12 Music for the Audiologist

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Without explicitly recognizing it, audiologists have all of the tools for the understanding and analysis of music. In some cases any limitation can be traced to lack of application of a concept and in other cases it is merely terminology. The musical notes versus the frequency in Hz is one such area.

LETTERS AND FREQUENCIES

Musicians use the letters A, Bb, C, whereas audiologists would say 440 Hz, 466 Hz, and 524 Hz. According to the situation and information required in both cases, this may tend to be an oversimplification. Depending on the musical instrument, the note A may have a fundamental (or tonic) on A, but also a range of higher frequency harmonics and overtones whose location and intensities define the musical instrument. Similarly, stating that a certain note (or vowel) is sung at 440 Hz ignores the fact that there is a rich harmonic structure that occurs at the higher frequencies. Accepting this limitation, a notation that has received widespread acceptance is to state the note as A[440 Hz] or more simply as A[440]. This means that the A on the second space of the treble cleff has a frequency of its fundamental of 440 Hz. Some notes along with their frequencies are given in Figure 12–1.

A convenience of the musical letter terminology is that octaves have the same letter notation—an octave higher than A is A. And a convenience of the frequency notation is that a doubling of the frequency number is one octave higher—880 Hz is one octave above 440 Hz. Clearly, the frequency notation can be more accurate, but within any one cultural style of playing, the letter terminology can be more than sufficient and more innately understood.

> **KEY POINT**
>
> A convenient notation uses both the musical note and its fundamental frequency.

LETTERS AND INTENSITIES

Another notational difference between music and the field of audiology is the specification of loudness and the actual

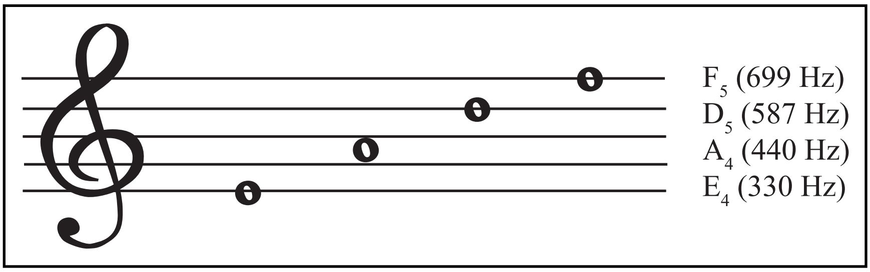

Figure 12–1. Several notes shown on a treble cleff along with their frequencies. *Note.* From *Musicians and the Prevention of Hearing Loss* (1st ed.), by M. Chasin, 1996, Clifton Park, NY: Delmar Learning. Reprinted with permission of Delmar Learning, a division of Thomson Learning.

intensity range. Musicians speak in terms of a note being *pianissimo* or *forte*, whereas an audiologist might refer to the level of intensity of a note as being 45 dB SPL or 105 dB SPL. Both are correct despite the slightly more accurate use of the decibel measure for the intensity of the sound. Of course, the reference to a note being pianissimo or *pp* refers to the loudness and not the intensity, but given this difference and the limitations of comparison of a perceptual and a physical measurement, the usage can still be fairly accurate. Musicians around the world can easily play a passage denoted as *mezzo forte* or *mf* with similar intensities because of an underlying familiarity of what the perceived intensity should be. Table 12–1 shows the approximate relationship over a number of musical instruments and styles for a stated loudness level and its corresponding intensity range.

Table 12–1. The approximate relationship between a musician's loudness judgment and the physical intensity measured in decibels (SPL)

Loudness Level	*Intensity (dB SPL)*
ppp	30–50
pp	45–55
p	50–60
mf	55–75
f	70–80
ff	80–90
fff	90–110

Note. From *Musicians and the Prevention of Hearing Loss* (1st ed.), by M. Chasin, 1996, Clifton Park, NY: Delmar Learning. Reprinted with permission of Delmar Learning, a division of Thomson Learning.

A BIT OF ACOUSTICS

Like all tubes and chambers, musical instruments behave acoustically as resonators. Resonators are structures (e.g., tubes) that serve to amplify sounds that are near the characteristic or resonant frequency. In some cases, the resonant frequency of the tube can be changed either by physically elongating it (such as a trombone) or by covering holes (like a clarinet). And similar to the human vocal tract, these resonators can be classified

Table 12–2. Examples of musical instruments that behave primarily as either a quarter wavelength or a half wavelength resonator

Quarter Wavelength Resonators	***Half Wavelength Resonators***
clarinet	saxophone
trumpet	oboe
trombone	guitar
tuba	violin
French horn	flute

as quarter wavelength, half wavelength, and Helmholtz resonators. Table 12–2 lists some musical instruments that are considered quarter wavelength and half wavelength resonators.

