ACTA ACUSTICA UNITED WITH ACUSTICA
Vol. 101 (2015) 224 – 237
DOI 10.3813/AAA.918821

How Does a Flute Player Adapt His Breathing and Playing to Musical Tasks?

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Summary
This study was triggered by the flute players' and teacher's claim that a high quality of playing cannot be reached without a precise control of the breathing, starting during preparatory phases. Among all the controls developed by the musician, the work focuses on the interactions between respiratory activity and hydrodynamical parameters during flute music performance. In order to study these interactions, the following parameters are measured during the playing of a flautist: muscle activation, chest-wall compartment displacement and volume, blowing pressure in the mouth, lip position, and radiated sound. All these measurements are taken simultaneously, using a combined set-up developed to acquire both respiratory and hydrodynamical data. Three musical excerpts with different complexities (one scale and two pieces of the flute repertory) are analyzed. The results show that in preparation to a long musical phrase, the player takes a deeper and longer inhalation than for a standard phrase and, that he needs to develop a specific control of flow for playing. This control of flow requires the flautist, as opposed to normal breathing conditions at rest, to coordinate the respiratory muscles while expiring. This control, in correlation with the lip geometry, allows the player to produce musical variations such as "dynamics". Additionally, the respiratory analyses show that the flautist develops three different patterns of chest volume variations, one for each of the three musical tasks. Finally, a simple, qualitative model is presented in order to link respiratory and aerodynamic parameters to muscular activity, mouth pressure and chest volume during flute playing.

PACS no. 43.75-z, 43.75.Qr, 43.75.St

1. Introduction

Music performance requires that the instrumentalist develops, through long training, an expert control of playing. In order to play the requested pitch, amplitude and timbre associated to musical pieces, the instrumentalist must control his fingers, lips and many respiratory parameters. This aim of this study is to understand how the flautist's respiratory activity and control parameters are linked to achieve musical tasks. Our first goal is to establish an experimental set-up which allows the simultaneous measurements of the hydrodynamical parameters (mouth pressure, motion of the lips, and radiated sound), and the respiratory parameters (chest-wall compartment volume variations and respiratory muscle activations). The hydrodynamical and aeroacoustical analyses give information on how to adjust the control parameters according to the musical tasks performed. The analysis of the respiratory parameters allows us to quantify the displacements of the chest-wall compartments during inspiration and expiration and to identify the muscular activation associated with the displacements. Simultaneous measurements of the parameters allow us to understand how they are linked together during musical tasks.

Before statistics can be used on the relevant parameters, one must understand how the flautist adapts and coordinates his playing technique according to different musical tasks and to the complexity of the score in order to obtain a fine understanding and definition of the parameters. Three musical tasks presenting different complexities in terms of register, dynamic and time duration were observed. The first excerpt is a G Major diatonic scale; the two next excerpts constitute pieces of the flute repertoire: Debussy *Prélude à l'après-midi d'un faune* and Beethoven *Leonore Overture n^{o}3*. Each excerpt was performed on an average four times until the quality of musical performance and data acquisition was deemed satisfactory. Therefore, three performances were selected out of twelve measurements.

First, you will find below a short synthesis of previous studies on flute respiratory and acoustical control param-

Received 20 March 2014,
accepted 21 January 2015.

eters and an overview of the acoustical, hydrodynamical and respiratory parameters used during flute playing; secondly, the methodology used, the results of the acoustical and respiratory measurements and a comparison with results of previous studies; and finally, a model that we developed connecting the respiratory and hydrodynamical parameters which, when combined with the pressure-volume curve of the respiratory system, allows us the estimation of the respiratory effort during the musical tasks.

2. Previous studies and control parameters

2.1. Previous studies

Among the numerous studies on musical instruments and more specifically on the flute and the player, this section discusses the most relevant studies related to our work. In his study, Fletcher [1] presents measurements of physical parameters of the performance technique used by a group of experienced flute players. Fletcher's objectives are to understand the physical basis of how some instruments are used to make music and to determine the physical criteria that characterize these instruments. Other studies dealing with acoustical or hydrodynamical descriptions include: Coltman [2, 3], Kergomard [4], Wolfe [5], Benade [6], Nederveen [7], Fabre [8], Nolle [9]. In relation to the analysis of flute control parameters, de la Cuadra's study [10], focuses on the comparison between a novice and an experienced flautist.

The sounds produced by flutes depend not only on the physical characteristics of the instrument but also on the control exerted by the musician. This is especially important when the air jet is shaped with the lips of the player which is the case for the flute in our study. Among other studies describing the influence of the player on the flute and on the sound produced, we can also cite Montgermont [11, 12] and Coltman [13].

Finally, more directly related to our study, we can mention three investigations conducted by Cossette [14, 15, 16]. The first study focuses on the respiratory mechanisms of professional flautists. Different pulmonary pressures, muscular activation and air volume have been measured in order to compare different musical exercises such as staccati and sustained tones at different frequencies and intensities. Cossette's study [14] shows that different flautists use different strategies to control mouth pressure, and that the individual mastery of the instrument permits to control airflow and velocity in order to produce the desired sound intensity and frequency.

The second study [15] focuses on professional flute playing with or without breath support, which in turn is associated with high quality playing. The concept of breath support is widely used amongst flute players and teachers. Work by Cossette [15] shows that breath support entails antagonistic contraction of nondiaphragmatic inspiratory muscles that tend to hold the rib cage at a higher lung volume than during normal breathing. This relieves the expiratory muscles from the task of producing the right mouth pressure, especially at the end of the phrases, so they can contribute more to the finer control of mouth pressure modulations required for high quality playing. Recordings included optoelectronic plethysmographic measurements of chest-wall volume (Vcw) and its compartments, surface electromyography of the scalene, sternocleidomastoid, parasternal, lateral abdominal, and rectus abdominus muscles, mouth pressure, and sound. Last study combines measurements performed in two different experimental set-ups (Montréal & Paris) in order to provide a global view, from breath to sound, of one flautist playing the flute. One of the experiments provides data on the flautist's respiratory behavior, while the aim of the second experiment was to gather data for the analysis of hydrodynamical and aeroacoustical flute playing control parameters. The objectives of this study was to understand how does the player adjust the different control parameters to produce the musical task required by the score and how does this modulate the resulting sound in the flute. Other studies on the respiratory parameters and music playing include studies on singers (e.g. Hixon [17], Pettersen [18]).

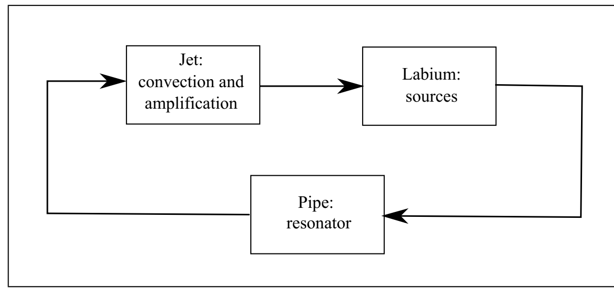

Figure 1. General description of flute operation as three independent blocks coupled together.

2.2. Overview of the acoustical and hydrodynamical parameters

Flute operation can globally be described as a coupling between the hydrodynamic modes of a jet and the acoustic modes of a resonator. Pipe resonances mostly depend on its geometry while the jet provides the necessary energy to sustain the oscillation. As discussed by Fabre [19] and commonly referred to in the literature [4, 13], the flute operation may be approximated by three independent blocks, Figure 1.

The different elements (jet, sources, resonator) interact locally and are therefore analysed separately and then concatenated to produce an illustration of the flute operation. The acoustic resonances of the resonator have been studied by Coltman [13], Kergomard [4], Fletcher [1], Wolfe [5], Benade [6] and Nederveen [7]. We focus here on the jet-labium configuration as the player controls both the jet characteristics and the lip to labium distance W. Assuming thin boundary layers in the lip channel, we obtain the jet flow Q by the product of velocity U and opening area A between the lips $Q = AU$. Assuming that the kinetic energy of the jet is dissipated in turbulence and that the pressure in the jet is atmospheric, we estimate the jet velocity from the mouth pressure P_m using Bernoulli's equation: $U = \sqrt{2P_m/\rho_0}$, where ρ_0 is the air density [20].

As in [1, 8, 10, 13, 23], these parameters can be described by using dimensionless numbers: the dimensionless jet velocity θ, ($\theta = U/fW$, where f is the fundamental frequency of the radiated sound), the Strouhal number Str_h, ($Str_h = fh/U$, where h is the height of the flue from where the jet flows) and the Reynolds number Re, ($Re = UD/\nu$, where D is the hydraulic diameter and ν the kinematic viscosity of the fluid). The hydraulic diameter D is defined as $D = 4A/p$, where p is the wet perimeter. Assuming that the lip area is an ellipse, the hydraulic diameter is defined by Blevins [21], as

$$D = \frac{4ab}{(a+b)(1+\frac{h}{4}+\frac{h^2}{64}+\frac{h^3}{256})} \quad (1)$$

where $h = (a-b)^2/(a+b)^2$, a is the semi-major axis and b, the semi-minor axis. In our set-up, the geometry of the lips (a and b) is tracked through image processing in order to estimate D.

