regions between the different media:
  - The large spectral feature spreading from around 440 to 700Hz is clearly the same for all media. Moreover, as mentioned above in the inter-media comparison, it is important to notice that the position of its maximum progressively shift to the higher frequencies as the viscosity increases: 520Hz water, then 570Hz for sucrose and finally 580Hz for glycerine (red colour in Table 11).
  - A region around 420 to 440Hz but only for water and sucrose. This region has also its maximum shifting to higher frequencies when the viscosity increases. Probably this region also exists for the glycerine but is incorporated in the large spectral feature spreading from 440 to 700Hz (orange colour in Table 11).
  - A region around 300 to 390 Hz but remaining with the maximum around the same place even if the viscosity increases (grey colour in Table 11).
  - Another region of interest identical to the three media can be considered around 160 to 310Hz (colour blue in Table 11). This region has its own sub-spectral features.
  - The last region 120-130Hz but this one will be commented in the discussion (green colour in Table 11).

- The main regions could be resumed to three as following:
  - Region 180-300Hz
  - Region 310-390Hz
  - and region 440-700Hz

<table>
<thead>
<tr>
<th>Characteristics</th>
<th>RO-water</th>
<th>Sucrose-water solution</th>
<th>Glycerine-water solution</th>
</tr>
</thead>
<tbody>
<tr>
<td>Number of SFs</td>
<td>7</td>
<td>6</td>
<td>5</td>
</tr>
<tr>
<td>SF (in Hz)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>(by order of apparition)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>No. 1</td>
<td>120</td>
<td>130 spreading then from 100 to 180Hz</td>
<td>130</td>
</tr>
<tr>
<td>No. 2</td>
<td>250-310</td>
<td>300-390</td>
<td>210-290</td>
</tr>
<tr>
<td>No. 3</td>
<td>190-240</td>
<td>180-220</td>
<td>440-700</td>
</tr>
<tr>
<td>No. 4</td>
<td>165</td>
<td>220-290</td>
<td>160-205</td>
</tr>
<tr>
<td>No. 5</td>
<td>320-370</td>
<td>475-700</td>
<td>310-370</td>
</tr>
<tr>
<td>No. 6</td>
<td>440-700</td>
<td>425-470</td>
<td>N.A.</td>
</tr>
<tr>
<td>No. 7</td>
<td>380-440</td>
<td>N.A.</td>
<td>N.A.</td>
</tr>
<tr>
<td>From which velocity at the stenosis starts the detection (in m/s)?</td>
<td>Between 1.5 and 2</td>
<td>Between 1 and 1.5</td>
<td>Between 2 and 2.5</td>
</tr>
</tbody>
</table>

Table 11: summary about spectral features function of the medium.
4.4.2. Intra-relations of flow, DOS, pressures (before and after the stenosis), ΔP and velocity at the stenosis

When the degree of stenosis increases, that means when the narrowing becomes more and more important and thus the section decreases, the velocity increases and the pressure downstream decreases whereas the pressure upstream increases. As a consequence, the pressure drop ΔP becomes more and more important. However, in the case of our system the flow remains constant until a certain limit and then decreases (already observable in Figure 34). This is due to the fact that the pump is not able anymore to strike against the pressure by giving more power. Consequently, relation between the parameters can be summarized as:

- Up to a certain limit, flow remains constant whereas DOS, ΔP, pressures (after and before the stenosis) and velocity increase
- After this limit: DOS, ΔP, pressures (after and before the stenosis) and velocity still increase but the flow decreases
- This limit in case of water is situated around DOS 44% and as well for sucrose-water solution. Considering glycerine-water solution, the limit comes later, around DOS 53%.
- Moreover the second part can be in fact divided in two: after another limit situated around DOS 75% for all media, the variations of the parameters are even stronger due to the fact the flow decreases more and more
- Figure 42 and Figure 43 present the evolution of the parameters as function of the increasing DOS for the same sequence of type 1, medium RO-water (the starting flow being around 630 mL/min).

Figure 42: evolutions of the flow and velocity at the stenosis as function of the DOS for a sequence of type 1, medium RO-water, starting flow being around 630mL/min.

Figure 43: evolutions of the pressures (before and after the stenosis) and the pressure drop ΔP as function of the DOS for the same sequence as used in Figure 42, medium RO-water.
4.4.3. **Total signal intensity and its relation with the detection of spectral features**

From Section 4.4.1, it is known that the spectral features are in direct relation with the velocity at the stenosis and that their number, positions and behaviour are modified as function of the increasing velocity at the stenosis. In this section the idea is to assess numerically or quantitatively the influence of the different parameters on the spectral features and to determine what are the key values of the system to distinguish the detection or not of spectral features. The set of data used is restricted to the physiological range.

4.4.3.1. **Medium: RO Water:**

In Materials and Methods section 3.1.4.4 was explained how the total signal intensity was calculated using an integration and in section 3.1.4.5 was described the methodology used in order to determine if spectral features are detected or not. Figure 44 presents the results of the total signal intensity as function of the velocity at the stenosis but also the detection of spectral features ("x" if SF not detected and "□" if SF detected) and the flow for the medium RO-water; information about the flow being given by means of the colour scale. Figure 45 presents the same graphic but with a special focus on the first velocities (lower than 2.5m/s). From these graphics, it is possible to distinguish 3 different zones of main interest:

- A first region which, in case of RO-water, is until a velocity at the stenosis equal to around 1.4-1.5 m/s
- A second region going from around 1.4-1.5 m/s to around 2 m/s
- And the last region for velocities at the stenosis greater than 2m/s

The first region is a zone where clearly no spectral features are detectable, whatever the value of the flow was and even if the flow was high. In this region, the value of total signal intensity remains mostly constant with a majority of point situated around $2\times10^4$ a.u. which corresponds thus to the noise level (or the noise baseline). It can be considered that the upper limit of this noise level is around $2.8\times10^5$ a.u.. Some points presenting a high value of total signal intensity do not lead nevertheless to the detection of spectral features. The limit situated around 1.4 to 1.5m/s is in agreement with the results found in Figure 36 and Figure 37 where the group including velocities at the stenosis between 1.5 and 2m/s was already presenting spectral features.

The second region is a kind of transitional region. In this region, it is possible to find at the same time points with spectral features detected and others with the SF not detected. It is remarkable that some points for which the SFs are detected remain nevertheless close to the noise baseline. In this region, a higher value of total signal intensity does not lead necessarily to the detection of the spectral features. The reason should be due to one or a combination of the other parameters (DOS and/or flow and/or ΔP). Considering again the values of total signal intensity, it is noticeable that from a velocity at the stenosis around 1.6 m/s the cloud of points start to distinguish itself more and more from the noise baseline.

The last region (from a velocity at the stenosis greater than 2m/s) is a region where almost all spectral features can be detected. The points for which the SFs are not detected are points remaining in the noise level and for which the flow is always below 600mL/min. In order to allow the detection of SFs of points with a flow between 400 and 600 mL/min, it is necessary to have a velocity at the stenosis greater than 2.9 m/s. To allow the detection of absolutely all spectral features, then a velocity at the stenosis of 3.7 m/s is required.

Other remarks are:

- A higher value of flow tends to have a higher value of total signal intensity.
- The maximum value of total signal intensity is given at around $3.2\times10^5$ a.u. for a DOS of 79%, a flow of 1128mL/min and a pressure of 88mmHg.
Figure 44: Total Signal Intensity as function of the velocity at the stenosis, the detection of spectral features and the flow (in colour bar), medium RO-water (n=518), in physiological range

Figure 45: zoom on the Figure 44: Total Signal Intensity as function of the velocity at the stenosis (up to 2.5m/s), the detection of spectral features and the flow (in colour bar), medium RO-water (n=518), in physiological range

In Figure 46 are plotted the flow and the velocity at the stenosis as function of the DOS but also the detection or not of spectral features as well as the ΔP. The different remarks from above are presented graphically as following:

- The green line represents the line of early detection of spectral features (so a velocity at the stenosis around 1.5 m/s)
- The blue line represents the velocity at the stenosis from which the cloud of points start to distinguish from the noise baseline (1.6m/s)
- In case of water, three other lines are present:
  - The first line with small dash points situated at 2m/s corresponds to the velocity at the stenosis from which all flows greater than 600mL/min have SFs detected.
- The second line with long dash points situated at 2.9 m/s corresponds to the velocity at the stenosis from which all flows greater than 400 mL/min have SFs detected.
- The last line with medium dash points situated at 3.7 m/s corresponds to the velocity at the stenosis from which all flows have SFs detected.
- In case of sucrose- and glycerine-water solutions, only one line exists.

From this graphic, it can be understood that in order to have the apparition of spectral features, as it is already known from above, the velocity at the stenosis has to surpass a lower limit. Moreover, it is also necessary that the flow and the DOS are also sufficient. Indeed, the first points to be detected (green line) are situated around a DOS of 61% and a flow of around 600 mL/min, pressure about 8 mmHg. Afterwards, when the velocity at the stenosis is increased, it might be possible to detect a point with a higher DOS but a lower flow, or, in the contrary, a point with a higher flow but a lower DOS. Nevertheless some limits are present in both directions. In term of DOS, it seems that the highest degrees of stenosis are not detectable in case of a flow below 300 mL/min. This should be due to the fact that not enough volume is flowing through the aperture and consequently does not lead to enough turbulences at the origin of the signal detected. On the contrary, it seems that below a DOS of 44% it might be difficult to be able to detect spectral features (except for one point with a DOS 33% but isolated). This value of 44% is in agreement with the section 4.4.2 where it was estimated that the flow starts to decrease from this value. However the database misses points having a very high flow associated to a lower DOS (below or equal to 40%). It is interesting to mention that relatively quickly it is possible to detect earlier DOS. Indeed from a velocity at the stenosis equal to 2 m/s it is already possible to detect from the lower limit of DOS; that means from DOS 44%.

In term of ΔP, the pressure difference does not seem to be particularly a limiting factor as points can be already detectable even if the pressure difference is around 10 mmHg. However the pressure difference allows having further indication about the position of the point; ΔP being always important if the flow is high and/or if the DOS is high. ΔP increases as the DOS and flow increase at the same time. The total signal intensity value follows the same principles as it is visible in Figure 47. From this figure, it is also possible to say that the cloud of points which remains with an integration value close to the noise baseline even when the velocity at the stenosis is very high (up to 3.7 m/s) corresponds in fact to the points with a very high DOS but a very low flow. This can be understood from Figure 34: indeed the amplitudes are the greatest (and thus the total signal intensity) for a stenosis included between 79 and 85%, afterwards the amplitudes decreasing again. Moreover it is important to mention that when a constant velocity at the stenosis is considered (so when following a line), that the value of integration will be smaller when the DOS is higher.

