Chapter 4

The Acoustics of Aspiration

In the previous chapter, we progressed from the recognition that aspiration was simply the puff of breath that we hear and feel after an aspirata to the concept that the addition of aspiration could define the spirant while the reduction of aspiration could define the media. As for the susurrata, we had to accept its weak constraint by prosodic aspiration through analogy; yet, the analogy is quite compelling within the functioning of the system.

Let us now delve more deeply into the intricacies of aspiration with an acoustic analysis. This step is quite necessary to understand the proof behind the status of the susurrata level and indeed to understand the workings of aspiration as the phonetic foundation of the Welsh mutation system as a whole..

4.1 The Acoustic Nature of Aspiration

The evidence for aspiration as the phonetic parameter of the fortis-lenis scale as it is realized in the Welsh mutation system rests most directly upon acoustic phonetic analysis.[1] Since it is in the acoustics that we see the most striking evidence, we shall concentrate most heavily upon spectrographic analysis. Of course, the acoustic signal must be produced by the physiological apparatus; but as we shall see, the nature of aspiration makes it highly unlikely that anyone would have successfully examined the physiological evidence before the acoustic.

When we look back at the spectrogram in figure 2.1, we see that the main energy for the consonant appears to fill a vertical plane "above" the horizontal plane of the vowel. To be sure, the locus of the consonant may well be within the horizontal plane of the vowel; but even when it is, the focus of energy is seen to occur in the higher frequencies.[2] Once again, the locus is the spot on the spectrogram to or from which the vowel formants appear to deviate, and it indicates the position of obstruction of the consonant. This position is quite independent of the obstruction prosodies with which it is simply coarticulated within the syllabic frame.

The energy at the higher frequencies associated with the consonant in effect constrains the vocalic emission. However, since these acoustic characteristics are not positional features and are therefore not among the obstruction features proper (reflected in the locus), we must look for them among the obstruction prosodies.

Furthermore, as we have seen in chapter 3, the mark of the fortis-lenis scale is aspiration. Since aspiration can occur as an obstruction prosody without an obstruction position (see section 3.1.a), let us first examine the energy distribution in [ha] or [^{h}a] (the difference is purely notational) in the sprectrogram in figure 4.1.

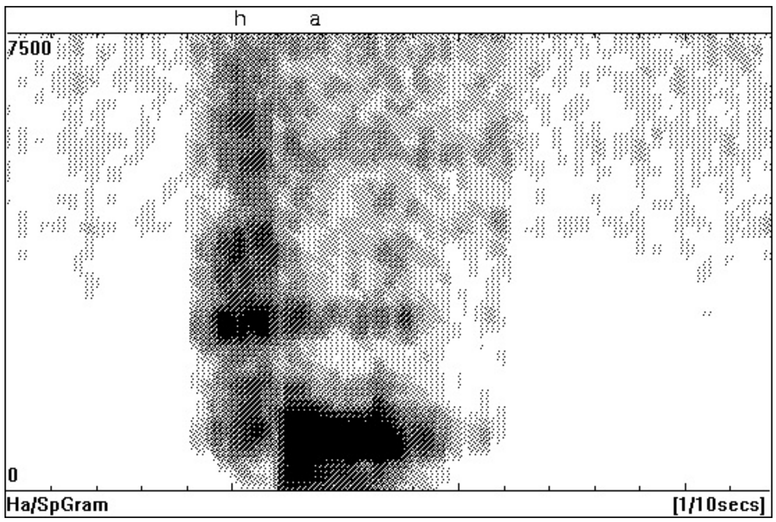

Figure 4.1: [ha]

What we see here is a vowel constrained by a rather impressive region of energy high in the spectrum. The phonetic literature places the upper limit of this energy "usually" around 6500cps.[3] Such a concentration is often called "white noise" or simply "noise."[4] For those with a musical background, we may contrast the noise of high-level frequency emission with the harmonics of the vowel – the difference between the noise of banging on several high-pitch adjacent keys of a piano and the harmonic sound produced in playing a chord in the lower range.

Of course, if we were to produce the aspiration with greater force, the cloud of noise would be darker on the spectrogram, for the amplitude (loudness) would be greater at those frequencies. Actually, since the entire utterance could be produced with greater or lesser force or amplitude, what we are interested in here is the *relative* distribution of energy,[5] not the absolute distribution.

When we consider the acoustic nature of aspiration in its most basic form – simple (prosodic) aspirate constraint – the overriding mark of the feature is that of high-frequency noise. Given the fact that the consonant is a constraint on the vowel, then the feature of aspiration can be seen as the most basic feature of consonantality, for it consists of high-frequency noise from the opposite end of the spectrum constraining the lower-level harmonics of the syllabic vowel.