The structure of the jet is related to the Reynolds number. The jet is laminar for soft blowing conditions. Theory indicates that the transition from laminar to turbulent jet seems to occur in the range of $Re = 2000 - 3000$, following Mankbadi [22]. However, this transition is difficult to predict. When blowing harder, the jet becomes turbulent. Turbulence is known to produce a breathy wide band noise [23, 24]. When this noise is filtered by the passive resonances of the pipe, it constitutes an important part of the perceived characteristics of flute sound.

The jet transverse oscillation induced by a harmonic acoustic perturbation is expressed as the propagation of a wave of growing amplitude. Following Rayleigh [25] and Mattingly [26] and as discussed by de la Cuadra [10], the convection velocity as well as the spatial amplification factor of the wave are function of the dimensionless frequency: the Strouhal number. Following de la Cuadra [10] and Nolle [9], the jet instability appears to be maximal around:

$$0.02 < Str_h = fh/U < 0.05 \quad (2)$$

depending on the jet velocity profile. Keeping the Strouhal number in such a range is also part of the control by the player.

In Figure 1, the jet acts as an amplifier and delay. The intrinsically unstable jet is submitted to a transverse acoustic velocity, so that the jet instability is triggered by the acoustical perturbation. The acoustic velocity due to the acoustic energy accumulated in the pipe therefore creates an initial perturbation on the jet that is amplified while it is convected downstream towards the labium, resulting in a time delay. Relations between this time delay and passive resonance in the flute are discussed in the literature by Coltman [13], Fabre [8] and Auvray [27]. The flautist is able to adjust the delay by changing the blowing pressure, which modifies the jet velocity U, or by changing the length of the jet W, which corresponds to a change of distance between the lips and the labium. This is why a dimensionless velocity, $\theta = U/fW$, is used as a describer. The convection velocity of perturbations of the jet is about 30% to 50% of the jet center line velocity, [10]. The theory [13, 19, 27], indicates that the optimal condition corresponding to half-period delay on the jet may then be expressed as

$$\theta = U/fW = 4 \ldots 7 \quad (3)$$

Combining equations (2) and (3), the optimal range of the thickness ratio W/h of the jet is

$$3 < W/h < 12 \quad (4)$$

In the case of a short channel like the lips, the maximum jet instability occurring at $Str_h \approx 0.03$ indicates an optimal value of $W/h \approx 8$.

Thus, the theory indicates optimal values of the dimensionless parameters θ, W/h and an upper limit of the Reynolds number, in correlation with the total jet flow Q. Playing the flute requires the adjustment of these different parameters, first, in order to guarantee the oscillation at the requested frequency and, once this is achieved, to produce specific time shaping of these parameters in order to achieve expressive intentions.

2.3. Overview of respiratory parameters

This section provides an overview of the respiratory parameters associated to flute playing by a healthy musician. Although all components of the respiratory system are essential to its good functioning, we limit our description to the main respiratory concepts and mechanisms relevant to flute playing. More detailed information on respiratory mechanics can be found in [17, 28, 29]. The different parameters described below include the pulmonary volumes, the main respiratory muscles and the pressure-volume curve of the respiratory system.

At first, we focus on the air movement into and out of the lungs required for flute playing. Pressure variations in the lungs and in the pulmonary airways create pressure gradients that regulate pulmonary ventilation. The muscles, by contracting, create forces which deform the structure of the respiratory system. The structure displacements modify the volumes of the cavities which, in turn, create pressure variations. Respiration depends on passive (elasticity, surface tension and gravity which tend to take back the lung structure to its resting position) and active forces (muscle activation). The elastic recoil of the respiratory system results from the respective resting states of the lungs and chest wall. Figure 2 shows a sketch of the so called static volume-pressure curve of the respiratory system (Prs) including both the lung (Pl) and chest-wall (Pw) behaviors. Figure 3 represents a sketch of spirometric tracings of the static pulmonary volume subdivisions: Total Lung Capacity (TLC), Vital Capacity (VC), Residual Volume (RV), Inspiratory Capacity (IC), Functional Residual Capacity (FRC), Inspiratory Reserve Volume (IRV), Tidal Volume (TV) and Expiratory Reserve Volume (ERV).

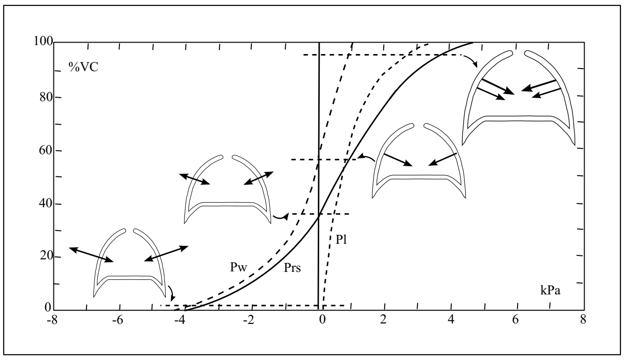

Figure 2. Sketch of static volume-pressure curves of the lungs (Pl), chest wall (Pw) and total respiratory system (Prs) during relaxation. The arrows in the lung drawings indicate the static forces exerted by the lung and the chest wall at different volumes. Figure issued from [30, 31].

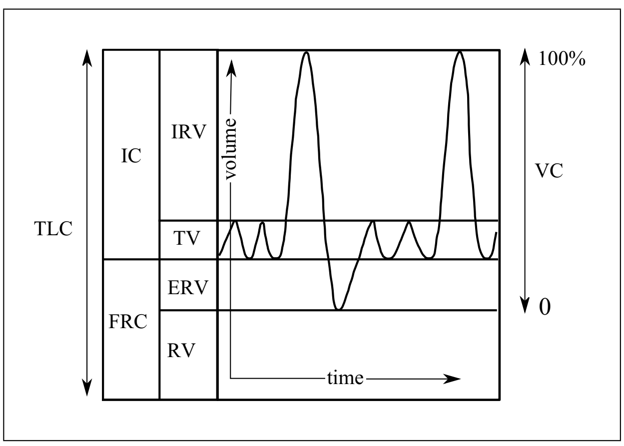

Figure 3. Sketch of spirometric tracings of static pulmonary volume and capacity subdivisions: Total Lung Capacity (TLC), Vital Capacity (VC), Residual Volume (RV), Inspiratory Capacity (IC), Functional Residual Capacity (FRC), Inspiratory Reserve Volume (IRV), Tidal Volume (TV) and Expiratory Reserve Volume (ERV). Figure adapted from [30, 31].

Pulmonary pressure and passive forces change according to the pulmonary volumes. At Total Lung Capacity (TLC), when the lungs are totally filled with air, the passive forces exerted on the system are strong enough (pressure approximately of 4kPa) so that, if respiratory muscles are relaxed, air naturally tends to go out of the lungs until the resting volume, Functional Residual Capacity (FRC), is reached. At FRC, passive forces (elasticity, surface tension and gravity) of the lungs and the chest wall are equal and opposite. When all the air in the lungs is maximally blown out, the volume of air that remains in the lungs is the Residual Volume (RV). At this volume and when muscles are relaxed, passive forces are oriented outwards and tend to make the air come in until FRC is reached. The air comprised between Total Lung Capacity (TLC) and Residual Volume (RV) is called the Vital Capacity (VC) and is the air available to play the flute or another wind instrument. Vital Capacity varies according to size, age, gender, and origins. Tidal Volume (TV) commonly refers to the air used during quiet breathing.

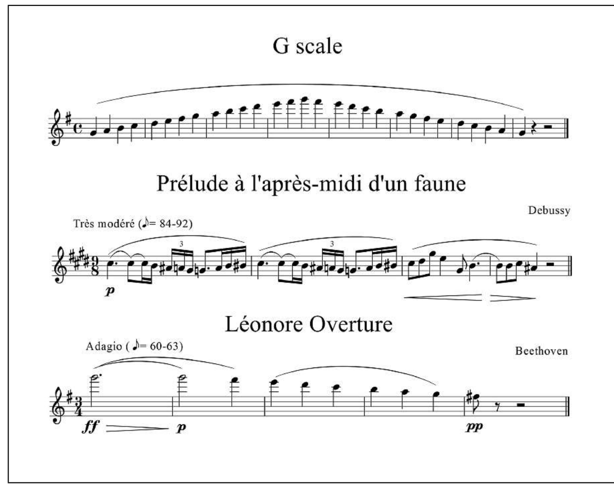

Figure 4. Scores of the three musical tasks.