Figure 46: flow and velocity at the stenosis as function of the DOS, the detection of spectral features and ΔP, medium RO-water (n=518), in physiological range
4.4.3.2. **Medium: sucrose-water solution**

In case of sucrose-water solution (Figure 48 and Figure 49), the noise level is around $2 \times 10^3$ a.u. and the upper limit can be defined around $2.3 \times 10^4$ a.u. Again, until a velocity at the stenosis between 1.5 and 1.6 m/s the points remain in the noise level and only after this area the values of the total signal intensity start to increase and distinguish from the noise baseline. Contrary to water, after this limit is reached, an increase of the velocity at the stenosis induces generally an increase of the value of the total signal intensity, due to the fact that there is not a decrease of the amplitudes after a certain value of DOS. Some points remain nevertheless at the noise level but only up to a velocity at the stenosis around 3 m/s. The maximum value of integration is about $1 \times 10^5$ a.u. (DOS 65%, 1333 mL/min, 32 mmHg). The early detection of SF starts already from around 1.2 or 1.3 m/s (in agreement with results from Figure 38) and all data have their SF detected from a velocity at the stenosis greater than 2.6 m/s.
Figure 49: zoom on Figure 48: Total Signal Intensity as function of the velocity at the stenosis (up to 2.5m/s), the detection of spectral features and the flow (in colour bar), medium sucrose-water solution (n=287), in physiological range.

Figure 50: flow and velocity at the stenosis as function of the DOS, the detection of spectral features and ΔP, medium sucrose-water solution (n=287), in physiological range.
4.4.3.3. **Medium: glycerine-water solution**

For the last medium, glycerine-water solution, the noise level is situated around $2 \times 10^4$ a.u. and the upper limit can be placed around $2.25 \times 10^4$ a.u. The majority of the cloud of points at the noise level is until a velocity at the stenosis equal to 1.8 m/s, afterwards the total signal intensity starts to increase progressively. Some points remain still at this level until a velocity at the stenosis equal to 2.8 m/s. The maximum value of total signal intensity for this set of data is around $6 \times 10^4$ a.u. (75%, 1257 mL/min, 84 mmHg). Early detection of spectral features is in comparison to the other media relatively late starting from a velocity at the stenosis around 2 m/s; value being again in agreement to the value mentioned in section 4.4.1.3. The detection of all spectral features can be considered as complete from a velocity at the stenosis around 2.7 m/s.

**Figure 51:** Total Signal Intensity as function of the velocity at the stenosis, the detection of spectral features and the flow (in colour bar), medium: glycerine-water solution (n=299), in physiological range

**Figure 52:** zoom on Figure 51: Total Signal Intensity as function of the velocity at the stenosis (up to 3 m/s), the detection of spectral features and the flow (in colour bar), medium: glycerine-water solution (n=299), in physiological range
Contrary to water and sucrose-water solution, the earlier detection of SFs is later as already mentioned above. Moreover Figure 53 introduces the further indication that the earliest detectable point is in the range of the highest DOS. This point is indeed situated at DOS 85\% with a flow equal to 280mL/min and a pressure of 20mmHg. The detection of lower DOS is furthermore worse as the lowest DOS detectable is around 53\%.

\[\text{Figure 53: flow and velocity at the stenosis as function of the DOS, the detection of spectral features and } \Delta P, \text{ medium: glycerine-water solution (n=299), in physiological range.}\]

\subsection*{4.4.3.4. All media:}

Table 12 presents an overview of the most important results presented in sections 4.4.3.1 to 4.4.3.3 as function of each medium. Consequently, when considering a viscosity increasing, the most important result is that the lowest detectable DOS is greater (from 44\% for water and sucrose to 53\% for glycerine) but also that the first detectable points are more situated in the highest DOS area. Furthermore when the viscosity increases, the zone of detectability tends to decrease. To allow the detection of SFs, the system is submitted to a double condition: a minimum value of DOS (44 or 53\%) as well as a minimum velocity at the stenosis.

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Medium</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total signal intensity value of the noise baseline (x10^7) a.u.</td>
<td>RO-water</td>
</tr>
<tr>
<td>Upper limit of the noise baseline (x10^7) a.u.</td>
<td>2</td>
</tr>
<tr>
<td>Velocity at the stenosis from which the values of total signal intensity start distinguishing themselves from the noise baseline (in m/s)</td>
<td>1.6</td>
</tr>
<tr>
<td>Maximum value of total signal intensity (x10^7 a.u.) at a DOS (%), at a flow (mL/min) and at pressure drop (mmHg)</td>
<td>3.2 @79@1128@88</td>
</tr>
<tr>
<td>Velocity at the stenosis from which the spectral features start to be detected, early detection (in m/s)</td>
<td>1.5</td>
</tr>
<tr>
<td>First point to have its SFs detected (in mL/min) at DOS (%) and at pressure (mmHg)</td>
<td>600 @ 61@ 8</td>
</tr>
<tr>
<td>Velocity at the stenosis from which the</td>
<td>2 (if flow &gt; 600mL/min)</td>
</tr>
</tbody>
</table>
spectral features are all detected (in m/s) 2.9 (if flow > 400mL/min) 3.7 (all flows considered)

<table>
<thead>
<tr>
<th>The velocity at the stenosis until which one some points still remain in the noise level</th>
<th>4.2</th>
<th>3</th>
<th>2.8</th>
</tr>
</thead>
<tbody>
<tr>
<td>Lowest DOS detectable (in %) at flow (mL/min) and at pressure (mmHg)</td>
<td>44 @ 1321 @ 6 (33** @ 1146 @ 7)</td>
<td>44 @ 1321 @ 8 (37*** @ 811 @ 1)</td>
<td>53 @ 1198 @ 10</td>
</tr>
</tbody>
</table>

Results come from a set of data restricted to the physiological range

*from 2m/s, in case of RO-water, remains a cloud of points for which the flow is below 600mL/min and for which no SFs are detected. All points with a flow greater than 400mL/min have SFs detected from a velocity equal to 2.8m/s. All points, all flows considered, have SFs detected from a velocity equal to 3.6m/s. This situation is particular to the RO-water and due to the fact that the total signal intensity is at its maximum for stenoses between 79% and 85% and then its value decreases.

** A point at DOS 33% is detectable but the point is isolated.

*** A cloud of point being in contradiction with the other data, 1.3m/s should be considered if these points are excluded.

Table 12: overview of the main parameters in relation to the detection – or not – of spectral features for the three media

4.4.4. Reynolds Number

Now that the system is well known, it is necessary to try to understand what is the underlining reason of the presence – or not – of spectral features. As described in Materials and Methods section 3.1.5, the final equation used to determine the Reynolds Number $Re$ is:

$$Re = \frac{4\rho Q}{\mu C}$$  \hspace{1cm} \text{Equation 28}

where:
- $\rho$: the density of the fluid (in kg.m$^{-3}$)
- $Q$: flow (in m$^3$/s)
- $C$: the circumference of the form (in m)
- $\mu$: the dynamic viscosity of the fluid (in kg.m$^{-1}$s$^{-1}$)

In appendices section 7.5 is available information relative to the densities and dynamic viscosities of the media. Data for the circumference are available in appendices section 7.4. Figure 54 represents the results of the Reynolds Number as function of the velocity at the stenosis, the detection of spectral features (“x” if not detected and “□” if detected) and the total signal intensity values (using the colour bar), data being limited to the physiological range; Figure 54 being for the medium RO-water (n=518).

Figure 54: Reynolds number as function of the velocity at the stenosis, the detection of spectral features and the Total Signal Intensity, medium RO-water and data in physiological range (n=518)

In order to better understand the evolution of the Reynolds Number, it is necessary to refer to Figure 55. If the Reynolds Number points of a sequence of type 1 were plotted with a continuous line, it would be found that
the aspect of this line would be the same as the green line. This green line owns 3 different sections as the velocity at the stenosis increases and to understand this line, it is necessary to come back to the Equation 28. Considering the range of temperatures of the experiment (from around 25°C to 28°C), the densities and dynamic viscosities of the medium can be considered as constants and consequently the Reynolds Number can be roughly approximated as:

\[ Re = \frac{4\rho Q}{\mu C} = c \cdot \frac{Q}{C} \quad \text{Equation 31} \]

where \( c \) is a constant. By further approximation, the circumference \( C \) could be replaced by the inverse of the DOS as it is easier to think in terms of DOS instead of circumference. As a consequence, the evolution of the Reynolds Number as function of the increasing velocity can be explained as following:

- **Section 1 with increasing Reynolds Number**: this is due to the fact that until a DOS 44% (in the case of RO-water), the section and thus the circumference \( C \) decreases (thus the DOS increases) but the flow \( Q \) remains constant. Consequently considering Equation 31, the Reynolds Number increases as the numerator remains constant but the denominator decreases.

- **Section 2 with plateau**: in this situation, as DOS 44% is reached (44% in case of water and sucrose while 53% in case of glycerine), the flow \( Q \) starts to decrease and the decrease of the flow is approximately the same as the decrease of the circumference (and thus the increase of the DOS). The ratio remains consequently constant explaining why the Reynolds points are situated on a same line.

- **Section 3 with decreasing Reynolds Number**: in this last section, the decrease of the flow \( Q \) is greater than the decrease of the section or circumference \( C \) (and thus the increase of the DOS); the ratio becoming smaller, the curve is falling down.

Considering the evolution of the Reynolds number as function of the other parameters:

- A red arrow corresponds to a line where all the DOS are equal and could be called an “iso-DOS line”. As the circumference is directly linked to the DOS, it can be also called an “iso-circumference line”. In case of water, the left part of the graphic corresponds to the lowest DOS (0% to 44%), the middle part for the intermediate DOS (from DOS 44% to around 75%) and the right part of the graphic to the highest DOS (DOS greater than 75%). In case of sucrose the first iso-DOS line can be defined as mentioned previously around DOS 44% and for glycerine around DOS 53%. The second iso-DOS line is situated in the same region for all media, around DOS 75%.

- When following the direction of a red arrow, the flow increases. For an identical DOS, if the flow is greater, the Reynolds number will be bigger, see Equation 31

- In the contrary, when following the direction of the blue arrow, two sections need to be distinguished due to the effect described for the Figure 42: the section (1) corresponds to the part where the flow remains constant (DOS lower than 44 or 53%). In section (2), the flow decreases.

- Considering \( \Delta P \), this one increases following the direction of a red arrow of an iso-DOS line (because the flow increases) and also increases following the orange arrow (because the DOS increases).