Simply from a theoretical standpoint then, we can hypothesize that the degree of aspiration constraining the vowel is indeed the mark of consonantality. The greater the amount of aspiration relative to the vocalic emissions of the lower frequencies, the greater is the force or strength of the consonant over that of the vowel. It is this very concept of relative strength that traditionally lies at the heart of the fortis-lenis scale and thence of the Welsh mutation system..

4.2 The Fortis-Lenis Scale as High-to-Low Frequency Ratio

Our line of investigation thus leads us to an examination of the prosodic obstruction feature of aspiration as the key to the fortis-lenis scale. Certainly, this would appear to be our best and most direct chance not only of reconciling the relationships in the previous chapter to the acoustic nature of aspiration but also of finding a single phonetic parameter upon which to base the scale.

4.2.a The Segmental Failure. Since the notion of strength (compare Latin *fortis* 'strong') traditionally underlies the fortis-lenis scale and aspiration is the feature that ties together degrees along the scale (as seen in chapter 3), it may seem odd that no one has ever attempted to justify the fortis-lenis scale by the feature of aspiration. The basic problem has been that linguists have relied upon the letter in analysis in the guise of cross-sectional segmentation. As aspiration occurs simultaneously with the consonant it constrains, there is no way to segment it "out" of the consonant by traditional, sequential means.

In effect, the failure of the traditional analysisto isolate aspiration as the feature involved in the Welsh fortis-lenis scale is due to the persistence of using letters rather than sound in our analyses. This is just the sort of orthographic issue masquerading as phonetics that Saussure warned us against a century ago.

The dynamic approach used here avoids the problems of segmentation by insisting upon the fact that orthographic analysis, no matter how it may be disguised, is no substitute for real phonetic analysis. Phonetic analysis must rather be based upon the sound system and not upon the writing system, and the only two units isolated in the sound system itself are, once again, features and syllables.

4.2.b The High-to-Low Frequency Ratios. Let us once and for all dispense with the segment and examine the real evidence – the evidence of the spectrogram. Spectrograms provide us not simply with some impressive set of charts, but rather with the most direct graphic representation we have of the actual acoustics of the sounds. Where the spectrograph and our "native intuition" (which is, more often than not, our "literate intuition") differ on what is actually produced, arguing against what lies on the spectrogram is tantamount to arguing against the measuring stick: Even if our eyes say that one line is longer than another in an optical illusion, the measuring stick provides us with our only reliable scientific proof.

In the appendix, spectrograms are provided for the three main positions of articulation – labial, dental, and velar – as they occur in Welsh. Each spectrogram represents a series of four syllables beginning with (initially constrained by) the consonantal obstructions from lenis to fortis coarticulated with one of the seven tense vowels of Welsh. For example, spectrogram 1.e represents the labial obstructions constraining the high back vowel – [vu] - [bu] - [p^hu] - [fu].

Let us excerpt the utterance under discussion – spectrogram 1.e in the appendix – and represent it as figure 4.2. This combination of consonant and vowel is used here since both are grave – both the locus and the first two formant frequencies are relatively low and the spectrum as a whole is condensed. This allows us to see the consonant/vowel relationships in a more concise and precise manner.

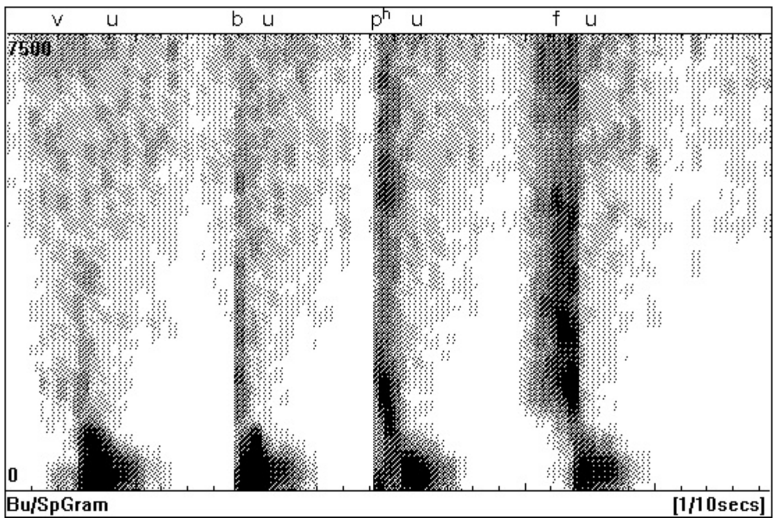

Figure 4.2: Spectrogram of [vu] - [bu] - [p^hu] - [fu]

In the spectrogram in figure 4.2, the vowel is constrained or obstructed at the points indicated at the top for each designated consonant. Once again, [v] is the {labial} position obstructed by the {1h} degree of aspiration; [b] is the {labial} position obstructed by the {2h} degree of aspiration; [p^h] is the {labial} position obstructed by the {3h} degree of aspiration; and [f] is the {labial} position obstructed by the {4h} degree if aspiration.