Active forces resulting from muscular contraction enlarge the chest-wall cavity during inspiration and decrease it during expiration. When contracting, the main inspiratory muscle, the diaphragm, a dome-shaped muscle and tendon structure, flattens. This creates a depression in the thoracic compartment and an in-draught in the lungs. This “descent” of the diaphragm (actually, rather flattened dome) pushes the abdominal viscera down and causes a “swelling” belly. Then, as the phrenic center (diaphragm center) is stabilized, the lower ribs, on which the diaphragmatic muscle fibres are inserted, elevate and create an expansion of the lower part of the thorax. As stated previously, during a tidal expiration, the thorax passively returns to its resting state at FRC, while, during a forced expiration, air displacement is considerable and requires more force. The action of the diaphragm is completed by other inspiratory muscles (e.g. scalene, sternocleidomastoidian, external intercostals), and expiration is forced by the expiratory muscles.

3. Musical tasks presentation and introduction of the flautist

The aim of the present work is to study the control exercised by the flautist during various musical tasks entailing different musical and/or respiratory complexities. More specifically, our goal is to observe how a flute player adapts his breathing and playing to musical tasks. The flute player is asked to perform three musical tasks, Figure 4: a G major scale and two pieces of the flute repertoire. The scale on two octaves constitutes for a flute player a practice routine which does not require any special musical or respiratory effort. The second task is to play the flute solo at the beginning of an orchestral piece, Debussy *Prélude à l’après-midi d’un faune*. The tempo is moderate and the excerpt is long. Traditionally, the flautist is expected to play this musical passage in one breath. Time duration is the principal challenge, made even more demanding by a crescendo-descrescendo indicated at the end. As the flautist plays solo, a high quality and musical sound is sought. The last is a Beethoven excerpt: *Leonore Overture*. Similarly to the Debussy, this excerpt is the beginning of a repertory piece, but this one is played by the woodwind instrument section. The difficulty of this excerpt resides in its length, its dynamic changes (from *ff* to *pp*) and in the fact that it is played in the third register, which typically requires higher pressures.

A musician volunteered to play after a recruitment announcement was made through the Schulich School of Music at McGill University. The flautist is a woman who was 47 years old at the moment of the measurements. Trained as a professional flute player, she had an extensive playing experience (over 250 public concerts) and played regularly over 20 years.

4. Measurements

4.1. Acoustical

As stated previously, one of our goals was to measure simultaneously the acoustical and the respiratory parameters. The experimental set-up is based on the one described by de la Cuadra [10] for the acoustical parameters and on the one by Cossette [16] for the respiratory parameters. This section presents the acoustical parameters only.

The experiment was conducted in the Music Performance and Body Laboratory (MPBL), a room ($80m^3$) without anechoic treatment, which provided an environment similar to that found in a normal practice room. To measure the pressure in the mouth, we used a soft tube connected to a calibrated differential pressure sensor (±100 cm H_2O, UT-PDP-100, Scireq Inc.). While the presence of the measuring tube in the mouth is disturbing at the beginning of the session, the player taking part in our experiments seemed to accommodate rapidly and claimed to have played with her usual sound quality by the end of the session for the three excerpts analysed in this paper. Under normal playing conditions, the lip opening is the strongest constriction on the flow path from the lungs to the outside. Therefore, we assume that the mouth pressure provides a fair estimation of the lung pressure. The radiated sound, recorded at sampling rate of 44280 Hz, was measured with an external microphone (Neumann TLM-103) placed 1 meter from the flautist. The camera device used to film the lips of the flautist was slightly modified from the one used by de la Cuadra [10] in order to make it compatible with the OptoElectronic Plethysmograph (OEP). The camera was attached 2 cm from the extremity of the flute head. In this set-up, the camera catches a transverse view of the lips. To catch the frontal view, a mirror was placed near the embouchure forming an angle of approximately 45 degrees with the flute. Images were taken at a rate of 25 images per second, which provides a sufficiently large sampling rate to capture the control dynamics. Figure 5 shows a schematic view of the set-up.

4.2. Respiratory

As stated previously, in the respiratory component of this study, we focus on air volume variations and on principal and surface muscle activations that occur during flute playing.

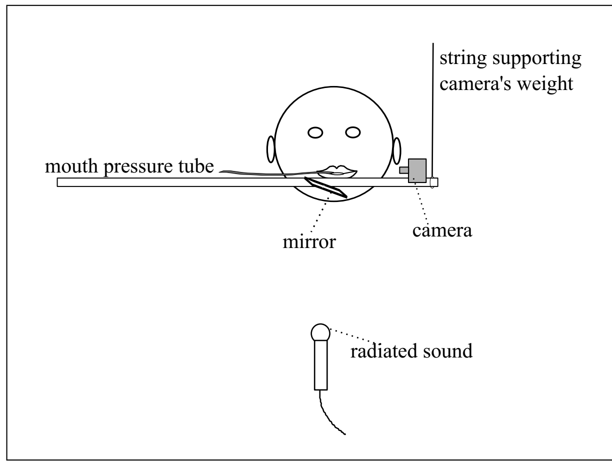

Figure 5. Schematic view of the set-up. The radiated sound is measured a meter from the player's mouth.

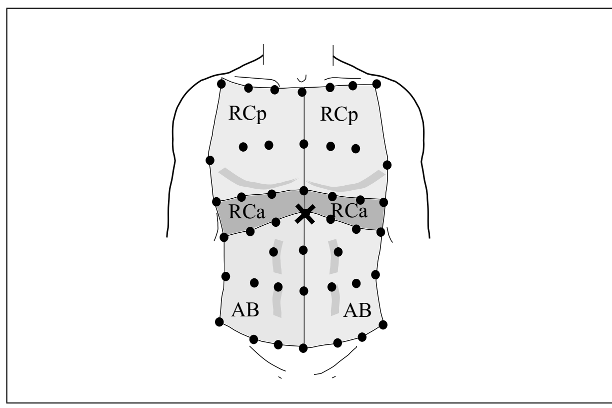

Figure 6. Sketch showing the markers' positions on the three compartments of the thorax: the pulmonary rib-cage compartment (RC_p), the abdominal rib-cage compartment (RC_a) and the abdominal compartment (AB). The cross corresponds to the xyphoidal transverse plane.

The chest wall is divided in three compartments: the pulmonary rib-cage compartment (RC_p), the abdominal rib-cage compartment RC_a) and the abdominal compartment (AB), as shown in Figure 6.

These chest-wall volumes are measured by OptoElectronic Plethysmography (OEP, Smart System, BTS) as in [15, 16]. The OEP consists of 9 infrared video cameras tracking 89 hemispherical 10 mm diameter reflective markers apposed on the chest wall of the flautist as shown on Figure 6 for the frontal view. The markers are positioned in seven rows between the clavicle and the iliac crest, [32]. With the 3D coordinates of the markers, Gauss' theorem is used to calculate the volume variations as described by Cala et al. [33]. The data recorded with the OEP system, sampled at 60Hz, allow the reconstruction of the three chest-wall compartment displacements and their volume changes.

As stated previously, we also measured the activation of the main respiratory muscles which contraction is easily and non-invasively measurable with surface electromyography (EMG) during flute playing: scalene, sternocleidomastoidian, rectus abdominus and lateral abdominal muscles (internal and external obliques, and transverse combined). Intercostal muscles also contribute to both the inspiration and the expiration but, as they are superposed, these muscles are difficult to measure and are thus not included in this study. Muscular activity is measured with a wireless 16-channel electromyogram system (BTS, Milan, Italy). To check the appropriate placement of the electrodes, the flute player was asked to do specific movements, as explained in Cossette's study [15]. The signals are sampled and recorded at 960 Hz and, during the analysis process, rectified and low-pass filtered (2 Hz, Butterworth).

A recording session lasts approximately two hours and a half, the first hour being mostly spent on preparation: positioning of the infra-red reflective markers on the player's chest wall, positioning and test of the EMG electrodes. Playing then takes approximately one hour thirty minutes. Twelve tasks were recorded out of which three were selected, analyzed and presented in this paper. In order to simplify data representation and comparison, respiratory volumes and muscular activity are expressed against time as a percentage of the maximal volume or maximal activation reached during a vital capacity (VC) manoeuvre (% max VC). Our flautist has a VC of 3.7 liters.

5. Results

We analyze the three musical tasks in order to connect the respiratory and hydrodynamical control parameters. The air contribution and the pressure used for each excerpt are plotted in a mouth pressure-chest volume diagram. Then, while taking into account the different complexities of each musical task, the acoustical and respiratory parameters are observed and compared in order to better understand the flautist's control.