Quarter Wavelength Resonators

A quarter wavelength resonance occurs whenever a tube has one "open" end and one "closed" end. These occur often and are typically first studied at the high school level. If one pinches a straw at the bottom and blows across the top of the straw, one can hear a unique frequency that is governed only by the length of the straw. And if someone had strong enough lungs, blowing harder would elicit an additional frequency at exactly three times the frequency of the previous one. This is one important feature of a quarter wavelength resonator–successive resonances are at odd-numbered multiples of the resonant frequency, so that no matter what the tonic note is in this type of resonator, other harmonics can be heard. We see this in behind-the-ear hearing aid acoustics: the hearing aid receiver tubing + earhook + earmold tubing length combine to generate a resonance at about 1000 Hz. Because the hearing aid is closed at the receiver end and open at the end of the earmold, this functions as a quarter wavelength resonator. There are successive "tubing-related" resonances at 3000 Hz and 5000 Hz—or at the odd-numbered multiples of 1000 Hz. In a behind-the-ear hearing aid electroacoustic response there are also resonances in between these wavelength resonances and these are related to the mechanical properties of the hearing aid receiver. Prior to the mid-1980s hearing aids typically used either class A or class B output stages having a mechanical receiver-related resonance at 2000 Hz, but since the advent of the class D output stage, most receivers possess a 2700 to 3000 Hz resonance and may be coincidental with the second mode of the tubing-related resonance at 3000 Hz.

The formula for a quarter wavelength resonator is given by:

$$F = (2k - 1)v/4L$$

Where,
F = frequency (Hz)
v = speed of sound
L = length of the tube
k = mode or resonance number

The term $(2k - 1)$ is merely a convenience to show that the resonant frequency F not only occurs at $v/4L$ but also at $3v/4L$ and $5v/4L$. Specifically, if $k = 1$, then the term $(2k - 1)$ is simply 1. If $k = 2$ (the second mode of resonance) then the term $(2k - 1)$ is 3 and so on. This formula is also used in speech acoustics and explains why for the vowel [a] as in *f<u>a</u>ther* where the mouth is closed at the vocal chords and open at the open lips, the resonant pattern of [a] has odd-numbered multiples of the primary resonance 500 Hz. The 500 Hz can be calculated from the above formula and is based on the length of the human vocal tract (about 17 cm). Subsequent vocal tract resonances (also called *formants*) are at 1500 Hz (3 × 500 Hz), at 2500 Hz (5 × 500 Hz), and so on.

Clarinets and trumpets are closed at the lips and open at the other end and as such behave primarily as quarter wavelength resonators. Other than the fundamental (e.g., A[440]), there are inherent resonances from these instruments at 1320 Hz (i.e., 3 × 440 Hz) and 2200 Hz (5 × 440 Hz). Figure 12–2 shows that the "length" of the clarinet is from the mouthpiece down to the first noncovered hole. The length below the noncovered hole does not contribute to the acoustics of the instrument.

KEY POINT

Clarinets and brass instruments have odd-numbered multiples of its fundamental frequency.

One aspect of having odd-numbered multiples of the fundamental or primary resonance is that in each octave there is less energy than if there were resonances at integer numbers of the fundamental (e.g., violin). The harmonic structure is less dense for a quarter wavelength resonator than for a half wavelength resonator. Another aspect of quarter wavelength resonators is that they have a "register key" and not an "octave key." In the clarinet the register key increases the frequency of the note by three times the fundamental, which is in line with the expectation