As we look at the spectrogram, we should notice that a trace of the darkest areas for each consonantal obstruction appears to plot a graph from the lower left to the upper right. What this means is that the lenis-most consonant has its greatest concentration of noise energy relatively low, the next-most-lenis has it slightly higher, the next-most-fortis has it higher still, and the fortis-most has its greatest concentration relatively high. Of course, for the fricatives (the first and fourth), the concentration is realized during the obstruction *per se*; while for the stops (the second and third), the concentration is realized in the explosive release of the consonant after closure.

As we progress "up" the fortis-lenis scale for all of the combinations represented in the appendix, we note that the relative energy concentration does indeed increase commensurately (although, to be sure, some combinations are more difficult to ascertain than others – and indeed, in some the aspirate spectral energy is off the screen for the fourth syllable, as we would expect).

From this evidence, it is clear that the fortis-lenis scale is marked by a progressively increasing high-to-low frequency energy emission ratio: **The more fortis the obstruction, the greater is the ratio of high frequency emission to low frequency emission**. Since the high frequency noise is the realm of aspiration, then we indeed have a ready definition of the degrees of aspiration determined in chapter 3: **Fortis aspiration is defined as relatively high frequency emission constraining the syllabic vowel in the utterance of a syllable.**

Thus, as the locus is the point to or from which the vocalic formant frequencies deviate and so reflect the position of obstruction, the degree of fortis aspiration – the high-to-low frequency energy ratio – reflects the degree of obstruction along the fortis-lenis scale. Of course, this determination is pertinent only to those languages that do in fact make use of an aspirate fortis-lenis scale in their phonological systems.[6]

4.3 The Physiological Corroboration

The acoustic signal is produced by the physiology – the various physical apparati that go into the production of speech sound. Given the type of signal produced as aspiration, we can deduce where this signal emanates from.

First of all, the aspiration is limited neither by the position of obstruction nor by any other prosodic feature in the obstruction division. For the Welsh mutation system, this fact is made very obvious by the manner in which aspiration required for the functioning of the system is realized along with nasalization. As noted in section 3.2.c, the alveopalatal affricate is required by the functioning of the system to be coarticulated with nasality and thus becomes a nasal alveopalatal affricate. Moreover, the nasal alveopalatal affricate derived from the voiceless aspirated radical must, also by the functioning of the system, be realized as a voiceless aspirated nasal alveopalatal affricate.

Such a phenomenon as a voiceless aspirated nasal alveopalatal affricate is by no means a "highly marked" segment, for it is not a segment at all. It is merely the coarticulation of a set of features, only one of which is appropriate to the main obstruction division – alveopalatal. Other, prosodic features are required by the functioning of the mutation system – the nasality and the increased aspiration along the fortis-lenis scale. The feature of aspiration in particular is imposed to a heightened degree regardless of the position of obstruction and the nasal prosody.

We must therefore look beyond the physiological domain of the obstruction division to find the realm of this aspiration. Indeed, this domain cannot exist within the acoustic chambers of the syllable division at all, for aspiration as voiceless whisper can be realized throughout the entire speech event.

The place to look for the physiological impetus for this fortis aspiration is therefore in the larynx. In the late 1960's, Joseph S. Perkell conducted a series of cineradiographic experiments, including an examination of the activities in the larynx.[7] Cineradiography involves the examination of x-ray moving pictures of the vocal apparati synchronized with a tape recording of the sounds produced.[8]

In one experiment, Perkell recorded the activity of the orifice of the larynx. Since the aspirate [h]-sound is produced at the larynx, we should expect that the volume of air passing through the larynx should increase with an increase of this aspiration. Moreover, if there is an increase in the volume of air passing through the larynx, we should also expect a widening of the soft tissue at the orifice to accommodate the increased volume of air.

This is precisely what we find in Perkell's cineradiographic data. Perkell recorded the nonsense utterances [həzɛ́], [hədɛ́], [hətɛ́], and [həsɛ́]. The internal vowels in the stress-accented syllables correspond to the susurrata, the media, the tenuis/aspirata, and the spirant of the fortis-lenis scale in degree of prosodic constraint.[9] At the point of widest dispersion, approximately 75msec before the consonantal release, the widths of the orifice of the larynx are approximately 4.1mm, 5.6mm, 7.2mm, and 9.4mm, respectively. This is represented graphically in figure 4.2.