5.1. Mouth pressure-chest volume diagram

Figure 7 shows the mouth pressure-chest volume diagram for the three tasks. In a first step, the curve cannot be associated to the relaxation curve described in the 2.3 section (Figure 2), as the esophageal and gastric pressures were not measured in this study. However, this diagram allows a comparison of the air volume and pressure contributions for the three excerpts.

Tidal volume is determined by averaging end-inspiratory and end-expiratory volumes during a 1-minute quiet breathing period (maximal and minimal volumes over 10 cycles of quiet breathing). Our flautist's average Tidal Volume occurs between 28% and 48% of her Vital Capacity as shown by the dotted loop on Figure 7. All pressures are measured as a difference to the atmospheric pressure, which is represented by the vertical line at $P = 0$. The residual volume corresponds to 0 % of the VC. Inspiration before playing corresponds to negative pressure

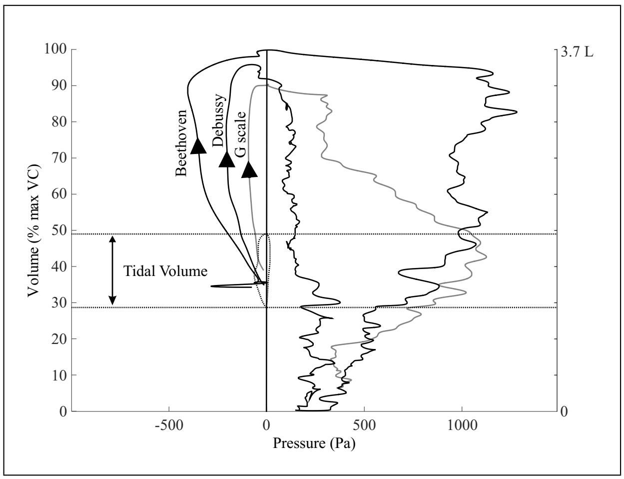

Figure 7. Mouth pressure-chest volume curves for the three musical tasks. Horizontal dotted lines represent Tidal Volume and the dotted loop, an averaged cycle of quiet breathing.

values. The air flow used to produce the sounds is associated with a decrease of the chest volume at positive mouth pressures. The other tracings end when the sound production ends. Note that the highest volume of air is taken for the Beethoven excerpt (approximately 100% of VC) and the lowest one, is for the G scale (around 90% of VC). The flautist uses almost all of her Vital Capacity for Beethoven and Debussy excerpts, while she uses 82% of her VC, from 90% to 8%, for the G scale. As for pressure variations, we note that the highest pressure is mobilized for the Beethoven excerpt, around 1000 Pa. The lowest ones are observed during Debussy excerpt, varying between approximately 200 Pa and 400 Pa.

5.2. Hydrodynamical and respiratory analysis

Hydrodynamical and respiratory data are synchronized and presented together. Figures 8, 9 and 10 show measurements of radiated sound, mouth pressure, opening area between the lips, distance of the lips to the labium, flow of the jet, total volume, muscular activation, Reynolds number and dimensionless velocity θ respectively for the G scale, the Debussy and the Beethoven.

G scale:
Figure 8 shows that mouth pressure roughly follows pitch variations, particularly in the higher register (between the vertical lines 2 and 3). Indeed, pitch increases with a factor of 4, while mouth pressure increases by a factor of 3,6. When pitch decreases, mouth pressure decreases by the same factor. While pitch rises, the area between the lips decreases from 8 to $5mm^2$. We assume that this is done in order to keep low flow variations and prevent extreme increment of loudness in the high register. Mouth pressure (and therefore velocity) is almost constant between vertical lines 1 and 2, suggesting that the decrease of θ is mostly due to the stability of W and U, while the frequency increases. During the second octave (between vertical lines 2 and 3), θ stays relatively constant, the ratio U/f being compensated by a diminution of the labium

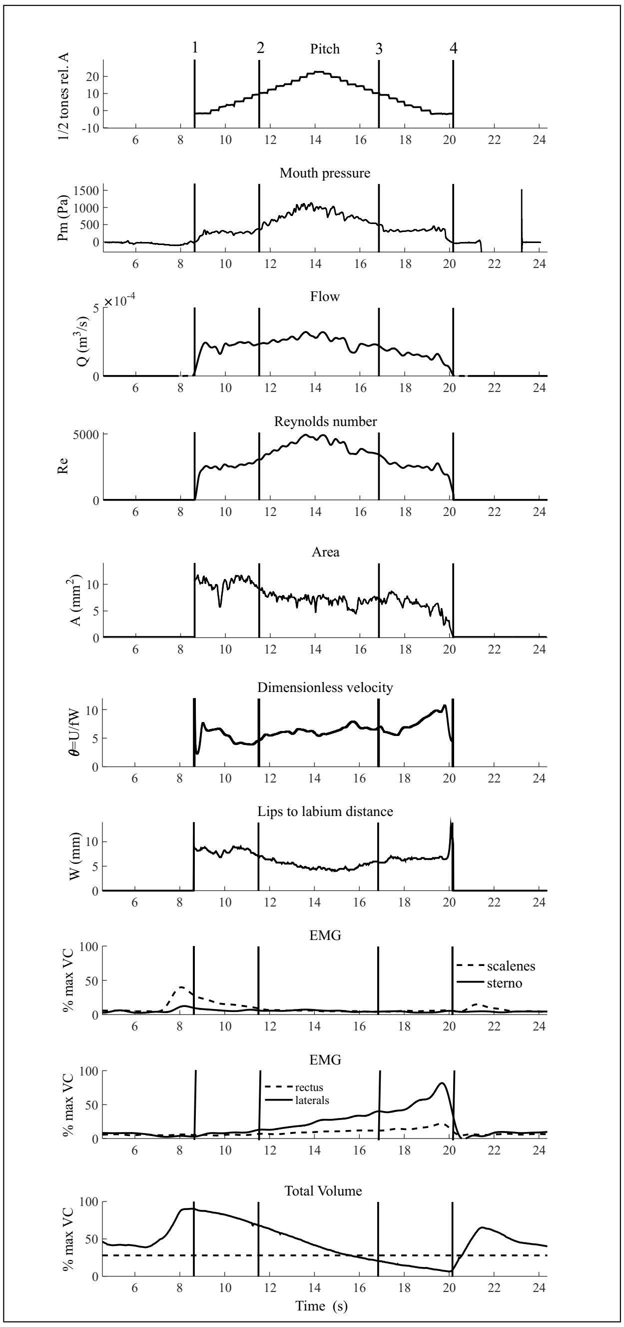

Figure 8. Representation of pitch, hydrodynamical and respiratory parameters for the G scale. Pitch in semitones relative to A440Hz, mouth pressure P_m, flow Q, Reynolds number Re, area between the lips A, dimensionless velocity θ, distance from the lips to the labium W, muscular activation of sternocleidomastoidians, scalenes, rectus abdominus and laterals, and total chest-wall volume in %VC. The vertical lines represent the beginning of sound production and the limits between each register. The dashed horizontal line on the total chest-wall volume plot indicates the FRC (Functional Residual Capacity).

distance W. Finally, between vertical lines 3 and 4, mouth pressure (and the velocity as well) is again kept relatively constant, suggesting that the increase of θ is due to the stability of W and U, while the pitch decreases. θ variations during G scale playing lie between 4 and 11. A similar behavior is observed between pitch variations and Reynolds number which increases by a 2.75 factor between 2500 and 5000 between lines 2 and 3. Please note that Reynolds number and flow Q follow similar paths.

Concerning muscular activation, Figure 8 shows that inspiratory and expiratory muscles are not activated at the same time during G scale playing; indeed, the inspiratory muscles are activated before line 2 only while the expiratory ones are after line 2 only. Furthermore, at the end of the inspiration, the activation of the inspiratory muscles, the scalenes and sternocleidomastoidians, are respectively 40% and 12% of the maximal activation reached during a vital capacity manoeuvre.

Debussy excerpt:

From Figure 9, we note that for the two first musical structures (between the vertical lines 1 and 3), mouth pressure remains almost constant but increases up to around 400 Pa for the last phrase (after line 3). At the end, mouth pressure seems to be higher than at the beginning although the melody occurs around similar pitches. The player seems to produce the indicated crescendo by increasing the dimensionless jet velocity rather than by increasing the air flow. Indeed, in order to play this long excerpt up to its end, the flautist seems to save air, as is clearly reflected in the flow data which is approximately 2.8 times smaller than the one used for the G scale. The crescendo-decrescendo (from 25s to 40s) is executed by modulating the area of the lips, thus the flow. Little variations (between 6 and 7.5 mm) are observed on W.Reynolds number is also correlated with pitch at the end of the Debussy excerpt (mostly after the vertical line 3, Figure 9). When comparing the Reynolds number values between Debussy and the G scale, we note much smaller values in Debussy (between 1000 and 2200). These differences may result from the smaller values in lip area and hydraulic diameter D. The crescendo-decrescendo at the end is clearly reflected by this number. The fluctuations in dimensionless velocity (between 4 and 6) are smaller than those of the G scale, perhaps because of lower pressure and velocity.