- The total signal intensity follows the same tendency as the \( \Delta P \), that means increasing when following the direction of a red arrow of an iso-DOS line and also increasing when following the direction of the orange arrow. Distinction between blue and cyan for the colour bar was placed at 2.84e4 a.u. for water, 2.27e4 a.u. for sucrose and 2.25e4 a.u. for glycerine, corresponding roughly to the limit of the noise baseline as defined in Table 12.
Considering the critical Reynolds Number (see Theory, section 2.2.6), it was mentioned that the limits are not clear and depending on the sources, different critical numbers could be found. Some sources state a Reynolds Number greater than 3000 to mark the distinction between transitional and turbulent flows but other sources state 4000. Considering both numbers, according to the results, it seems that the distinction between spectral features detected and not detected is due to the modification of the type of flow, due to the passage from the transitional to the turbulent state. However, this is with the necessity of a minimum stenosis. Below DOS 44%, even if the Reynolds Number is high, there is no detection of spectral features. It corresponds to the zone (1) of Figure 56. The limit between detected and not detected SF is relatively clear and is situated at an iso-DOS line 44%. After this limit is reached, in order to get the detection of spectral features, there is a bottom limit situated around a Reynolds Number of 3800. Nevertheless as the DOS is increasing, this limit goes down to finally reach around 2800 for the highest stenoses. The region below this limit, zone (2) corresponds thus to points where spectral features cannot be detected while zone (3) corresponds to the zone where almost all points have spectral features detected. Consequently the generation of special sounds (spectral features) in the vascular access seems to be under a double condition: firstly the modification of the type of flow from the transitional to the turbulent state (consequently Re > Re_{critical}) but also a necessary minimum of degree of stenosis (which is at the origin of the perturbation of the flow).
Figure 56: delimitation of the zone of detection of spectral features, medium RO-water

Figure 57 and Figure 58 represent the results of the Reynolds Number but this time for respectively the sucrose- and the glycerine-water solutions. Results concerning these media follow the same principles as mentioned for RO-water; distinctions come from the Reynolds Number. In case of sucrose, when considering a DOS sufficient (eliminating the same points as previously mentioned in section 4.4.3.2), the limit for the Reynolds start about 800 to finally reach around 500. In case of glycerine, the zone (2) seems nevertheless to have disappeared.

Figure 57: Reynolds number as function of the velocity at the stenosis, the detection of spectral features and the Total Signal Intensity, medium sucrose-water solution and data in physiological range (n=287)
4.4.5. **Analogy to electricity: relation of the total signal intensity and the product of ΔP and the flow**

In electricity, an important relation is established about the instantaneous electrical power $P$ delivered to a component as:

$$ P = I(t) \cdot V(t) $$

Equation 32

where $P$ is the instantaneous electrical power in watts (or joules per second), $I(t)$ the current through it measured in amperes and $V(t)$ the potential difference (or voltage drop) across the component expressed in volts. As it can be observed from Figure 46 and Figure 47, it seems to have a similitude between the total signal intensity given by the integration and the product of the pressure drop $ΔP$ by the flow. If a regression is performed considering that the power $P$ is similar to the total signal intensity, the current $I$ to the flow and the potential difference (or voltage drop) to the pressure drop $ΔP$, results are presented in Figure 59 to Figure 61. In this case the set of data used was the physiological range but only the points for which spectral features were detected. It can be seen that this relation works well in the case of the glycerine-water solution with an $r^2$ equal to 0.897. However in the case of the sucrose-water solution and the RO-water solution, results are less promising with a $r^2$ respectively equal to 0.63 and 0.757.
Figure 59: regression of the total signal intensity as a function of the product of the pressure drop $\Delta P$ and the flow, medium glycerine-water solution, in physiological range but only with the data where spectral features were detected ($n=75$)

Figure 60: regression of the total signal intensity as a function of the product of the pressure drop $\Delta P$ and the flow, medium RO-water solution, in physiological range but only with the data where spectral features were detected ($n=157$)
4.5. Transmission through the needle and recording at the arterial line using the piezoelectric sensor

First intention was to use the needle directly in the system described in Materials and Methods section 3.1.1 and to have one sensor placed on the vascular access while another placed on the arterial line as presented in Figure 62. In this case it would have been possible to compare directly the sounds generated in the vascular access with the ones transmitted through the needle, final aim being to detect these sounds at the dialysis generator. However, the signal being too weak for the piezoelectric sensor, this method could not been implemented. Consequently, it was necessary to perform this study in two steps. The first step implied to perform the recordings and saved them (corresponding to all the results presented up to now); the second step to play them after amplification using the system described in Materials and Methods section 3.2.1.

Figure 62: wished system of comparison between recorded signal on the vascular access and the transmitted signal through the needle on the arterial line

Figure 63 to Figure 66 present the results of the transmission through the needle and recorded using a piezoelectric sensor. Each graphic presents firstly the spectrum of the wav file that was played using the speaker during the record, corresponding thus to the original signal. Corresponding amplitudes are presented on the left axis and the signal is plotted in red. On the right axis are presented the amplitudes of the transmitted signals through the needle, recorded by the piezoelectric sensor. A first spectrum (colour cyan) corresponds to the results of the transmission with the needle disconnected, whereas the blue spectrum corresponds to the results with the needle connected. The disconnected needle transmission was studied in order to assure that no another way of transmission other than through the needle was present. From the figures, it can be seen that indeed, in case of the needle disconnected, the signal remained flat; indicating thus that the only way of transmission was through the needle. For each figure are indicated the corresponding flow, DOS and pressures that were recorded during the flow experiment.
Figure 63 to Figure 66 present results of the transmission through the needle. Scales were done in such a way that the maximum of the original signal reaches almost the same height as the maximum of the transmitted signal. However, it is not possible to compare the values of the amplitudes due to the fact that two different sensors were used. It is thus not possible to determine the factor of loss due to the transmission.

Comparing the shapes of the spectra, it can be seen that both spectra follow the same tendency and the shapes are roughly the same. Nevertheless, the transmitted system presents clearly in the area from about 180Hz to 270Hz a weaker transmission on either side of 250Hz, inducing a complete modification of the aspects of the spectral features in this region. For example, in the Figure 63 in the region from 180 to 300Hz, there are three peaks (210, 260 and 295Hz), while the transmitted signal owns also three peaks but at different position. In Figure 64, a huge part of the signal is lost at 200 and at around 280Hz, modifying completely locally the shape of the spectral feature. Moreover, it is important to mention that for the higher frequencies (greater than 300Hz), the transmitted system has tendency to have weaker amplitudes, especially visible in Figure 64. The shape remains exactly the same but with a kind of translation directly to the bottom.

![Comparison between original and transmitted (connected and disconnected needle) signals through the needle, for a signal that was with: flow = 1263 mL/min, DOS = 70%, P\textsubscript{before}=344 mmHg and P\textsubscript{after}=144 mmHg](image)

![Comparison between original and transmitted (connected and disconnected needle) signals through the needle, for a signal that was with: flow = 1040 mL/min, DOS = 85%, P\textsubscript{before}=358 mmHg and P\textsubscript{after}=104 mmHg](image)

Regarding Figure 65 and Figure 66 where the spectral features are less important, the shapes are really identical but like shifted or translated to the bottom. The results also clearly show that the signal to noise ratio (SNR) was relatively bad. However, it remains still possible to recognize spectral features in the transmitted signal. The modification of the shape of the signal in the area from 180 to 270Hz is particularly problematic as it has been seen in section 4.4.1 that this area owns very important spectral features which moreover belongs to the
one which are the earliest detected (the earliest SFs being always in the lower frequencies, that means below 320Hz).

Figure 65: Comparison between original and transmitted (connected and disconnected needle) signals through the needle, for a signal that was with: flow = 688 mL/min, DOS = 85%, \(P_{\text{before}} = 170\) mmHg and \(P_{\text{after}} = 52\) mmHg

Figure 66: Comparison between original and transmitted (connected and disconnected needle) signals through the needle, for a signal that was with: flow = 559 mL/min, DOS = 85%, \(P_{\text{before}} = 122\) mmHg and \(P_{\text{after}} = 38\) mmHg
5. DISCUSSION:

Even if the model used for the flow experiments was reduced to its simplest forms, corresponding to a simple representation of a vascular access with a unique and linear geometrical configuration, the model presented interesting results as well as results in agreement with the literature. This model offered the easy possibility to control each parameter and to assess their influence on the acoustics, which is not possible when going directly to the bed of the patients and doing measurements. Furthermore the parameters that were used are parameters that can be normally controlled or monitored during the HemoDialysis sessions. For example the flow can be estimated using the Transonic (86) or ionic dialysance. The pressure difference can be estimated using the dialysis generator but in the particular case where the stenosis is in present in the section between the two needles. The three media used allowed to have a comparison of the parameter viscosity which is in relation with the haematocrit of the patient that can vary for a same patient (intra-patient) but also when comparing with other patients (inter-patients). The haematocrit of the patient is regularly controlled by a blood test. The system used seemed to be closer to the behaviour of what is currently happening in a graft than a fistula, particularly about the fact that the pressures upstream the stenosis are increasing in the case of the presence of a stenosis (7).

The model of vascular access with an external control of the degree of stenosis was performed with well reproducible parameters and a good stability. The generated degrees of stenosis in percentage were well reproducible with an averaged standard deviation equal to 0.4. When using identical settings to check the stability of the system, results indicated a variation of the flow below 2% and a variation of the pressures (before and after the point of stenosis) below 3%. Variation of the total signal intensity (integration) from 70.5 to 800.5Hz was below 6%. In term of reproducibility, when gathering all points of equal DOS and same medium for which the variation of the flow and pressures were less than 1%, variation of the total signal intensity was mainly below 4%. The system owned consequently a good stability as well as a good reproducibility. Comparing the value of the total signal intensity of 2 or 3 signals does not indicate if both signals have the same shape. Indeed they can have different shapes but a value of integration equal. However, the forms of the shapes was manually compared for some of the signals compared and their shape were indeed really very close to each other, indicating thus that the total signal intensity could be taken to compare them.