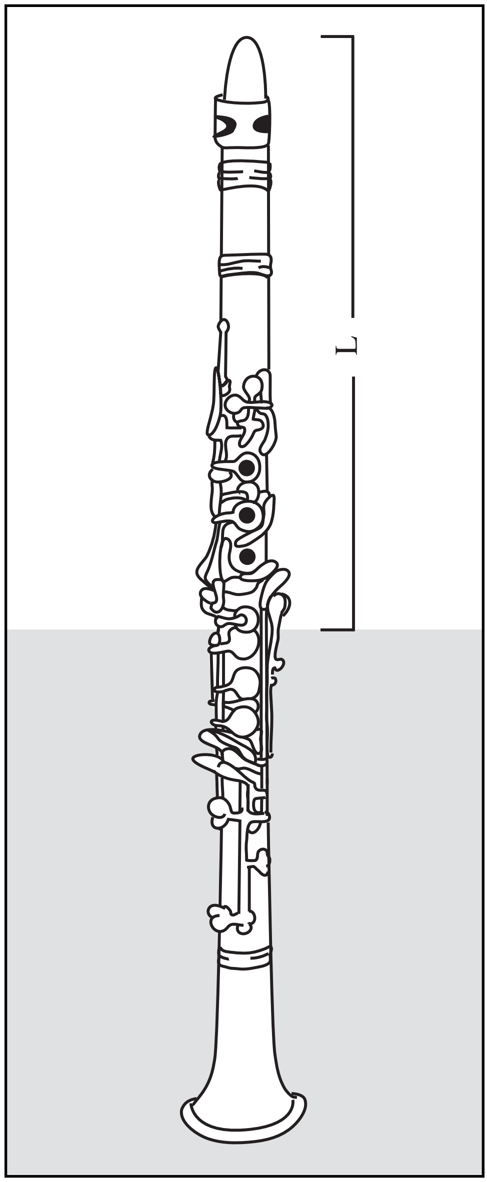

Figure 12–2. The "length" of the clarinet is from the mouthpiece down to the first noncovered hole. The region below the first noncovered hole (shaded in light gray) does not contribute to the pitch. *Note.* From *Musicians and the Prevention of Hearing Loss* (1st ed.), by M. Chasin, 1996, Clifton Park, NY: Delmar Learning. Reprinted with permission of Delmar Learning, a division of Thomson Learning.

of all quarter wavelength resonators. When one plays middle C (concert) on a clarinet the note is 262 Hz, and when the register key is depressed, the note changes to high G [784], which is almost exactly 3×262 Hz. Essentially G[784] is one and one half octaves above concert C [262].

Half Wavelength Resonators

Unlike the quarter wavelength resonators that require a closed end and an open end, half wavelength resonators occur in tubes that are either closed at both ends or open at both ends. Flutes and piccollo function as half wavelength resonators that are open at both ends and violins and guitars function as half wavelength resonators that are closed at both ends. In the stringed instrument category, it is the string that is held rigidly at both ends.

The formula for a half wavelength resonator is given by:

$$F = kv/2L$$

Where again,
F = frequency (Hz)
v = speed of sound
L = length of the tube
k = mode or resonance number

In this formula, the higher frequency harmonics are merely integer multiples of the primary or fundamental frequency or the tonic. In a one half wavelength resonator instrument such as the flute or violin, the first resonance above concert C[262] would be one octave higher at C[524]. The next would be an octave higher again at C[786], and so on but always remaining the tonic. One half wavelength resonator instruments can have "octave keys" where their use increases the frequency by exactly one octave (a doubling of frequency). Figure 12–3 shows the clarinet (a quarter wavelength instrument) and a flute (a half wavelength instrument) playing the same *concert* note (G[392]), normalized for playing intensity, demonstrating the differing resonant structures.

Conical Instruments Are Really Half Wavelength Resonators

For reasons beyond the scope of this book, it turns out that conical or gradually flaring tube instruments also behave as half wavelength instruments. The oboe and saxophones are closed at the mouthpiece end and open at the other end, but because of their natural conical flare of the tube, they behave acoustically as if they are half wavelength resonator instruments. Both the oboe and the saxophone have an octave key that serves to double the frequency of playing.

KEY POINT

Stringed instruments as well as the saxophone and oboe have integer multiples of their fundamental frequency.

An aspect of all half wavelength resonator instruments is that the harmonic structure is denser than that of an equivalently sized quarter wavelength instrument. Within each octave, there are two points of energy (at the octaves), whereas for quarter wavelength instruments there is only one (or stated differently, two points of resonant energy every octave and one half).