Similarly to the G scale, muscle activation during Debussy switches from inspiratory to expiratory around line 2. However, the inspiratory muscle activation is more important than in the G scale (respectively 22% vs 12% of the maximal VC activation (% max VC) for the sternocleidomastoidians and 45 % vs 40 % max VC for the scalenes). This is directly correlated with the total air contained in the lungs at the end of the inspiration which is 90% of VC for the G scale and 95% for the Debussy excerpt but also to the length of the musical task. As mentioned before, the flautist uses almost all of her VC for Debussy excerpt, resulting in expiratory muscle activation respectively at 22% and 74% for the rectus and laterals. Even if close to all the VC air is used to play Debussy, the activation of the expiratory muscles is lower during playing than during the VC manoeuvre as the latter requires stronger expiratory muscle activation to fully expel air at a faster pace.

We also note that muscular activation is longer in the Debussy excerpt than during the scale: inspiratory muscles

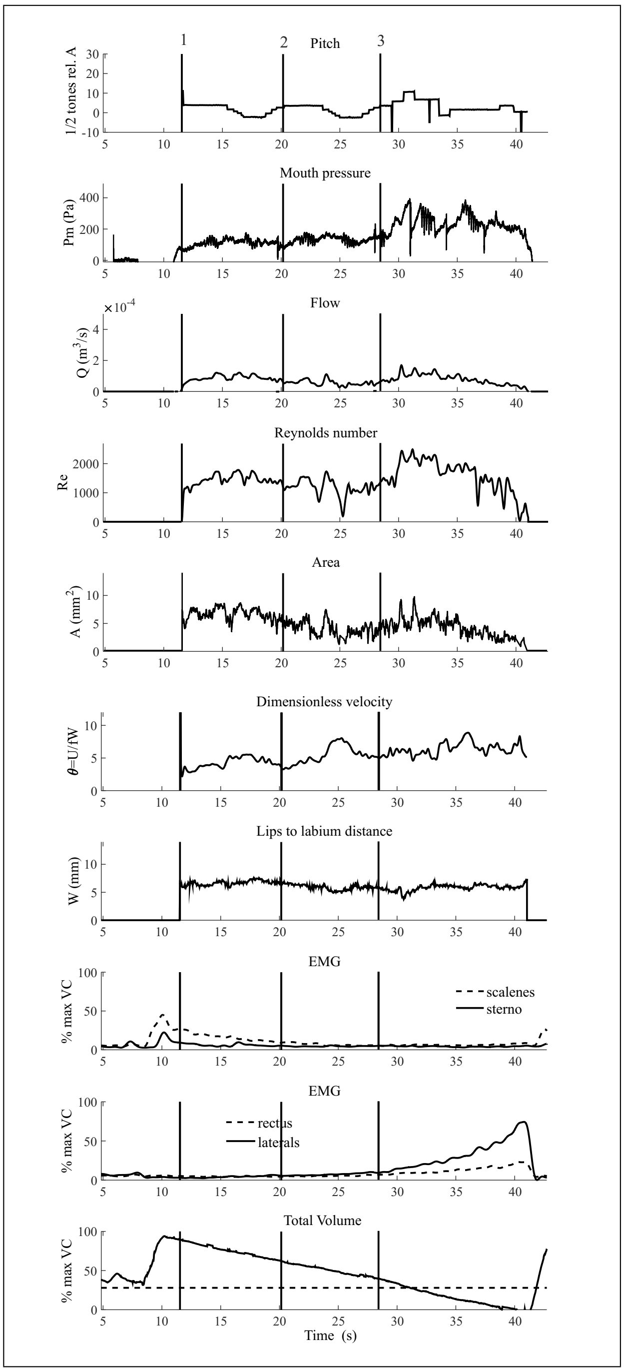

Figure 9. Representation of pitch, hydrodynamical and respiratory parameters for Debussy excerpt. Pitch in semitones relative to A440Hz, mouth pressure P_m, flow Q, Reynolds number Re, area between the lips A, dimensionless velocity θ, distance from the lips to the labium W, muscular activation of sternocleidomastoidians, scalenes, rectus abdominus and laterals and total chest-wall volume in % VC. Vertical line 1 represents the beginning of the sound production, vertical line 2, transition from the first musical structure to the second one and, line 3, transition from the second musical structure to the third one. The dashed horizontal line on the total chest-wall volume plot indicates the FRC (Functional Residual Capacity).

are activated about 10 s during Debussy against 3 s during the scale; expiratory muscles, for 12 s during Debussy against 8 s for the scale. The control of the outgoing air volume, thus the air flow, results from the combined activation of the muscles in conjunction with the control of the opening area of the lips. Between lines 1 and 2, the contraction of the inspiratory muscles controls the flow of air going out; between lines 2 and 3, no muscles are activated but we observe a decrease in the lip area that may help to control the air exhaust and thus the flow. Finally, after line 3, the exhalation is controlled by the expiratory muscles. After the 35th second, the decrescendo is performed by a decrease of the lip area and an increase of the expiratory muscle activation. This coaction allows the maintenance of a controlled low flow throughout the excerpt.

Beethoven excerpt:
Mouth pressure at the beginning of the Beethoven excerpt is the same as that in the high register of the G scale. Indeed, the note is the same. In this excerpt, pitch decreases while mouth pressure also globally goes down. Tracings show fast pressure variations that are heard as vibrato. The strong decrescendo on the first note of the score is clearly reflected on the tracings which demonstrate the combined action of many of the parameters. Indeed, the area of the lips decreases by a factor of 2 in 1s and the flow by a 1.6 factor, while mouth pressure remains constant and the lips get closer to the labium by 1 mm. A fast relaxation of the inspiratory muscles (respectively from 64% to 8% and 57% to 15% for the scalenes and sternocleidomastoidians) results in a quick volume variation. The rest of the excerpt, a long decrescendo, shows that the flow decrease is controlled by an increase of the expiratory muscle activation and a decline of the lip area. The slight increase of the distance of the lips to the labium W may help to stay in tune despite the jet velocity and flow decays. The decrescendo and the decay of pitch and flow appear to be reflected in the Reynolds number. Once again, flow and Reynolds number appear to be strongly correlated. However, variations in dimensionless velocity are small (between 6 and 8).

Figure 10 shows a slight contraction of the expiratory muscles from the beginning of the excerpt. Indeed, the flautist needs to produce a high pressure to create the requested *ff* and may do this by creating a compression of the abdomen with the abdominal muscles. At the end of the excerpt, the flautist has used all of her Vital Capacity and activates her expiratory muscles at 26% for the rectus and 75% for the laterals.

Chest-wall compartment contributions:
A Konno-Mead diagram [34] shows the contribution of each chest-wall compartment during the inspiratory and expiratory phases. Figure 11 depicts the volume variations of the upper thorax compartment (V_{RCp}) against the variations of the abdominal compartment (V_{ab}) for the three musical tasks. The black circle represents the beginning of the inspirations, the crosses, the beginning of sound production for each excerpt, the arrows, the direction of the tracings and the gray line, the linear function corresponding to an equal contribution of each compartment.