Using this model, accordingly to the literature (62) (63), it was found that the bandwidth of interest was effectively from 0 to 1000Hz and indeed that the energy tended to decrease with increasing frequency (64) (65) (66) (67) (68) (69). As expected, an increase of the severity of the stenosis induced an increase of the amplitudes. Moreover, as suggested by (62) (63) an increase of the flow also induced an increase of the amplitudes. Combining both results using the velocity at the stenosis, it leaded that the amplitudes increased as the velocity at the stenosis increased. However in the particular case of the water medium it was noticed that the amplitudes were maximal for a DOS around 79 to 85% and were decreasing afterwards, inducing that the amplitudes were maximal for a velocity at the stenosis between 6 and 7m/s. In term of spectral features, the bandwidth of interest 0 – 1000Hz could be further reduced to 150 – 800Hz. Among all media and all viscosities used, the main spectral features were found located firstly at 180 – 300Hz, then at 310 – 390Hz and finally at 440 – 700Hz. When comparing with the results obtained by the different authors presented in Table 3, results are in agreement. Interesting are the results obtained in (14) where three more specific regions of spectral features were found: 246.6, 410.3 and 645.8Hz. 246.6 corresponds effectively to the first spectral found at 180 – 300Hz. Concerning 645.8Hz, this spectral feature is integrated in the broad spectral feature found at 440 – 700Hz with the distinction that the maximum was found about 500Hz for water and about 580Hz for sucrose and glycerine. SF situated at 410.3Hz was indeed found as being a spectral feature in the case of water but was found around 450Hz for sucrose and absent in the case of glycerine. Still considering all media and viscosities, it is important to underline that the earliest spectral features always appeared in the low frequencies (320Hz ≤) but progressively, as the velocity at the stenosis was increasing, the increase of the amplitudes in the high frequencies (≥320Hz) were proportionally more important than for the low frequencies. This can explain why in (10) was found that the specific region was at 625 – 700 and 875 – 1000. Indeed the author was recording directly at the stenosis, thus where the velocity is the greatest and consequently where the high frequencies are also the most important proportionally in the spectrum. Additionally to these results, the study of (14) also underlined that when their patients had their vascular access corrected by angioplasty, the frequency spectrum distribution experienced a significant fall and shifted to lower frequency zone. In view of the results again, this remark can be explained as following: the angioplasty has for consequence to reduce the stenosis, thus after angioplasty the degree of stenosis is less, leading to a lower velocity in the stenosis. Other interesting result found during the analysis of the spectral features was that the position of the maximum of a spectral feature did not generally shift but its associated area was broader. Additionally when the viscosity of the medium was greater, it was found that less spectral features were detectable with amplitudes generally less important.

The most important result that came out from this study is that the appearance of spectral features is submitted to a double condition: firstly a degree of stenosis of at least 44% in case of RO-water and sucrose-water solution while 53% for glycerine-water solution. These values are in agreement with the KDOQI guidelines (7) stating that a reduction of the vessel induced by a stenosis of 50% starts to be the critical point at.
which the flow starts to decreases dramatically, which is also what was noticed in the system. The second important aspect that was already underlined by the study of the spectra as function of the velocities is that a minimum velocity at the stenosis around at least 1.2 to 1.3 m/s to obtain the first spectral features. In the contrary, when the flow is too low and/or the stenosis too important, the detection of spectral features became impossible. This result is in agreement with (14) stating that when the obstruction is too severe (greater than 95%), the sounds may not be produced because of low blood flow. Our study introduced furthermore that this limit could be even earlier than 95%. In view of the necessity to have a certain degree of stenosis but also a certain flow to have the detection of spectral features, a stenosis could be compared to what can be seen, or heard, in music. When blowing in the mouthpiece of a trumpet (only the mouthpiece without the trumpet behind), sounds will be high-pitched while when blowing in the mouthpiece of a trombone, sounds will be deeper. Difference about the two mouthpieces is the area: the area of the aperture of the mouthpiece the trumpet is smaller. Of course, these results are considered with air and not with a liquid. Always relative to the velocity at the stenosis, it might be considered for all media that when the velocity at the stenosis is greater than 2.6m/s, that the detection of spectral features is almost always done. In (87), a significant venous stenosis was described with Doppler ultrasonography as a lumen diameter below 3mm or a maximum systolic peak velocity over 3 to 4m/s, or both, which is in agreement with the results. In (88) a stenosis was considered significant if the peak systolic velocity was greater than 310 cm/s for a graft or 375cm/s for a fistula or a narrowing of 50% or more at the grayscale imaging. As mentioned before, the source of the acoustical energy is believed to be related to the turbulence (77) produced by a partially occluded vessel but also by the modification of the type of flow, from laminar to turbulent. Results about the Reynolds Number confirmed this idea, with the fact that the Reynolds Number associated to the zone where spectral features are audible is a zone where the Reynolds Number could be associated to a turbulent flow. The stenosis disturbs locally the flow and the perturbations and certainly the turbulences created downstream should be at the origin of the sounds. It can be thought that when the velocity is greater, mainly due to a stronger stenosis, a jet is created (identically to a hosepipe), idea also supported by (81). In this situation the higher the velocity would be, the stronger this jet would be and also the bigger the zone downstream the stenosis where perturbations (and turbulences) are created would be, consequently the larger the vibrations and the stronger the sounds. In the results, the velocity at the stenosis plays the most important role and it is a good tool as it combines at the same time results due to the DOS but also due to the flow. The velocity presents furthermore the advantage to be assessable using an echodoppler device. Accordingly it would be possible to assess the exactitudes of the results using and echodoppler.

Results given in term of transmission are promising. Even if the system needed to be amplified, the results clearly showed that a transmission through the needle is possible, furthermore with a general shape of the transmitted signal relatively close to the original signal. Differences might be due to the system itself used, that means the fact that a speaker was used with its own intrinsic properties as well as a new sensor (piezoelectric) that might have different intrinsic properties compared to the sensor used previously. The previous sensor was not used as its sensitivity was not enough to allow the detection of the transmitted signal in the configuration described in 3.2.1. In the contrary, the piezoelectric sensor was not used in the purpose of the flow experiments described in section 3.1.1 due to problems of fixation as well as a sensor this time too sensible and which was most of the time saturated. Eventually a part of the transmission could be effectively lost due to its passage through the needle but it was not possible to assess the value of the dumping system due to the differences between the two sensors as well as the fact that a speaker was used. The system could not be done in one step that means with the piezoelectric sensor on the arterial line with the needle directly inserted in the vascular access as no signal could be detected, even in the strongest configurations using a very high flow. Hopefully, this problem could be solved by finding a better sensor (piezoelectric sensor or another type) but this sensor should need to fulfil the following requirements: a high sensibility especially in the area from about 150 to 800Hz as well as the capacity to furnish an excellent signal to noise ratio. As it is visible for example in Figure 66, the SNR was extremely low.

In terms of limitations, the model was limited to its simplest form and did not take into consideration for example the “Y” configuration corresponding to the anastomosis met in terms of vascular access and did not take also all physiological parameters that can be encountered in vivo as for example the compliance; the human body being an extraordinary complex system. The parameters used have been selected as they were estimated as having an important impact in terms of acoustics but also as the practitioners consider these parameters as important. Moreover these parameters present the advantage for some of them to be monitored in current practise of the haemodialysis. The experiments were performed at a temperature between 25 and 28° which corresponds to roughly around 10 degrees less than a normal patient. However this should not have important consequences on the acoustic and the results obtained due to the small differences for the selected parameters between both temperatures. The study did not imply the use of blood for practical reasons due to the difficulties linked with working with blood. Identical work using blood would be interesting to be performed.

Contrary to a large majority of the articles published in the field which used an analysis in the frequency-time domain (mainly using wavelets as (12), (13) or (11)), the signal processing used involved the FFT (Fast Fourier Transform) which is only in the frequency domain. The main reason justifying the use of
wavelets compared to a FFT in the previous studies is that the FFT is not able to localize the observed frequency components in time and also justified by the fact that the blood flow is a aperiodic signal. The idea of this study was to study the influences of the different parameters on the acoustics on a general aspect and thus not at a specific time of the signal. This also allowed being free of one more parameter in an already multi-dimensional study. As a direct consequence the flow used during the flow experiments was a continuous flow and not a pulsatile flow, for which the use of the FFT is appropriate.

Concerning the results related to the spectra, the cleaning of the spectra was an important part of the signal processing work. Indeed, some signals were suffering of large peaks due to acoustic interferences, mainly due to the presence of the 50Hz and its harmonics but also as well as a perturbation around 120 to 130Hz due to intrinsic acoustic properties of the built system. The method used for the cleaning was used in order to limit the impact of the corruption on the final shape of the spectra. The choice of replacing the values of interference by the local mean of the system was judged as being the best option and it was also decided to be done more precisely by a progressive mean that allowed keeping the local tendency of the signal. Consequently if the local signal was increasing, the final result gave an increasing signal, identically if the signal was decreasing and obviously if the signal was constant, it remained constant. This method avoided having an eventual shape of the spectrum in the form of “stairs”. The lowest part of the spectrum was intensely corrupted by the 50Hz that was extremely strong in some spectra, reason why the part below the 70Hz was excluded of the analysis. Other reasons being also that this part was not described in the literature as being a part of interest in the acoustics as well as the fact that the recording properties of the microphone were not adequate for the lowest frequencies. In fact the whole region up to around 120 and 130Hz was relatively due to the strong 50Hz but also the strong 100Hz, first harmonic of the 50Hz and the area around 120-130Hz that will be discussed later on. The reason why the region around 70Hz to 120-130Hz was finally kept is due to the fact that this region is particularly of interest in the case of the sucrose-water solution where a large majority of the energy is concentrated (in the region around 100 to 180Hz). Otherwise if only the media RO-water and glycerine-water solution would have been used, this region would have been not further studied. Clearly the region which presented the most interest, all media considered, started around 150 to finish around 800Hz. Concerning the spectral features which are present in the area around the 120 and 130Hz are of particular interest as mentioned in section 4.4.1.4. These spectral features effectively existed but, as previously mentioned, a strong interference due to intrinsic interferences of the system was present over this area. Even if the spectral features were really existing, it is possible that the final aspect given by the mean spectra (see Figure 36 to Figure 41) were over-estimated and that the importance of this spectral features might not be so important. In case of further work, it would be necessary to use filters during the acquisition of the recordings (especially a band-cut filter for the 50Hz). Pre-processing would be an important part of the work, especially in the case of an implementation with real patients, due to the fact that the environment of the patients might be at the origin of many perturbations due to the other medical devices present in the room.

