THE PHYSIOLOGICAL DEMANDS OF WIND INSTRUMENT PERFORMANCE*

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Summary: Requirements on blowing pressure and lip tension in the playing of woodwind and brass instruments are examined and related to the sound-producing mechanism in each case. Loud playing of high notes on brass instruments is found to be the most physiologically demanding situation, but all instruments have particular requirements for precise physiological control.

1. INTRODUCTION

The playing of musical wind instruments goes back to the dawn of human history, but it is only recently that we have begun to understand in detail the physical principles governing sound production and the physiological variables that must be controlled by the player during performance. Along with this goes a better understanding of the design and construction of the instruments themselves, but that, as they say, is another story.

Setting aside the pipe organ, we can divide musical wind instruments into three classes: reed-driven instruments such as the clarinet, oboe, bassoon and saxophone; lip-driven brass instruments such as the trumpet, trombone and tuba; and air-jet driven instruments of the flute family. In all of these, the player must learn to control the pitch of the note being played by manipulating finger keys, valves or slides, and then must carefully control the actual sound-producing mechanism to produce a satisfactory result. This requires deliberate control of physiological variables such as lip position and tension, blowing pressure, and perhaps vocal-tract configuration. It is the purpose of the present paper to describe what is known of the requirements on each of these variables. Details of the acoustics of the instruments themselves can be found in Fletcher and Rossing (1998).

2. REED-DRIVEN INSTRUMENTS

The clarinet is perhaps the simplest and most studied of the woodwind instruments, because it has an essentially cylindrical tube and a single flat reed with simple geometry. The player's lips enclose the reed and the mouthpiece against which it is clamped with a gap of about 1mm at the tip, and the player applies air pressure that tends to close the reed against the mouthpiece. Analysis of the physics of this situation shows that the reed will begin to vibrate, and thus cause oscillations in the air flow through the aperture between it and the mouthpiece into the instrument tube, once the blowing pressure exceeds one-third of the value required to completely close the reed against the mouthpiece face. To ensure stable playing, the player ordinarily uses a pressure that is one-half to two-thirds of this closing pressure.

* Originally published as "Les exigences physiologique lors du jou des instruments à vent" in *Médecine des Arts* (2000).

To first order, this is all that is required, and the instrument will sound whatever note is dictated by the fingering. In practice there are a few subtleties. In the first place, the production of high notes is aided if the player adjusts the lips so that the vibrating part of the reed is shortened, and there is also an associated reduction of the mouth volume by raising the tongue. This generally increases the closing pressure a little, so that normal blowing pressure is also a little raised. To reduce the loudness of the sound, the player tenses the lips so that the reed aperture is reduced and less air flows through into the instrument. This also causes a small decrease in closing pressure, and so in optimal blowing pressure.

As shown in Figure 1, for normal clarinet playing, the blowing pressure is typically 2 to 3 kilopascals (kPa) for soft playing, and 4 to 4.5kPa for loud playing over the whole pitch range of the instrument (Fuks and Sundberg, 1997), though jazz players may sometimes use a higher blowing pressure to produce an incisive or even rough tone quality. These pressures should be compared with normal sub-glottal pressures of about 300Pa for speech and perhaps 1kPa in singing, and are not so high as to cause much physiological stress. (For those not familiar with these pressure units, 1kPa is equivalent to about 10cm water or 7.5mm mercury. A scale translation is given in each figure.)

Playing technique for the saxophone is in many ways similar to that for the clarinet, and jazz players often switch between the two instruments. The saxophone also has a single flat reed but differs from the clarinet in having a wide-mouthed conical bore. Blowing pressure for the alto saxophone is typically about 2kPa for soft playing, but may rise as high as 8kPa in the middle register for very loud playing where a harsh tone quality is desired, as shown in Figure 1.