Figure 11, inspiration occurs in two phases: first, the abdominal volume (V_{ab}) increases and, second, the chest-wall volume follows. Contrarily and as exemplified in Fig-

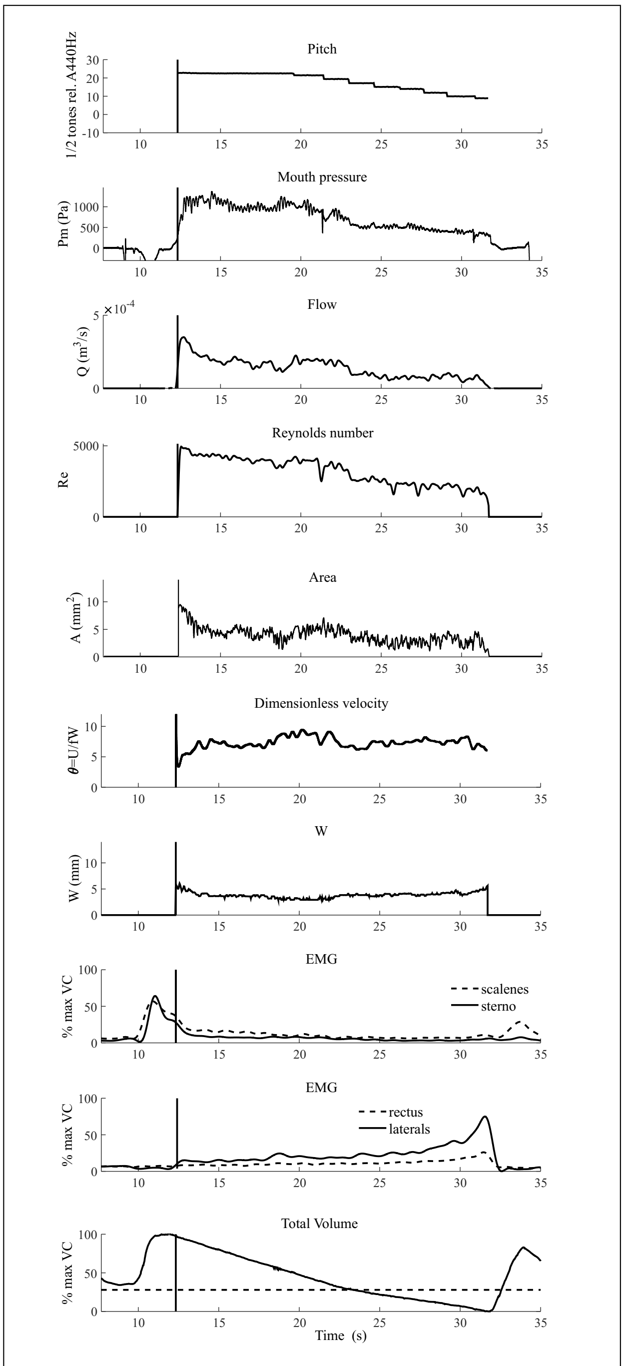

Figure 10. Representation of pitch, hydrodynamical and respiratory parameters for Beethoven excerpt. Pitch in semitones relative to A440Hz, mouth pressure P_m, flow Q, Reynolds number Re, area between the lips A, dimensionless velocity θ, distance from the lips to the labium W, muscular activation of sternocleidomastoidians, scalenes, rectus abdominus and laterals, and total chest-wall volume in %VC. The vertical line represents the beginning of sound production. The dashed horizontal line on the total chest-wall volume plot indicates the FRC (Functional Residual Capacity).

ure 11, the expiratory phase varies from one musical task to the other.

During the G scale, the contribution of each compartment is approximately equivalent, the expiration phase roughly follows a linear function.

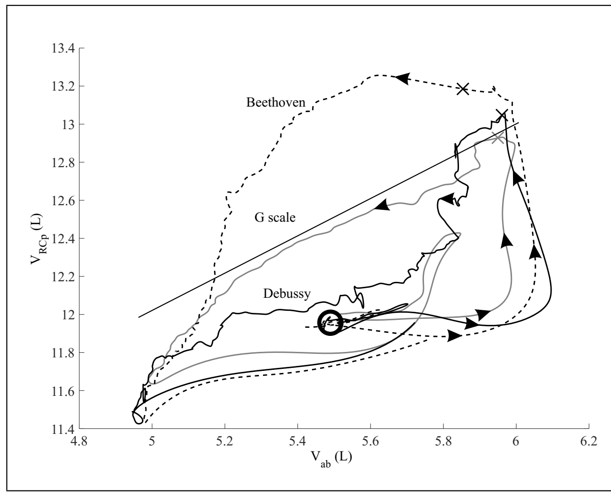

Figure 11. Konno-Mead diagram for the three musical tasks: Debussy excerpt (dark line), Beethoven excerpt (dashed line) and G scale (dotted line). Volume variations of the upper thorax compartment (V_{RCp}) are shown against volume variations of the abdominal volume (V_{ab}). The gray line represents the slope for equal contributions of V_{RCp} and V_{ab} determined by the linear function: $V_{RCp} = V_{ab} + 7$.

The beginning of the Debussy excerpt (Figure 11) displays a higher diminution of the upper thorax compartment (from 13L to 12.2 L) than of the abdominal one (6L to 5.6L). This is shown by a steeper slope than the one of the linear function. For most of the rest of the excerpt, the contribution of these two compartments is approximately the same (the slope is close to 1).

Interestingly, during the first decrescendo of the Beethoven excerpt, the chest-wall volume continues to increase while the abdomen is decreasing. This is almost certainly due to the action of the expiratory muscles which are pushing and transferring pressure from the abdominal compartment to the thoracic one by compressing forcefully the abdomen while the diaphragm is relaxed. This action compresses the chest-wall volume and helps increase the pressure in the lungs in order to produce the required pressure to play the high *ff* note. During the following decrescendo, the slope is slightly more important than the linear function especially in the V_{RCp}, suggesting that it is produced by a major decrease in the upper thorax volume.

6. Discussion

6.1. Comparison between previous studies and our results

We compare the analysis of our data for each excerpt with results from previous publications by de la Cuadra [10], Fletcher [1], Cossette [14, 15, 16], and Montgermont [11].

Two octave diatonic scale:
Cossette's [16] and de la Cuadra's [10], show that mouth pressure increases with frequency, when ascending diatonic scales are played at constant dynamic. Our results show that pitch increases by a factor of 4, while mouth

pressure increases by a factor of 3,6 while playing a G scale. These ratios are slightly higher than the ones of de la Cuadra [10] who shows that mouth pressure increases by a factor 2 over a diatonic scale, while frequency increases by a factor of 3, which is equivalent to a factor of 1.4 for the jet velocity U. Furthermore, these ratios seem to be in the same order of magnitude than those of Cossette's study: mouth pressure increases by a factor of 3.3, while pitch increases by a factor of 4. Interestingly, our measurements show that the relation between mouth pressure and frequency is not linear over the two octaves as, during the first octave, mouth pressure remains stable. Montgermont [11] also discusses the dependence of mouth pressure on dynamics: when going from *pp* to *mf* and from *mf* to *ff*, P_m increases by 100 Pa.

As also noted by Montgermont [11], flute players may use different strategies to balance jet velocity and jet length. The dimensionless jet velocity θ allows a comparison of the different strategies used by players. Total jet flow Q is also related to the players' strategy. While dimensionless jet velocity θ is related to the over/under playing of a frequency regime as well as to the harmonic development of a tone, jet flow is related to the acoustical power of a sound. The player can therefore control the complementary aspects of loudness separately: the harmonic richness and the acoustical power of sound.

As observed in our results, de la Cuadra [10] and Cossette [16] note that an increment in jet velocity seems to be compensated by a decrease of the lip hole area A which may result in a decrease of jet flow Q. This may help to prevent an increment of loudness in the higher register. De la Cuadra reports a range of flow between 100mL/s to 400mL/s, which is a little higher than the values reported here.

For an ascending diatonic scale (always by a factor of 3 for the frequency), de la Cuadra [10] shows that jet length W decreases by a factor of 1.8 while Montgermont [11] shows variations of W from 8 mm to 4 mm, as observed during our second octave.

According to Montgermont [11], dimensionless velocity θ should be around 7 for optimal phase oscillation (comfortable playing zone). Furthermore, values between 7 and 17 help to produce more energy on the higher harmonics. Additionally, our measurements show similar pattern of the dimensionless velocity as the one observed by Cossette [16]. Indeed during an ascending scale, θ decreases with frequency for the first octave and is kept stable for the second one. At last, our results show similar variations of dimensionless velocity to Cossette's work [16], in fact θ evolves between 4 and 15 for the two diatonic scales.

De la Cuadra [10] shows that Reynolds number increases with frequency and dynamic from 1000 to 3500 during a diatonic scale (less than two octaves). (In de la Cuadra's study, Reynolds number is expressed as Uh/ν and not with D). For a two octave scale, our results report a Reynolds number between 2000 and 5500 and suggest that Reynolds number is correlated with flow. The muscular activation we found is consistent with Cossette's observations [16] during a scale. Effectively, Figure 8 shows that the inspiratory muscles are activated during expiration and then switch to expiratory muscle contraction.

In Cossette's study [16], the flautist plays the entire two octaves ascending diatonic D scale over the Functional Residual Capacity. In our study, the flautist plays an ascending and descending G diatonic scale within a breath, approximately at the same tempo, which requires her to use more air as the scale contains twice more notes and lasts twice longer. Furthermore, Cossette's flautist [16] has a VC of 5,6 L while ours has a 3,7 L VC. As a result, our flautist uses a higher percentage of her air vital capacity, probably because of her lower vital capacity.