Regarding the results mentioning that the DOS of 44% and 53% are the starting point from where it is possible to detect spectral features, it might be possible that the detection could be in fact earlier when flow are higher. Indeed in Figure 46, the whole set of data is missing points for the highest flows (greater than 1L/min) for DOS below 44%. On the view of the results from this same figure, it is obvious that the acoustical technique is a perfect technique for a patient with a high flow in his vascular access. Indeed, the higher the flow in the vascular access and the sooner it is possible to detect the spectral features. According to the results, limitations of this technique is important for patients with a flow below 500mL/min: their stenosis would be detected relatively late using the acoustical technique, which is even worse as described in Figure 11 because this area of low flow corresponds to the area of high risk of thrombosis. Moreover the limitation is even worse as when the stenosis of the patient is increasing, the flow decreases even more and consequently the detection is even worse.
6. OUTLOOK:

Further works concerning the results might be necessary. It would be for example necessary to access the influence of the diameter of the tubing on the acoustics. In the system, the tubing had a diameter of about 5mm which is a bit less than in practise where the vessel are generally about or greater than 6mm as related in section 2.3.4. Furthermore, the generated shape of the stenosis corresponded to a progressive closure of the vertical axis with a small asymmetry due to a quicker closure of the bottom part of the stenosis than the upper part and only one configuration or one type of stenosis was used in the purpose of this study. Works assessing the effect of the type that means the form as well as the length of the stenosis would be necessary. (10) mentioned that the form and particularly the length of the stenosis have a direct impact on the acoustics. As the stenosis is the element at the origin of the creation of sounds due to the modifications of the hemodynamic that it induces, it is doubtless conceivable that a modification about the stenosis itself will induce modifications in the spectral features created. It is necessary to know how different could be the shapes of the spectral features according to the geometry of the stenosis. The positioning of the sensor, especially the fact that the sensor is before or after the stenosis as well as the distance from the sensor to the stenosis are two important parameters that need to be assessed. It might be eventually possible to assess the factor of dumping of the signal according to the distance relative to the stenosis. Using such information, it might be possible to assess how far the signal could be detected and eventually such information could be used to allow a determination of an approximate distance at which the stenosis might be. Of course, the shape of the vascular access itself should play an important role due and assessing the effects on the acoustics using different configurations might be more than useful. Contrary to the literature where the studies were performed by mixing without any distinctions the results coming from grafts and fistulas, it might be necessary to evaluate the differences due to these two types of vascular access. Configuration as well as the properties of the graft are different, as it corresponds to a synthetic tubing and thus impact on the acoustics might be also different, the vessel reacting differently.

In terms of signal processing techniques, due to the difference that the flow used in this study was a continuous flow while the blood flow in hemodialysed patients is pulsatile, it would be necessary to implement a technique, as it was done mainly in the literature, using a time-frequency analysis; results in the systolic and diastolic part of the signal being different, (66) and (70) supporting that the bet detection is during the diastolic part of the signal. However, as the required time for the calculations is not important due to the speed of the current computers, it might be still interesting to perform a FFT analysis in order to see if special elements could be seen in the FFT analysis. This would not take too much more time and could eventually bring important information.

What about the acoustical technique and its application? Supposing that a cartography of relationship between the main parameters could be performed in the case of real patients and for different configurations of vascular access as it was obtained in Figure 47. What are the parameters that could help to determine an approximation of the stenosis? The flow could be easily determined as it is already determined sometimes in routine using for example the Transonic which uses ultrasound and a saline bolus in order to determine the flow in the vascular access. Otherwise other techniques implemented in the dialysis therapy device could be use, as for example the determination using the ionic dialysance (89). Knowing the flow, it could be possible to have an idea on which line we are on the figure. Adding information concerning the value of the total signal intensity, it might be also possible to restrict the area of probability of the stenosis. Moreover using the information provided by the shape of the spectrum, it would be also possible to have an approximation of the velocity at the stenosis. Using these 3 parameters, it might be in this situation possible to determine an order of possible degree of stenosis. Obviously the situation is well more complex and the chance of being able to have such cartographies seems to be unfortunately weak, (9) mentioning that the spectral results they got showed a wide inter-subject variability, probably due to the broad anatomical differences. However it does not mean that the acoustical technique does not present any interest.

In sight of the current results, it seems that the initial project of having an audio sensor at the pressure sensor of the dialysis generator seems to be inadequate for two main reasons: the first reason is the distance between the sensor and the vascular access, considering that the further the sensor is and the less the signal is transmitted. Additionally for the second main reason that the closer to the machine and the more the interferences are present and stronger. Combining both reasons it seems consequently impossible to be able to detect sounds from the vascular access at this position. Nevertheless, the technique might be still possible at a close distance from the vascular access, apparently at the shortest distance possible from the needle. (16) and (17) own already a patent about an acoustical methodology using a double stethoscope system that needed to be placed on the vascular access. However this methodology might remain strongly user’s skills-dependent. Indeed the use of the stethoscope is not so easy and modifications in the positioning (pressing more or less on the vascular access, positioning of the head of the stethoscope might engender not negligible differences on the acoustics. Sato underlined the influence on the results of how the sensor is attached as well as the condition of the skin or changes due to the movement of patient (12). Additionally such technique needs to know some important
marking points of the vascular access of the patient for the positioning of the stethoscope, sensors being generally put on the marking points of the anastomosis. Alternative to this methodology would be to have the sensor placed on the arterial line, always at a fixed position on the tubing system. This would have for effect to avoid the user skill necessity. In this case a fixation using a system identical to the fixation system used for the ultrasound sensor of the Transonic as presented in Figure 67 could be used. The system of fixation should assure a perfect contact of the audio sensor on the tubing system and also the need of any air between both. System would be identical to the one of Figure 68.

![Figure 67: ultrasound sensor and its system of fixation on the tubing system (tribute to Transonic)](image)

![Figure 68: realisation of the acoustical technique in routine](image)

In case of the application of this system, it would be preferable to stop the extracorporeal circulation of the dialysis during the time of the sounds acquisition as the presence of the narrowing of the needle is itself a stenosis and would modify strongly the acoustics if the pump was pulling the blood into the needle (it would have exactly the same results as the stenosis created in the study). As a consequence, even if a system of
cartography for real vascular accesses might be not possible to perform in vivo, the acoustical technique would be still offer the possibility to allow the detection of a stenosis. Performed in a routine process, for example once a week, the system should help the practitioners to mention if a risk of creation of stenosis is present or not. In this case, it would be necessary to have a reference which should be done a few days after the medical imaging examinations done in routine to the patient (angiography), where it is known that there is no stenosis (or eventually an already known status of stenosis). By performing an acoustical analysis in routine (once a week for example) and comparing the weekly results of the new spectra against the reference, it might be possible to evaluate if a risk of development of a stenosis is real or not. Modifications in the spectra and appearance (or modifications of the shape in case of an already present stenosis) of spectral features would be an indication that a stenosis is developing. Combined to indications offered by the monitoring of the flow and an eventual decrease of the flow could be a further indication that something wrong in the vascular access is happening. Furthermore, the technique could be eventually improved by adding a second sensor on the venous line. Using comparisons between the two signals might give more indications in order to eventually precise the location of the stenosis (before the arterial needle, between the two needles or after the venous needle) as increasing the reliability of the analysis. Concerning the limitation of the acoustical system, that means for patients having a low flow, it could be possible to ask them to do a physical effort, this would consequently engenders a higher flow that could enhance the detection of spectral features. However, patients being aging, precautions have of course to be taken.
7. **APPENDICES:**

7.1. **Datasheets**

7.1.1. Miniature pre-polarized condenser transducer microphone AKG C411L

![Figure 69: datasheet of the microphone AKG C411L, first page](image-url)
6 Specifications

Type: pre-polarized condenser transducer
Polar pattern: figure 8
Frequency range: 10 Hz to 18,000 Hz
Sensitivity at 1 kHz: 1 mV/√Pa (vibration pickup)
Impedance: 200 Ω, unbalanced
Recommended load impedance: ≥1000 Ω
Max. SPL for 1%/3% THD: 96 / 103 dB SPL
Power requirement: C 411II PP: 9 to 52 V universal phantom power
                  C 411II L: B 29 L battery power supply,
                  MPA III L phantom adapter,
                  AKG WMS bodypack transmitters
Current consumption: approx. 2.2 mA
Cable length/Connector: C 411II PP: 3 m (10 ft.) / 3-pin male XLR
                        C 411II L: 1.5 m (5 ft.) / 3-pin mini XLR
Finish: matte black
Size: 27 x 14 x 9.5 mm (1 x 0.6 x 0.4 in.)
Net/shipping weight: C 411II PP: 98 g (3.5 oz.) / 225 g (8 oz.)
                     C 411II L: 18 g (0.6 oz.) / 150 g (5.3 oz.)

This product conforms to EN 50 082-1 provided it is connected to equipment with a CE mark.

**Frequency Response**

**Polar Diagram**

Cleaning: To clean the pickup case, use a soft cloth moistened with water.
7.1.2. **Battery supply AKG B29L**

Figure 71: datasheet of the battery supply AKG B29L.
7.1.3. **External soundcard Creative Soundblaster X-Fi Surround 5.1 Pro USB**

![Creative Soundblaster X-Fi Surround 5.1 Pro USB Image]

> **Figure 72: specifications from the website of Creative of the Sound Blaster X-Fi Surround 5.1 Pro USB, page 1**
7.1.4. Flowmeter Digmesa FHK article number 937-45XX/01

The datasheet presents information about measurements according to the diameter of the tubing system connected. Information is available for 1, 2, 1.5, 2, 2.5, 3, 4 and 5.6mm. 5.6mm being the closest to the diameter of the tubing system used during the experiment, information of measurements are presented for this value.
Figure 74: datasheet of the flowmeter Digmesa FHK Article number 937-45XX/01, page 1
Figure 75: datasheet of the flowmeter Digmesa FHK Article number 937-45XX/01, page 2
Figure 76: datasheet of the flowmeter Digmesa FHK Article number 937-45XX/01, page 11
7.1.5. Pulse counter DFM 100

Figure 77: datasheet of the pulse counter DFM 100, page 1
Durchflussmessgerät DFM 100


Tropfen für Tropfen

Die Messung einer Durchflussmenge beginnt stets mit der Umwandlung der analog (mechanischen) Größe in eine elektrische Größe.

Für geringe Durchflussmengen bis zu wenigen Kubikzentimetern ist die Tropfenzählung die geeignete und wohl genaueste Erfassungsmethode. Hierbei wird die zu messende Flüssigkeit Tropfen für Tropfen durch eine Lichtschranke geleitet und die einzelnen Tropfen werden gezählt. Abhängig von der Viskosität der jeweiligen Flüssigkeit entsprechen ein Tropfen immer einem bestimmten Volumen. Diese Methode ist z. B. in der Medizin zur Dosierung von Medikamenten oder aber im Chemie- oder Lebensmittelbereich weit verbreitet.