Double-reed instruments, such as the oboe and bassoon, have a very narrow conical bore and a narrow reed with two vibrating tongues bound together. The reed aperture is much smaller than in the single-reed instruments and, because the reed is curved across its width and there is significant flow resistance in the narrow reed channel, a higher blowing pressure is required to make it vibrate. The blowing pressure used by skilled players increases by about a factor two between soft and loud playing, and rises by about a factor two across the compass of the instrument, as shown in Figure 1. Pressures of around 10kPa, as required for high loud notes on the oboe

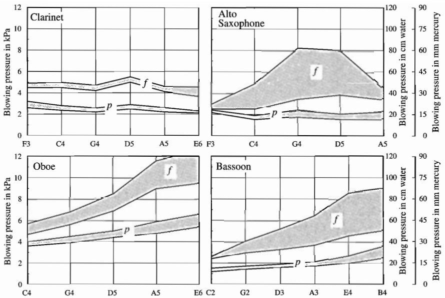

Figure 1. Typical blowing pressure ranges across the musical compass for clarinet, alto saxophone, oboe, and bassoon, for *piano* and *forte* playing. [Data from Fuks and Sundberg (1996).]

or bassoon, impose a significant physiological strain on the player if the condition must be maintained for a long section of music, but this usually results only in facial reddening. For less-skilled players, there may be significant difficulty in maintaining the lips in position on the reed, because mouth pressure tends to blow the lips open. There is no remedy for this except regular practice, preferably begun at an early age, to strengthen the lip muscles.

The reed woodwinds, and particularly the double reeds, do not require a large air flow to produce a moderately loud sound, and players can therefore play quite long passages, up to perhaps 50 seconds in duration, without requiring to take a breath. This, too, imposes a physiological strain on the player because of the build-up of carbon dioxide concentration in the lungs. Normally such a build-up triggers a breathing reflex, but experience players are able to suppress this to a considerable extent. It has recently become common practice for woodwind players to become adept at the techniques of 'circular breathing,' in which the throat and mouth are filled with air from the lungs under pressure to maintain the instrument sound, and then sealed off from the trachea and nasal passages at the soft palate so that a quick breath may be taken through the nose. This technique, which has been used by Australian Aboriginal didjeridu players for thousands of years, allows the player to continue playing without interruption for an indefinite time.

It has already been mentioned that the volume of the mouth is typically reduced for playing high notes and increased for very low notes, as is clear from the lowered chin of bassoon players. There is another aspect of respiratory tract physiology that also appears to enter performance technique, and this concerns the larynx. Mukai (1989) made observations of the larynx of many wind instrument players during performance in the laboratory, using a nasendoscope, and found that, while novice players typically had wide open larynxes, experienced players of all varieties of wind instruments mostly adducted their vocal folds to constrict greatly the laryngeal opening. In the case of players using vibrato, the vocal folds tended to vibrate in synchrony with the vibrato. There do not appear to have been further investigations of this finding in the case of reed instrument players.

3. LIP-DRIVEN BRASS INSTRUMENTS

While the player's lips take the place of the reed in brass instruments, their operation is very different. The reason is that, while pressure in the player's mouth tends to close a reed valve, it tends to open a lip valve. The exact motion of a player's lips is complex and to some extent under conscious control, although the player does not generally realise what changes are being made. The lips may either blow outwards towards the instrument, like an outward-swinging door, or move laterally like a sliding door. More realistically they may combine both these movements or may even have a wave-like motion (Yoshikawa, 1995; Adachi and Sato, 1996).

The important thing acoustically is that the lips are able to act as a sound-generating valve only very close to their natural resonance frequency. This means that lip muscle tension must be adjusted very carefully by the player to match the pitch of each note, and must be increased greatly for high notes. The accuracy of tension adjustment required increases in the upper range of the instrument where the frequencies of

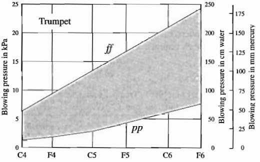

Figure 2. Typical blowing pressure range across the musical compass for the trumpet in *pianissimo* and *fortissimo* playing [Data from Fletcher and Tarnopolsky (1999).]

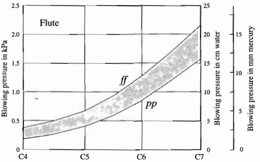

Figure 3. Typical blowing pressure range across the musical compass for the flute, in *pianissimo* and *fortissimo* playing. [Data from Fletcher (1975).]

the natural modes of the horn are close together. For a French horn or a 'natural' trumpet without valves, some of these notes differ by only a semitone, or 7% in frequency, and this requires an accuracy greater than this in the control of lip tension. Small wonder that amateur horn players sometimes 'fluff' notes on their entries!

This high lip tension brings physiological difficulties of muscle tiredness, but the lips are supported by the rim of the mouthpiece cup so that they do not blow out uncontrollably. More importantly, a high lip tension requires a high mouth pressure to force the lips open at all and, if a very loud sound is required, the necessary blowing pressure becomes extreme.