Debussy Prélude à l'après-midi d'un faune:
As explained previously, this piece does not require a high dynamic or intensity but air requirement is high as the first phrase is very long and ends with a crescendo-decrescendo. As this excerpt is in the first octave of the precedent scale in a *pp* dynamic, mouth pressure is in the same range and reflects the frequency variations. Cossette [16] observes mouth pressure variations between 250 and 700 Pa; for the last phrase, our values are somewhat lower. As observed by Cossette, the crescendo-decrescendo in the last part of the solo is performed by modulating the area of the lips. Again, as our flautist has a smaller Vital Capacity than the one in Cossette's study, she saves air and produces lower pressures and air velocity than the flautist in Cossette's study. The little variations observed on W, between 6 and 7.5 mm, are in the same order of magnitude as the ones in Cossette's study, which are between 4.5 and 5.5 mm. In that study, dimensionless velocity θ shows the musical structure. Indeed, the three slurs are clearly distinguishable, however θ values are lower in our study than in Cossette's (respectively between 4 and 8, and between 7 and 13). This may be a direct consequence of a lower velocity.

Similarly to the G scale and to Cossette's study, the inspiratory and expiratory muscle activations do not overlap during Debussy and the switch occurs at the FRC of the abdominal volume. However, the activation of the sternocleidomastoidian muscles is more important than the activation reported by Cossette, 22 % against 7%. On the contrary, the scalene activation is less important in our study: 45% against 80%. The two subjects use their inspiratory muscles differently. This is also in accordance to other findings from Cossette [15] which demonstrate that some flautists recruit more their sternocleidomastoidians and other flautists, more their scalenes.

Moreover, our flute player activates her expiratory muscles at a much greater level (22% and 74% respectively for the rectus and laterals) than the one reported in the previous study [16] (5 % for both muscles). Once again, it should be correlated with the vital capacity of the two flautists and the pulmonary volume at which they are playing. Furthermore, our results are more correlated with Cossette's study [15], which shows expiratory muscles activation between 40 and 100%. This activity increases with the decrease of the air volume. Finally, our results show that flow and modulation of the exit of air may be controlled by the contraction of the inspiratory muscles, by the slow action of the expiratory muscles or by a reduction of the lips area when the muscles are not activated.

Beethoven Leonore Overture:
Leonore Overture is also a slow and long piece but, in contrast to the Debussy excerpt, it requires more intensity and is played at a higher pitch. With these requirements, it is consistent that mouth pressure and jet velocity are in the same range as for the top range of the scale. On a sustained note with decrescendo, de la Cuadra [10] observes significant decreases in flow, in Reynolds number, and in the lip area measurements. Our results show the same trend. The values decrease slowly with the decrescendo until the end of the phrase. Flow is in the range of the one observed by de la Cuadra, between 1.10^{-4} and 4.10^{-4} m^3/s. Please note that during this decrescendo, tracings show a fast relaxation of the inspiratory muscles and an increasing contraction of the expiratory muscles. Mouth pressure is compensated by slightly adjusting the jet length W to keep θ almost constant and, as discussed by de la Cuadra [10], θ remains almost stable around 7. Reynolds number values correspond to those in the high register of the diatonic scale and are also correlated with flow. Contrarily to the other excerpts, the activations of the inspiratory and expiratory muscles are superimposed from the beginning of the excerpt. Cossette [14] shows that to play in the high register, the expiratory activity is increased in order to compress the lung volume and increase the pressure. Furthermore, by contracting, the expiratory muscles push the diaphragm up (if relaxed), and create a transfer of pressure from the abdomen to the chest-wall cavities.

Finally, three different motions of the rib cage are distinguished during the expiration of the three excerpts. Interestingly, Cossette [14] found three patterns similar to these during sustained tones, but in three distinct flautists.

6.2. Proposal of a model based on observations

Previous studies [11, 13, 14, 16, 17] show different analyses of the respiratory and/or hydrodynamical parameters; however, the protocols of those studies do not include the simultaneous measurements of the various parameters. In this section, we aim to develop a model that highlights the player's breathing strategy for the different musical tasks performed. Based on the simultaneous observations of the parameters gathered through the study, we wish to establish a model that will let us infer the muscular activities from the blowing pressure and the pulmonary volume. The model requires that we 1) estimate the position of the diaphragm in order to analyze and understand the variations of the three compartments; 2) identify the constant volume which corresponds to the viscera; and finally, 3) determine the actual pulmonary volume used by the flautist.

6.2.1. Identification of the diaphragm position

According to Aliverti's findings [35], the diaphragm position can be approximated by observing the abdominal

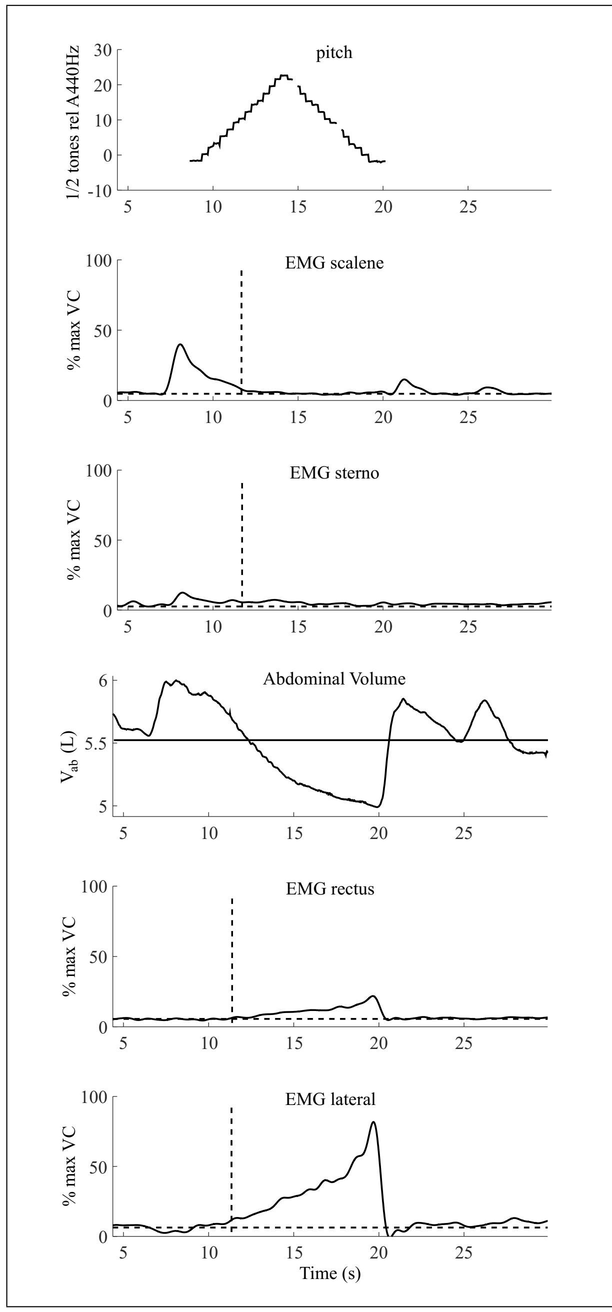

Figure 12. G scale. Detected pitch (semitones relative to A = 440 Hz), EMG scalenes, EMG sternocleidomastoidians, abdominal volume (% max VC), EMG rectus and EMG lateral abdominals. The dashed vertical line shows the switch between inspiratory and expiratory muscular activations.

volume. In order to illustrate our model, we first focus on the G scale, a simple task that does not require any special effort. Figure 12 shows the detected pitch, the activation of the respiratory muscles (in % the maximum activity during VC) and the abdominal volume (V_{ab}).

Figures 8 and 12 show that expiration splits in two phases during the G scale. First, from the beginning up to around 8.5 s to 12 s, the inspiratory muscles contract, holds the elastic recoil of the respiratory system and slows down the expiration. Secondly, after 12 s (dashed vertical line), the inspiratory contraction switches to an expiratory one.

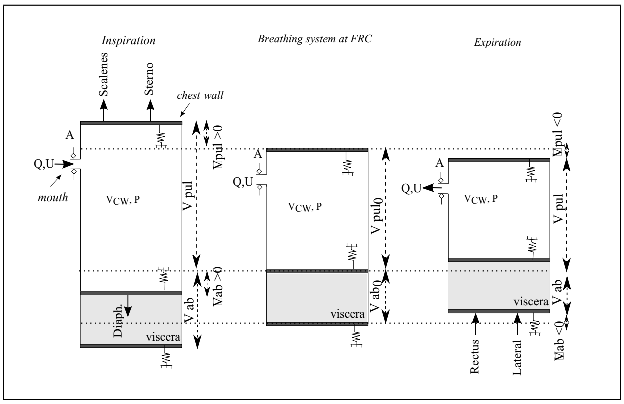

Figure 13. Model of the flautist's thorax and mouth at different respiratory volumes: at FRC (centre), and at pulmonary volumes above FRC (left) and under FRC (right). The gray block corresponds to the incompressible volume of the viscera, and the white block corresponds to the chest-wall cavity volume, above the diaphragm. The dotted lines represent the boundaries of FRC for both compartments. Arrows indicate the direction of the force applied by inspiratory and expiratory muscles.