Für größere Durchflussmengen ist diese Methode natürlich ungeeignet, hier setzt man aufgrund der höheren zu fördernden Mengen meist das Prinzip eines Schaufelrades ein. Dabei wird die Flüssigkeit durch eine Düse auf ein Schaufelrad geleitet, sodass die Drehgeschwindigkeit des Rades proportional zur Durchflussmenge ist.


<table>
<thead>
<tr>
<th>Tabelle 1: Technische Daten Durchflussmesser</th>
</tr>
</thead>
<tbody>
<tr>
<td>Typ:</td>
</tr>
<tr>
<td>Nennweite:</td>
</tr>
<tr>
<td>Schlauchinnen:</td>
</tr>
<tr>
<td>Durchmesser:</td>
</tr>
<tr>
<td>Min. Durchfluss:</td>
</tr>
<tr>
<td>Max. Durchfluss:</td>
</tr>
<tr>
<td>Druck:</td>
</tr>
<tr>
<td>Temperatur:</td>
</tr>
<tr>
<td>Abmessungen:</td>
</tr>
</tbody>
</table>

Figure 78: datasheet of the pulse counter DFM 100, page 2
Überwunden, dass das Rad nicht in Drehung versetzt werden kann.

Darüber hinaus ist es jedoch wichtig, dass man die Durchflussmessung für eine bestimmte Anwendung vor allem mit einem geeigneten Sensor ausführen muss, da dies die Genauigkeit der Messung erhöht.

Die chemischen Eigenschaften (Säure, usw.), sowie die Viskosität der Flüssigkeiten, die mit dem Monitor gemessen werden soll, sind in Tabelle 1 und den technischen Daten der Hersteller aufgeführt, die bei ELV erhältlich sind. Die Industrie hilft durch Durchflussmessung für nahezu alle Anwendungsbereiche und -mengen bereit.

Intelligent messen

Wollen Sie die Durchflussmessung erfassen, so ist zunächst eine Zählung der Impulse erforderlich. Diese ist jedoch bei manchen Sensorsystemen nicht möglich, da sie auf einer Anzeige genauer Mengenangaben und keine Impulsanzahl bieten. Deshalb ist eine zusätzliche technische Anzeige erforderlich, die die Impulse in eine gängige Messgröße umrechnen kann. Bei manchen Sensoren kann dies jedoch nicht erforderlich sein, da sie die Impulse im Echtzeitbetrieb aufzeichnen können.

Table 2: Messtechnische Daten

<table>
<thead>
<tr>
<th>Datasheet: DFM 100, page 3</th>
</tr>
</thead>
</table>

Bedienung und Funktion

Die technischen Daten des Durchflussmessgeräts sind in Tabelle 2 zusammengefasst. Die Spannungsversorgung erfolgt über ein Steckernetzteil, das man für 3,5 mm Klinkenstecker an 110 VU anschließt. Alle Anzeigen sind genauso wie die anderen Displaygeräte in einem EEPROM abgelegt und können ohne jedes Abschalten der Spannungsversorgung erneuert werden.

Die Anzeige „Rechtstasten“ auf der Frontscheibe des Geräts zeigt die aktuelle Anzeige an, die durch Druck auf die Tasten „Rechts“ und „Links“ verändert werden kann. Die Anzeige „Links“ zeigt die letzte Anzeige an, die durch Druck auf die Tasten „Links“ verändert werden kann.


Die Tasten „Set/Reset“ dienen der Einstellung der Anzeige. Durch Druck auf die Taste „Set/Reset“ wird die aktuelle Anzeige gespeichert und die Taste „Set/Reset“ zeigt an, dass die Anzeige gespeichert ist.

Die Tasten „Rechts“ und „Links“ dienen der Veränderung der Anzeige. Durch Druck auf die Taste „Rechts“ wird die aktuelle Anzeige um eine Einheit vergrößert, und durch Druck auf die Taste „Links“ wird die aktuelle Anzeige um eine Einheit verringert.


Die Tasten „Set/Reset“ dienen der Einstellung der Anzeige. Durch Druck auf die Taste „Set/Reset“ wird die aktuelle Anzeige gespeichert und die Taste „Set/Reset“ zeigt an, dass die Anzeige gespeichert ist.

Die Tasten „Rechts“ und „Links“ dienen der Veränderung der Anzeige. Durch Druck auf die Taste „Rechts“ wird die aktuelle Anzeige um eine Einheit vergrößert, und durch Druck auf die Taste „Links“ wird die aktuelle Anzeige um eine Einheit verringert.


Die Tasten „Set/Reset“ dienen der Einstellung der Anzeige. Durch Druck auf die Taste „Set/Reset“ wird die aktuelle Anzeige gespeichert und die Taste „Set/Reset“ zeigt an, dass die Anzeige gespeichert ist.

Die Tasten „Rechts“ und „Links“ dienen der Veränderung der Anzeige. Durch Druck auf die Taste „Rechts“ wird die aktuelle Anzeige um eine Einheit vergrößert, und durch Druck auf die Taste „Links“ wird die aktuelle Anzeige um eine Einheit verringert.
Schaltung

Die zweiteilige Schaltung des Durchflussmessgerätes ist in Abbildung 1 und 2 dargestellt.


Herkunft der Schaltung ist der Mikrocontroller IC1 (ELV C0125). Hierbei handelt es sich um einen bereits programmierten Controller vom Typ 87C52, der innehalt über Programm- und Datenpeicher verfügbar. Die externen Komponenten Q1, C5 und C6 bilden die Leistungshandhabung und bestimmen die Rechengeschwindigkeit des Controllers.

Um den Controller nach einem Abtastsstrom, z. B. durch Einbinde der Betriebsspannung, definitiv zurückzusetzen, ist mit IC4 ein Watchdog aufgebaut. Das Gatter IC4 C bildet mit R2, R3 und C3 einen Kondensator, der mit einer Frequenz von ca. 0,5 Hz schwankt. Dieses Signal ist auf dem Reset-Eingang Pin 9 des IC1 geschaltet und setzt diesen bei High-Pegel zurück. Wechelt der Reset-Pin auf Low-Pegel, beginnt der Controller sein Programm abzuarbeiten. Dabei liegen an Pin 2 des IC 1 reguläre Impulse an. Diese werden durch das Gatter IC 4A geprüft und erzeugen über IC4 B, C 1 und R1 positive Spikes. Diese gelangen über die Diode D1 und R3 auf den Kondensator C3 und halten diesen auf High-Pegel, wodurch der Kondensator (IC 4 C) nicht mehr schwingt und der Reset-Pin des IC 1 auf Low-Pegel gehalten wird. Bleiben also die regelmäßigen Impulse an Pin 2 des Controllers aufgrund eines Abstaus aus, wird der Kondensator IC 4 C gespeist und setzt den Controller zurück.

Die Leiterschritte ST 1 bis ST 3 dienen zum Anschluss des Durchflussmessgeräts an die Steuerung der ST 2 und ST 3 er-hält. Der Signalausgang der Sensoren ist mit ST 1 verbunden. Da dieser meist als Oopen-Kollektorausgang ausgeführt ist, dient R 16 als dazu entsprechender Pull-Up-Widerstand. Der Widerstand R 16 und der Kondensator C 4 unterliegen Störspitzen und das Gatter IC 4 D nimmt eine Signalleitung vor, bevor das Signal dem Controller IC 1 und den Pins 12 und 13 zugeführt wird.

Der Schaltkreis ist mit den Bauteilen T 2, T 1 und R 12 bis R 14 aufgebaut. Der Arbeitsweise der Pegel am Pin 8 des IC 1 auf Low-Potential, wird der Transistor T 2 durchgesteuert, der wiederum über R 13 den Transistor T 2 durchhält. Dieser zieht die Schaltanlage (ST 4) nach Mas- se. Da bei kann man z.B. ein Relais zwischen ST 4 und ST 6 (12-V-Versetzen) oder ST 4 und ST 5 (5-V-Versetzen) anschließen, das bei aktiviertem Schaltkreis aktiviert wird. Die Diode D 2 verhindert Spannungsspitzen beim Abschalten des Relais.

Die Pegeln Pin 1 bis Pin 5 und Pin 32 bis Pin 39 des IC 1 dienen zur Steuerung der Anzeigen und sind auf die Buchsenleiste BU 2 geführt. Die Widerstände R 4 bis R 11 dienen als Vorwiderstände für die Anzeige und bestimmen deren Helligkeit. Pin 21 bis Pin 24 des IC 1 sind ebenfalls auf BU 2 geführt und hierzu von den Bedienstellen verstanden.

Die Schaltung der Anzeigen- und Bedienplatine des Durchflussmessgeräts ist in Abbildung 2 zu sehen. Die Tasten TA 100 bis TA 104 zeichnen bei Betätigung den entsprechenden Punkt des Mikrocontrollers nach Masse. Die 7-Segment-Anzeige DI 100 bis DI 104, sowie die LEDs D 100 bis D 106 arbeiten im Multiplexbetrieb. Dadurch wird die Zahl der zur Ansteuerung benötigten Leitungen verringert. Beim Multiplexbetrieb arbeitet die Anzeigeeinheit gleichzeitig mit den einzelnen Stellen der Anzeige nacheinander. Da dies mit einer Frequenz von ca. 60 Hz erfolgt, ermöglicht die innere Ausführung der Anzeigen, dass die einzelnen Anzeigen und die LEDs jeweils über eine der Leitungen A bis E aktiviert werden. Wechselt eine Leitung nach Masse, so steuert das entsprechende Transistor T 100 bis T 104 durch und legt die entsprechende Kette der LEDs auf High-Pegel.

Welche LED nun aktiv ist, wird durch die Signale S(0) bis S(7) bestimmt, die der Controller jeweils auf Masse-Potential zieht. Die anderen Anzeigenstellen bleiben dabei inaktiv, da sie über eine Taster gesichert sind, der Kapazität und quasi "in der Luft hängt".

Nachbau

Das Durchflussmessgerät ist auf zwei durchkontaktierten Leiterplatten mit den Abmessungen von je 80 x 52 mm untergebracht. Die Bedienerfläche befindet sich auf der rechten Seite, die Steckverbindungen am linken Ende. Der Steckerlektor ist mit der Masselektrode verbunden, die wiederum an die Masselektrode des Durchflussmessgeräts angeschlossen ist. Die Bedienung erfolgt über die Tasten auf der Bedienplatine. Die LED-Anzeigen sind für die erleichterte Steuerung des Durchflussmessgeräts vorgesehen. Dazu empfiehlt es sich,
Anschauung der fertig bestückten Anzeigee- und Bedienplatte mit zugehörigem Bestückungsplan

zu seinerzeit ein Lötspitze des SMD-Bauteile zu verlören und danach die Position zu überprüfen, bevor das zweite Pad angeleitet wurde. Bei den Dioden D1 und D2 ist auf richtige Polung entsprechend der Bestückungsanweis zu achten, die Dioden sind an der Katode markiert.