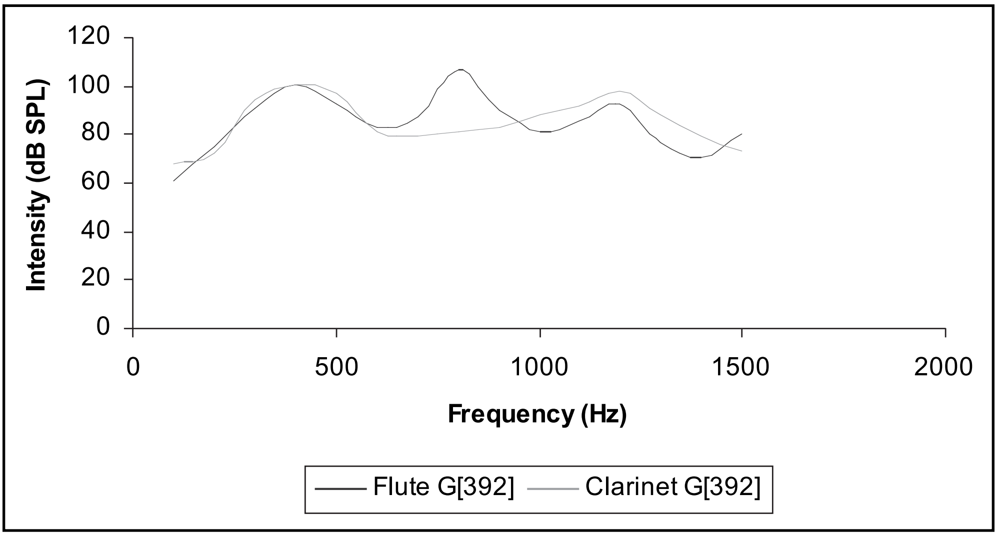

Figure 12–3. This shows the clarinet (a quarter wavelength instrument) and a flute (a half wavelength instrument) playing the same *concert* note (G[392]), normalized for playing intensity, demonstrating the differing resonant structures. The flute has twice as many resonances in any given frequency range as does the quarter wavelength resonator, the clarinet.

Volume-Related and Mechanical Resonances

Other than the two wavelength-related resonances (quarter and half) whose behavior can be ascertained from the end (or boundary) conditions of the tube and the length of the tube, there are resonances that are derived from the volume of air or mechanical characteristics of the wood of the instrument. These non-wavelength resonances are primarily found below 2000 Hz but can be seen as small magnitude ones in the higher frequencies. We have all placed a tuning fork on our knee and then turned around and placed it on the blackboard. While in contact with the blackboard, the tuning fork is much louder—we are driving the natural resonance of the blackboard, which is in the frequency region of the tuning fork sound. This natural resonance has to do with the size of the board and the material that it is made of.

KEY POINT

Instruments have a "fat" part that is difficult to play quietly.

Musical instruments understandably have these volume- or material-related resonances that serve to enhance the intensity of certain frequencies that are within the amplifying range of the resonance. A flute has a mechanical natural resonance at 880 Hz (which is coincidentally an A), and it is very difficult to play this note quietly. Musicians would refer to this as the fat part of their instrument and with training and skill can learn to harness this natural resonance and shape their musical selections with well-controlled intensity dynamics.

Percussive Instruments

Percussive instruments generate sounds by having a sudden hit of a structure or string. The result can be very tonal or atonal depending on the nature, composition, and shape of the instrument being hit. A characteristic of all percussive instruments is that the resulting sound is broadband in nature and has significant energy in the higher frequencies. It is best to consider the case of a waveform in the time domain. When a percussive instrument is hit, there is a "sudden" change in pressure to a much higher one in a short period of time. If you think about this in terms of the resulting wavelength, this first quarter of the wavelength (from quiet to an intense level), being very sudden, is also very short temporally. Therefore, the entire wavelength would be short as well indicating a high frequency sound. You cannot have a low frequency sudden sound. That is why all sounds in languages of the world that have plosives (e.g., aspiration, affricates, clicks, and pops) are high frequency.

KEY POINT

Percussion has significant high frequency sound energy.

This of course does not mean that all of the sound of that percussive instrument is high frequency. A bass drum has a significant amount of high frequency energy because it is hit suddenly, but also has a significant amount of low frequency energy because of the large surface area of the drum head and large volume of trapped air, which possesses a low frequency resonance.

SUMMARY

Musicians use the notes ranging from A to G along with sharps and flats, and audiologists use frequencies measured in Hz. A convenient notation is a combination of the two—A[440]—meaning that the fundamental (or tonic) of the note A is at 440 Hz. The nature of the higher frequency harmonic structure resulting from the played fundamental note will depend on the acoustic characteristics of the instrument. Instruments that are tubelike and are closed at the mouthpiece and open at the other end are considered to be quarter wavelength resonators and as such will have additional higher frequency resonances at odd-numbered multiples of the fundamental. The first additional higher frequency resonance of these instruments would be at three times (an octave and one half) the frequency of the fundamental. Examples of these instruments are the clarinet and the brass instruments. Instruments that are either closed at both ends (e.g., stringed instruments) or open at both ends (such as the flute) are considered half wavelength resonators and will have higher frequency resonances at integer multiples of the fundamental. The first additional resonance with these instruments will be one octave higher than the fundamental. Half wavelength resonator instruments can have an octave key, whereas quarter wavelength resonator instruments can have a register key (one and one half octaves). Some instruments that are closed at one end and open at the other still behave like half wavelength resonators, and these are those instruments that have a conical flare such as the oboe and the saxophone. The nature of the material, the shape, and the size of the instrument may also yield frequency regions that enhance the intensity of the sound. In the flute, this region is at 880 Hz, and is called the fat region.