Fletcher and Tarnopolsky (1999) have investigated these problems for the case of trumpet players, and the results are summarised in Figure 2. For soft playing, the necessary blowing pressure is moderate, though it doubles for each octave rise in pitch and is as high as 6kPa for notes at the top of the range. Increased loudness, however, requires increased blowing pressure, and expert players may exceed 20kPa for high notes played fortissimo. Indeed one player studied reached 25kPa. To set this in context, it implies a pressure in the lungs, throat and mouth of 150 to 190mm mercury, which is greater than systolic blood pressure! It is not surprising that professional orchestral trumpet players are usually sturdy in physique and that, even so, some of them report problems of dizziness and even muscle rupture.

With lower pitched instruments, the pressure problems are less. For the tuba, indeed, problems are rather those of excessive air flow demands in the loud playing of notes at the bottom of the range, leading to hyperventilation.

4. FLUTE-LIKE INSTRUMENTS

The third class of wind instruments is that in which sound is generated by the flow of an air jet across an aperture. The orchestral flute is the principal representative, but recorders, ocarinas, shakuhachi, and pan-pipes all have similar characteristics. The jet actually excites the air column of the instrument by blowing alternately into and out of the aperture, and this jet deflection is caused by sinuous waves propagating along its length from the small aperture between the player's lips. To sound a note, it is necessary that there be very nearly half a wavelength of this wave disturbance on the jet at the frequency of the note being played, and this requires precise control of lip position and of blowing pressure. Only in recorders, ocarinas and whistles is the geometry of the jet defined by a built-in airway.

Measurements on flute players (Fletcher, 1975) confirm the correctness of this theory of sound generation in these instruments. Players reduce the length of the air jet by pushing the lips forward, and increase the blowing pressure and thus the jet velocity, when playing high notes. In fact the jet lengths and blowing pressures used by flute players differ very little from one individual to another, as shown for the case of pressure in Figure 3. The blowing pressure is very closely doubled for each octave rise in pitch, so that it is proportional to the frequency of the note being played — the same result as for trumpet players, but for an entirely different reason! The blowing pressures used in flute playing are the lowest of any wind instrument, ranging from about 0.2kPa for low notes to about 2.5kPa at the top of the range, nearly independently of the loudness of the note being played, as shown in Figure 3. Blowing pressure therefore causes no physiological difficulty at all for flute players.

Since blowing pressure cannot be used to control loudness, the player changes the air flow into the instrument by varying the area of the opening between the lips — a larger opening means a greater air flow and thus a louder sound. The useful width of the air jet is limited, however, by the width of the embouchure hole in the instrument to about 12mm, and it is necessary that the jet be not too thick — the limit is about 1mm — if the sound quality is to be acceptable. An even loudness across the instrument compass also requires a smaller aperture for high notes to compensate for the increased blowing pressure. All these adjustments demand experience and practice, but do not present any physiological problems.

Whereas in most other wind instruments (except perhaps the oboe) the desired tone is nearly steady, flute players favour performance with pronounced vibrato. Measurements (Fletcher, 1975) show that this vibrato is accomplished by imposing a small oscillation on the air pressure in the mouth, with an amplitude about 10% of the steady pressure and a frequency of 5 to 6Hz. The result is not so much a regular oscillation in sound level or in frequency, both of which remain almost unaffected, but rather an oscillation in tone quality caused by variation in the amplitude of the upper harmonics of the sound.

It is not immediately clear how this vibrato is accomplished, and indeed it may vary from one school of playing to another. It could be by rhythmic oscillation of the abdominal muscles, by similar changes in lip tension and thus in lip aperture, or by oscillation of the vocal folds if they are significantly adducted. Mukai (1989) found a narrowing of the airway by the vocal folds for experienced flute players as for other instrumentalists, and an oscillation in airway area in synchrony with the vibrato, but recent studies have suggested that there may be more variation in technique from one individual to another than found in his work.

5. CONCLUSIONS

As set out in this brief review, the production of a well controlled sound from a musical wind instrument involves precise control of a number of physiological variables, particularly blowing pressure and lip configuration. The requirements on these variables are very different between the three classes of wind instruments, and some musical demands may impose quite extreme physiological stresses. It is to be hoped that, by understanding what is required and the reasons for it, players may improve both their technique and their playing comfort.

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