Danach sind die konventionellen Bauteile auf der Platteneinzelteil zu bestück- en, wobei merken die niedrigen, gefolgt von den höheren Bauteilen bestückt und verloren werden. Dabei sind folgende spezielle Hinweise zu beachten:

Der Spannungsteiler IC2 und der Quark Q1 sind liegend zu montieren, wobei der Spannungsteiler nach Abwinkeln seiner Anschlussleiste um 90° nach hinten (Ab- stand ca. 5 mm zum Bauteilkörper) zusätz- lich mit einer M3x8-mm-Zylinderschraube, eine Zahnrechte und ein M3- Muttern mit der Leiterplatte zu versehen. Die M3-Stiftleisten können mit einer M3x8-mm-Zylinderschraube, eine Zahnrechte und ein M3- Muttern mit der Leiterplatte zu versehen.

Nachdem die Steuerungsplatine komplett bestückt ist, können wir uns die An- zeigeplatine zu. Da beginnt die Bes- tückung mit der Widerstand, gefolgt vom (prinzipiell) 7-Segment-Anzeige (Orientierung am Dezimalpunkt der Anzeige, dies muss rechts unterliegen). Sie sind plan einzusetzen, sodass sich ein gleichmäßiger Stand aller sieben Anzeigen ergibt.

Die Einbaukante der Transistoren ergibt sich wieder aus dem Bestückungsdruck. Sie sind, wie die folgende und bestückende Leuchtbaule, so tief in die Platine einzusetzen, dass ihre Oberkante keinesfalls höher als die der 7-Segment-Anzeiger ergibt.

Das fertige Modul kann z. B. in einem Gehäuse mit einer Abdeckplatte montiert werden.

Figure 82: datasheet of the pulse counter DFM 100, page 6
7.1.6. Piezoelectric sensor

Figure 83: datasheet of the piezoelectric sensor, page 1

Piezofilm haben Limitierungen in einigen Anwendungsbereichen. Sie sind nur in relativ schwachen elektromechanischen Übertragern, verglichen mit Fasern, insbesondere bei Hochspannung und bei niederfrequenten Anwendungen.

Die (copolymer) Piezofolie darf bei max. 125 °C betrieben werden, während die reine PVDF Fläche lediglich bis 70 °C betrieben / gelagert werden sollte.

Hier einige Einsatzgebiete des Aufnehmers:

1. Aufgrund der günstigen Herstellungskosten eignen sich die Aufnehmer auch für kurzzeitige Messungen an Anlagen und Maschinen, für mobile Überwachung.
2. Integration in Anlagen und Maschinen zur effizienten Überwachung von Zuständen und Verschleißerscheinungen.
3. Anwendungen in der Gebäude- und Freiflächenüberwachung.
4. Überwachung und Steuerung von Haushaltsgeräten wie Waschmaschinen und Trockner.
5. Test- und Überwachungssensoren für Robotersysteme.
6. Anwendungen für welche die hochfrequente Auflösung von Signalen bis 150 kHz notwendig ist.
7. Variable Druckaufnehmer

Weitere Informationen erhalten Sie bitte der beiliegenden technischen Spezifikation.
Wir haben Ihr Interesse gewacht! Wenden Sie sich bitte an:

Sensing Technologies GmbH & Co. KG
Innovative piezo sensor solutions
Fahrenheilstraße 1, 28755 Bramsche
Telefon: +49 421 2208 402
Telefax: +49 421 2208 150
E-Mail: contact@sensingeo.net

Dieses Datenblatt behält Gültigkeit bis zur Freigabe und Vorveröffentlichung einer neuen Fassung.
<table>
<thead>
<tr>
<th>Parameter</th>
<th>PVDF FolienSensor</th>
<th>Copolymer FolienSensor</th>
<th>Einheit</th>
</tr>
</thead>
<tbody>
<tr>
<td>Folienstärke</td>
<td>9, 28, 52, 110</td>
<td>&lt; 1 bis 1200</td>
<td>µm (MICRON)</td>
</tr>
<tr>
<td>Piezo Belastungsspannung</td>
<td>32</td>
<td>100</td>
<td>N/m</td>
</tr>
<tr>
<td></td>
<td>72</td>
<td>72</td>
<td>N/m</td>
</tr>
<tr>
<td>Piezo Spannungskonstante</td>
<td>-230</td>
<td>-134</td>
<td>N/m²</td>
</tr>
<tr>
<td>Elektromechanischer Koeffizient</td>
<td>12</td>
<td>20</td>
<td>%</td>
</tr>
<tr>
<td>Zugsprungfaktor</td>
<td>16%</td>
<td>25 - 28 %</td>
<td></td>
</tr>
<tr>
<td>Kapazität</td>
<td>380 für 28 µm</td>
<td>68 für 100 µm</td>
<td>pF/cm² @ 1 kHz</td>
</tr>
<tr>
<td>Youngsches Modul</td>
<td>2 - 4</td>
<td>3 - 5</td>
<td>10⁶ N/m²</td>
</tr>
<tr>
<td>Schallgeschwindigkeit</td>
<td>1,8</td>
<td>3,0</td>
<td>10³ m/s</td>
</tr>
<tr>
<td>Pyroelektrischer Koeffizient</td>
<td>30</td>
<td>40</td>
<td>10⁻¹² C/m² · K</td>
</tr>
<tr>
<td>Permittivität</td>
<td>106 - 113</td>
<td>65 - 75</td>
<td>10⁻¹⁵ F/m</td>
</tr>
<tr>
<td>Relative Permittivität</td>
<td>12 - 13</td>
<td>7 - 8</td>
<td></td>
</tr>
<tr>
<td>Massendichte</td>
<td>1,78</td>
<td>1,82</td>
<td>10³ kg/m</td>
</tr>
<tr>
<td>Volumenwiderstand</td>
<td>&gt;10ⁱ⁷</td>
<td>&gt;10⁴</td>
<td>Ohm Meter</td>
</tr>
<tr>
<td>Oberflächenwiderstand</td>
<td>3,0</td>
<td>3,0</td>
<td>Ohm/sq cm für KIA</td>
</tr>
<tr>
<td>der Beschichtung</td>
<td>0,1</td>
<td>0,1</td>
<td>Ohm/sq cm für Aging</td>
</tr>
<tr>
<td>Dielektrizitätsverlust</td>
<td>0,02</td>
<td>0,015</td>
<td>8 1 kV/mm</td>
</tr>
<tr>
<td>Flächenfestigkeit</td>
<td>45 - 55</td>
<td>20 - 30</td>
<td>10⁴ N/m²</td>
</tr>
<tr>
<td>min. Temperatur</td>
<td>-40</td>
<td>-40</td>
<td>°C</td>
</tr>
<tr>
<td>max. Temperatur</td>
<td>-115</td>
<td>0,02</td>
<td>% H₂O</td>
</tr>
<tr>
<td>Wasseraufnahme</td>
<td>780 (30)</td>
<td>780 (30)</td>
<td>V/H₂O (V/µm) Dc, 8 25°C</td>
</tr>
<tr>
<td>max. Betriebsspannung</td>
<td>2000 (80)</td>
<td>2000 (80)</td>
<td>V/H₂O (V/µm) Dc, 8 25°C</td>
</tr>
<tr>
<td>Messverfahren</td>
<td>DSE</td>
<td>DSE</td>
<td></td>
</tr>
</tbody>
</table>

Figure 85: datasheet of the piezoelectric sensor, page 3
7.1.7. **Waterproof speaker model K28WP Visaton**

Figure 86: datasheet of the waterproof speaker model K28WP Visaton, page 1
Figure 87: datasheet of the waterproof speaker model K28WP Visaton, page 2
7.2. Spectrum of the pump

In order to assess if some spectral features might come from the pump and not from the stenosis, 4 series were performed with the sensor placed directly on the pump without a stenosis further on the system, see Figure 88 the 4 pictures on the left. These 4 series were compared to 4 other series performed again with the sensor directly on the pump but this time with a stenosis of DOS 79% further on the system, see Figure 88 the 4 pictures on the right. This stenosis was chosen as it corresponds to a stark stenosis and thus offering a great resistance to the flow for the pump. The idea was to check, if when a stenosis is created in the system, if the sounds coming from the pump are modified due to the fact that the pump needed to work against a resistance in the flow. Each series corresponds to 9 different voltages – and thus flows – to determine also if the increase of the voltage (and thus flow) might be also responsible of the transmissions. When comparing the pictures of the left to the pictures of the right in Figure 88, it can be noticed that the presence of a stenosis in the system did not lead to a significant increase of the amplitudes. Moreover no extra spectral features appeared and the general shape of the spectra remained almost the same. Considering that the system did not present any spectral features and remained always extremely flat in absence of stenosis for all types of flow (from low flow around 500mL/min to flow up to more than 1500mL/min), it can be considered that the pump is not responsible of the presence of spectral features in the spectra.
Figure 88: comparison between 4 series without a stenosis further in a system (left side) against 4 series with a stenosis of DOS 79% further in the system (right side)
7.3. **Explanations about programing code**

7.3.1. **FFT calculation**

The code for the calculation of the FFT was:

```matlab
for i=1:number_records %loop to repeat for the different
    signals of a sequence
    cd(rep_data_corrected) %to access the folder
    filename_wav=[num2str(i),'.wav']; %to determine the name
    of the file
    [signal_time, FS, nbits, readinfo] = wavread(filename_wav); %extracting the information from the
    wav file, especially the signal in the time but also the
    frequency sample FS
    signal_time=signal_time(48000:1392000,1); %Remove the
    first and the last second of the recording
    NFFT=2^nextpow2(length(signal_time)); %creation of the
    number of points
    signal_fft=fft(signal_time,NFFT); %calculation of the FFT
    using the integrated FFT function of Matlab
    signal_fft=signal_fft(1:NFFT/2); %one-sided FFT (to avoid
    the useless symmetry of data)
    signal_fft=abs(signal_fft); %absolute the signal
```

7.3.2. **Cleaning the signal**

Some signals suffering of the presence of very sharp and high peaks at the 50Hz frequency but also at the harmonics of 50Hz (100Hz, 150Hz and so on) and eventually at unregularly positions, a cleaning process of the different signals was performed. These unwanted peaks concentrating an important part of the energy need thus to be removed before processing the integration over the signal; otherwise results of the integration would be over-estimated for some of the signals. The cleaning process was performed in two steps, differentiated according to the type of unwanted peaks to remove. Figure 89 presents an example of a spectrum with the presence of important unwanted peaks at 50Hz, at the harmonics of 50Hz and also at an extra position nearly 130Hz.