This switch corresponds to the transition of the abdominal volume from above to under FRC. By looking into the axial distance of the abdominal volume at the xyphoidal tranverse plane, Aliverti [35] showed that, under conditions of quiet breathing and exercise, with and without expiratory flow limitation, instantaneous Dap (antero-posterior V_{ab} distance at the diaphragm level) can be approximately estimated from V_{ab}. At the abdominal resting volume when all muscles are relaxed, the diaphragm is in its resting position (cupola). When there is no antagonist muscle contraction, we can assume that the abdominal volume at the FRC corresponds to the incompressible volume of the viscera and that, at this time, the position of the diaphragm is roughly at the delimitation between the V_{ab} and the V_{RCa}. Finally, when V_{ab} is higher than the resting volume, the diaphragm is lower than its resting position and conversely. We propose a division of the thorax into two compartments separated by the diaphragm: the viscera volume (assumed to be incompressible) and the chest-wall volume.

6.2.2. Presentation of the model

Figure 13 depicts the proposed model of the flautist's thorax with the two principal compartments: the viscera volume and the chest-wall volume.

Figure 13, the respiratory system of the player is represented as a cylinder with moving pistons. Note that the mouth is represented by an opening on the thorax compartments, which is adjustable with the lip area A. This one also controls flow Q from the jet velocity U. The air duct being narrowed at the lips, the pressure into the lungs is assumed to be equal to mouth pressure. During inspiration (left), the flautist contracts inspiratory muscles (e.g. diaphragm, scalenes, sternocleidomastoidians) which increases the chest-wall cavity. On the contrary, below FRC (right), the flute player contracts expiratory muscles, (e.g. rectus and lateral abdominals) to force the air out. Although they are important actors in respiration, intercostal muscles are sometimes associated to inspiration and other times to expiration, [36, 37]. In addition, as their complexity and location makes it difficult to measure their activation with surface EMG, we did not include them in our study. The viscera block shows the incompressible volume of the viscera and the chest-wall block constitutes the volume above the diaphragm. In Figure 13,

- V_{ab} represents the measured abdominal volume
- V_{pul} is the sum of the measured V_{RCp} and V_{RCa} volumes, shown in Figure 6.

At rest, V_{ab} and V_{pul} respectively become V_{ab_0} and V_{pul_0}, and the viscera volume is equal to V_{ab_0}. The volume above the diaphragm, without the viscera volume, can then be expressed according to the measured parameters,

$$V_{CW} = V_{pul_0} + \Delta V_{pul} + \Delta V_{ab}, \tag{5}$$

where the sign of ΔV_{pul} and ΔV_{ab} is positive above abdominal FRC and negative under abdominal FRC. Furthermore, $V_{CW_{max}} - V_{CW_{min}} = VC$ (Vital Capacity). One of the key points that link this model to the measurements in the previous sections is that the volumes are measured using reflectors at fixed positions on the skin while the volumes in the model are moving following the diaphragm motion and thus V_{CW} only represents the air volume variations.

6.2.3. Minimal effort curve

In Figure 14, a curve, made of mouth pressure and chest volume measured when the active forces are zero (no muscular activity), is fitted to our measurements. This curve, that we call the minimal effort curve, is an interpolation between points of minimal muscular activity. Therefore, it is different from the relaxation curve of Figure 2 but may provide relevant information on the respiratory system during playing. A minimal effort condition appears only once in each of the measurements we conducted. For example, the minimal active force in the G scale occurs at the time indicated by the vertical dashed line on Figure 12. On the mouth pressure-chest volume diagram for the three musical tasks (Figure 14), each point of "no active force" is represented by a cross. The model is fitted to the experimental data through four points (crosses).

The minimal effort curve is represented by the dashed-line. The model, which is based on the pressures developed by muscle activation, shows that mouth pressures above the minimal effort curve require the activation of inspiratory muscles, while the ones below the static curve entail the contraction of the expiratory muscles. This means that above the curve, exhalation is at least partly controlled by the inspiratory muscles while, under the curve, abdominal muscles are the main agonists.

Figure 14 shows two distinct expiratory zones: the upper dark area which corresponds to the inspiratory effort produced to slow down the expiration; and the lower gray area which shows the effort produced by the expiratory muscles to push the air out. This model allows us to predict the muscular efforts that the flautist must produce for a given pressure and volume. The muscular actions and volume variations observed during the G scale and Debussy

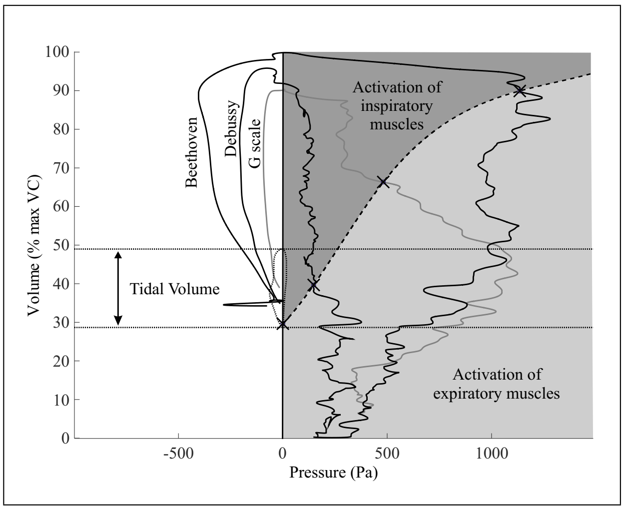

Figure 14. Mouth pressure - chest volume curves for the three musical tasks. Dashed-curve represents the minimum effort curve interpolated from FRC and minimal effort zones (crosses). Tidal volume is indicated by horizontal dash lines and the quiet breathing loop.

excerpt fit well with this model. However, the scenario is slightly different during the Beethoven excerpt. Indeed, the first *ff* note in the high register requires the flautist to increase the pressure by compressing the volume with the expiratory muscles at the beginning. The expiratory muscles are thus activated before the abdominal volume returns to FRC. However this area of muscular coaction is very restricted, thus the point of minimal effort can be assumed as the point where the muscular activity (inspiratory and expiratory) is minimal.

7. Conclusions and perspectives

A combined experimental set-up was used in order to have persistent data of the respiratory and hydrodynamical parameters of a flautist's performance. The data analysis provides information on the fine control required to play three musical tasks and shows how the flautist needs to adapt the control parameters to perform different musical complexities. Indeed, a long musical excerpt requires the flautist to take a high volume of air, then to adapt mouth pressure and other parameters to the dynamic and the specific demands of the musical task. Furthermore, a highly precise control of flow, directly correlated to the dynamic level, is required. During playing, flow control may be performed by the lip area to regulate dynamic variations as at the beginning of the Beetohven excerpt, but also by the respiratory muscles as in the Debussy excerpt. This phenomenon indicates and confirms that a strong coordination between the control at the lips and by the respiratory system of the flautist is necessary. Our results are in accordance with previous studies by Cossette [14, 15, 16], de la Cuadra [10] and Montgermont [11]. Furthermore, our measurements and analyses allowed us to provide a simplified model which links air volume and mouth pressure to muscular activation. The duration and the tempo of a musical task inform us on the air volume required, and when combined with mouth pressure, our model allows us to estimate the muscular activation (inspiratory or expiratory) of musical tasks such as a G scale and the Debussy excerpt. Even in the cases of more complex excerpts which require muscular co-activation to produce high pressure as in the Beethoven, our model provides the necessary elements to obtain a global view of the muscular activations. The concept of the minimal effort curve provides information on when inspiratory and/or expiratory muscles are activated and which muscles need to be recruited to obtain the required pressure and volume. Finally, this study described the fine control of the flautist's coordination during complex musical tasks, highlighting how respiratory and hydrodynamical control parameters are associated with the musical tasks.

A simplified model of the respiratory mechanics has been developed. Nevertheless, the activity of one of the most important respiratory muscles, the diaphragm, not monitored in the present study, was only deduced from the volume observations. Monitoring the diaphragmatic activity [38] would allow us to verify and further develop our model. The lip action, which was related to the control of flow, could be analysed more precisely by measuring facial muscle activation with electromyography. Our model was developed after observing one player only. This simplified model of the respiratory mechanics can now be used to compare different players and highlight the various strategies they have developed to play complex musical tasks.

Acknowledgement

The authors are grateful to Thomas Similowski for fruitful and stimulating discussions.

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