![Figure 89: a spectrum with unwanted peaks at 50Hz, harmonics of 50Hz and an extra peak around 130Hz](image-url)
In case of the 50Hz and its harmonics, the cleaning process was performed automatically. These peaks are generally defined by a very sharp and tight peak, with amplitude many times greater than the current average amplitude of the neighbouring signal and with a limited width. As noticeable in Figure 89, the average width of these peaks is generally lower than 3Hz, thus the signal has been divided in blocks of 1Hz starting from a value of 70.5Hz. This allows consequently that a multiple value of 50Hz should be situated in the centre of a block of 1Hz (e.g. 100Hz belongs to the block 99.5-100.5Hz and centred it). As it might happen that the maximum of the peak is not exactly situated at a multiple value of 50Hz due to a shift, the program firstly look for the position of the maximum value in a total of three blocks around the multiple of 50Hz (e.g. 98.5Hz to 101.5Hz for 100Hz).

The position of the maximum known, the block to which belongs the maximum (block\textsubscript{max}) but also the block just before (block\textsubscript{max}-1) and the block just after (block\textsubscript{max}+1) have values set temporary to 0. In the case of a maximum exactly situated at the border of two blocks, the values of a total of four blocks are finally set to 0 (presence of two block\textsubscript{max}). Figure 90 illustrates different examples of situations encountered when applying this method for a peak situated at 100Hz. Using a width of 3Hz enables to remove most of the unwanted peaks without cutting too much of the remaining signal which is of interest.

![Figure 90: cleaning process method for 50Hz or a multiple of 50Hz; example with 100Hz.](image)

Second part of the cleaning was done manually and destined to peaks with a non-constant position. A graphic presenting the first part of the signal (from 70.5Hz to 200.5Hz) where were always these peaks concentrated, was presented to the user, asking if an action is necessary. In case of a positive answer, the user was asked to click on the graphic in order to delimitate the positions of the unwanted peak using the function \texttt{ginput} from Matlab. Blocks where a click was performed had values temporary set to 0.

After determination of the unwanted positions by these two methods, signal was corrected by replacing the zero values by a progressive mean using the following procedure:

- Z defines the number of zero values in an interval due to the correction, X the value of the closest non-zero point before this interval and Y the closest non-zero point after this interval as represented in Figure 91. M corresponds to the median point of Z in case of an odd number of zero points; ML (median left) and MR (median right) correspond to the median points of Z in case of an even number of zero points.

![Figure 91: cleaning process method: definitions of M, ML, MR, X, Y and Z.](image)

- If the number of points of Z is odd: the value of the median point is defined as:

\[
\text{Median point } M = \frac{X + Y}{2}
\]  
Equation 33
- If the number of points of Z is even: the values of the left median point and the right median point are defined such as:

\[
\text{Left median point } ML = X + \frac{Y - X}{Z + 1} \cdot \text{position}_{ML} \tag{34}
\]

\[
\text{Right median point } MR = X + \frac{Y - X}{Z + 1} \cdot \text{position}_{MR} \tag{35}
\]

- Figure 92 represents concrete graphical explanations of the application with examples.
- The progressive mean method was implemented in order to conserve as much as possible the behaviour of the signal after cleaning. Figure 93 illustrates the three situations encountered and the final result.
- Figure 94 presents the results of the cleaning procedure applied to the spectrum of Figure 89.

<table>
<thead>
<tr>
<th>Case 1: Z = 1</th>
<th>Case 2: Z = odd</th>
<th>Case 3: Z = even</th>
</tr>
</thead>
<tbody>
<tr>
<td>Z = 1</td>
<td>Z = odd</td>
<td>Z = even</td>
</tr>
<tr>
<td>X 100</td>
<td>X 100</td>
<td>X 100</td>
</tr>
<tr>
<td>M 100</td>
<td>M 100</td>
<td>M 100</td>
</tr>
<tr>
<td>Y 200</td>
<td>Y 200</td>
<td>Y 200</td>
</tr>
<tr>
<td>X 100</td>
<td>X 100</td>
<td>X 100</td>
</tr>
<tr>
<td>M 100</td>
<td>M 100</td>
<td>M 100</td>
</tr>
<tr>
<td>Y 200</td>
<td>Y 200</td>
<td>Y 200</td>
</tr>
<tr>
<td>M = \frac{100 + 200}{2} = 150</td>
<td>M = \frac{100 + 200}{2} = 150</td>
<td></td>
</tr>
<tr>
<td>M1 = \frac{100 + 150}{2} = 125</td>
<td>M2 = \frac{150 + 200}{2} = 175</td>
<td></td>
</tr>
<tr>
<td>ML = \frac{100 + 200 - 100}{4 + 1} \cdot 2 = 140</td>
<td>MR = \frac{100 + 200 - 100}{4 + 1} \cdot 3 = 160</td>
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</tr>
<tr>
<td>M1 = \frac{100 + 140}{2} = 120</td>
<td>M2 = \frac{160 + 200}{2} = 180</td>
<td></td>
</tr>
</tbody>
</table>

Figure 92: concrete graphical explanations of the progressive mean method implemented with examples

Figure 93: results of the application of the progressive mean method (red = reconstructed signal)
7.3.3. Determination of spectral features: the reorganization of data in case of a sequence of type 2

In the case of a sequence of type 2, data needed to be reorganized in the way described in Figure 95.
7.4. Degrees of stenosis: more data

The Table 13 presents an overview of the main parameters of the DOS: the values of the DOS rounded as well the values not rounded, the width x, the height y, the circumference C and the cross-sectional area S with their mean and STD. The table includes the DOS 97% that was not used in the report. The values of the semi-major axis a and the semi-minor axis b can be determined simply by taking the half of respectively x and y. Figure 96 presents the ideal ellipses used for the determination of the circumference C as mentioned in section 3.1.5. Figure 97 represents the geometrical evolution on the 4 series used from DOS 0% to DOS 97%.

<table>
<thead>
<tr>
<th>Number of the stenosis</th>
<th>DOS rounded to the unit (in %)</th>
<th>DOS not rounded; mean (in %)</th>
<th>DOS not rounded; STD (in %)</th>
<th>Width x: mean (in mm)</th>
<th>Width x: STD (in mm)</th>
<th>Height y: mean (in mm)</th>
<th>Height y: STD (in mm)</th>
<th>Circumference C: mean (in mm)</th>
<th>Circumference C: STD (in mm)</th>
<th>Cross-sectional area S: mean (in mm²)</th>
<th>Cross-sectional area S: STD (in mm²)</th>
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</thead>
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<td>6.96</td>
<td>0.37</td>
<td>0.63</td>
<td>0.05</td>
</tr>
</tbody>
</table>

*mean and STD are always for n=4 as described in section 3.1.3.1

Table 13: Degrees of stenosis: the DOS rounded used in the report, the DOS not rounded, the width x in mm, the height y in mm, the circumference C in mm and the cross-sectional area S in mm² with their mean and STD.
Figure 96: ideal ellipses used for the determination of the circumference C

Figure 97: representation of the geometrical evolution of the increasing stenoses from DOS 0% to DOS 97%, the 4 series
7.5. Determination of the densities and viscosities of the three media

Regarding the medium RO-water, the medium was considered as “normal” water and data are coming directly from (81) without any extrapolation. The values of densities are coming from the appendix II of the book, page 408 and 409 from the table entitled “Appendix II. – Density and Viscosity of Water 0°C-40°C”. Figure 98 presents the necessary part of the appendix.

![Figure 98: extraction of the pages 408 and 409 of (81) for the determination of the viscosities and densities of water at 25° and 28°C.](image)

Regarding the medium sucrose-water solution, the weights of 10 samples of 1mL were measured at a temperature of 20°C. Before this it was necessary to assess the weight of each container. Table 14 presents the result of the weights. The mean was 1.1358 and the STD 0.0077. Assuming the mean and knowing the volume (1mL), it was possible to determine the density (g/cm³) of the sample which was equal to 1.1358 g/cm³. Considering the table A.1 “Density and Baume of Pure Sucrose Solutions (at 20°C)” page 780 of (79) and knowing the density, it was possible to determine the composition, equal to 31.5% in weight. In order to determine the values of the viscosities at 25° and 28° which were not available in these data, was used the tool of calculation of the website [http://www.sugartech.co.za/density/](http://www.sugartech.co.za/density/) based on the Sugar Technologists Manual by Z. Bubnik, P. Kadlec, D. Urban, M. Bruhns available from Bartens. Considering a purity of 100% and knowing that the brix is identical to the composition in % obtained, it was possible to get the values at 25° and 28°C. For the determination of the viscosities was used the table A.12. “Viscosity (in cp) of Pure Sucrose Solutions” page 795 of (79). It was necessary to perform extrapolations using regressions to get the values of viscosities for 31.5% at 25° and 28°C.

<table>
<thead>
<tr>
<th>Number of the samples</th>
<th>Weight of the container with 1mL (in g)</th>
<th>Weight of the container empty (in g)</th>
<th>Corresponding weight of the 1mL (in g)</th>
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</thead>
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Table 14: the 10 samples of 1mL of sucrose-water solution at temperature 20°C

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<th>Baume (degree)</th>
<th>Density (lb/ft³)</th>
<th>Baume (degree)</th>
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Table A.1 “Density and Baume of Pure Sucrose Solutions (at 20°C)” page 780 of (79)
Regarding the medium glycerine-water solution, the same methodology as used for the sucrose-water solution was used. The mean was 1.1308 and the STD 0.0075 and thus a density of 1.1308 g/cm³ at 20°C. Using the table 3 "Density and Percent of Glycerol" of (80) page 4, a composition of about 51.5% in weight was found, see Figure 101. In order to determine the density at 25°C, the value was extrapolated for the column corresponding to 25°C. In order to determine the value of the density at 28°C, regressions were performed for each percent of glycerol close to 51.5% using the data available at 15, 15.5, 20, 25 and 30°C. Using these regressions, it was possible to extrapolate a table of densities at the temperature 28°C and to finally determine the value of density at 28°C for 51.5%. To determine the values of viscosities was used the table 17 “Viscosity of
aqueous glycerol solutions in centipoises” page 11 of (80). Again it was necessary to perform regressions to obtain the final values at 25° and 28°C (see Figure 102).

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Figure 101: Density and percent of glycerol, table 3 page 4 of (80)
Table 17. Viscosity of Aqueous Glycerol Solutions in centipoises

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Figure 102: Viscosity of aqueous glycerol solutions in centipoises, table 17 page 11 of (80)
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