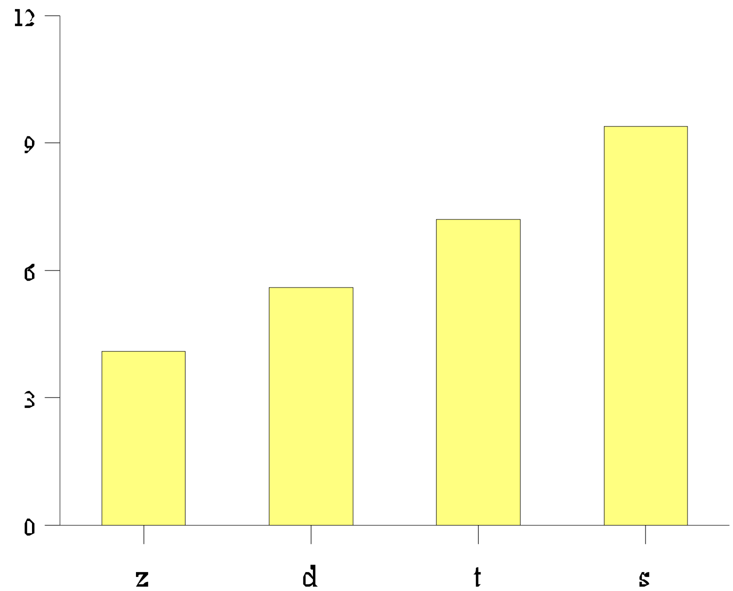

Figure 4.3: Width of the Orifice of the Larynx in Millimeters

Not only is there an increase of air pressure to produce the increase in the aspiration of the fortis-lenis scale, but the increase is quite regularly gradual, producing a rather precise arithmetic progression on the graph. To be sure, this progression reflects precisely the increase in acoustic aspiration demonstrated in the previous section and illustrated in the various spectrograms in the appendix.

Indeed, the time-frame of activity is constant throughout the scale, indicating that the volume producing the gradual scale is in fact the only significant variable. In each case, the orifice of the larynx expands beginning at approximately 150msec before the consonantal release and then contracts to a point of minimum dispersion at approximately 20msec before the consonantal release.

4.4 The Degree of Consonantality

Both the acoustic and the physiological evidence thus provide us with the phonetic justification of the fortis-lenis scale that serves as the foundation of the Welsh mutation system. Moreover, it also reveals the very nature of consonantality as opposed to vocality. Here, a rather insightful observation of Antoine Meillet should be taken into consideration:

> Certain principles of change are universal; for example, one will not be surprised to see the tendency to reduce the finals, to see intervocalic consonants undergo the influence of neighboring vowels and thus be made like them by becoming voiced or by losing a part of their closure.[10]

This observation can be compared with the following tenet from Paul Mermelstein's articulatory model for the study of speech production upon which the dynamic model developed in chapter 2 is based:

> Consonants are not defined directly in terms of variable values but by constraints on articulator position relative to the fixed structures. Articulators independent of the specific constraints are free to take on positions independent of the consonant under production subject to the requirement that they do not otherwise constrict the vocal tract.[11]

Taking these two observations together, we can arrive at a definition for consonantality itself. Both observations, in quite different ways, recognize that the consonant is not an independent entity in and of itself, but rather a constraint on the vowel. **The greater the degree of constraint within a given phonological system, the greater the degree of consonantality**.

Thus, fortis constraints or obstructions can be seen to be more consonant-like and less vowel-like, while lenis constraints or obstructions can be seen to be more vowel-like and less consonant-like. Since the fortis constraint is marked by a relatively greater degree of high-to-low frequency energy emission, and since this energy is the defining characteristic of fortis aspiration, then we can further define consonantality by aspiration: The greater the relative amount of fortis aspiration, the greater is the degree of constraint and the more consonant-like is the obstruction *in an aspirate fortis-lenis system*.

While not every language patterns along the lines of an aspirate fortis-lenis system, Welsh certainly does. Moreover, it is this system that provides the very phonetic foundation of the Welsh mutation system.

Notes to Chapter 5

1. As opposed, for example, to the Old Irish mutation system which rests upon physiological phonetics. For a contrast of the two systems, see Toby D. Griffen "Acoustic *versus* Physiological Lenition: The Revised Motor Theory in Action," *LACUS Forum* 25 (1999), 119-26.

2. As for the status of the word-final liquid, there is much debate over how consonantal the liquids are. Certainly, their concentration of energy in the lower frequencies is not at all problematic and can be handled through the simple process of abstraction introduced in the previous chapter. On the acoustic characteristics of the liquid, see especially Kenneth N. Stevens, "Articulatory-Acoustic-Auditory Relationships," in: *The Handbook of Phonetic Sciences*, ed. by William J. Hardcastle and John Laver, 462-506 (Oxford: Blackwell, 1997), pp. 488-89.

3. See, for example, Peter Strevens, "Spectra of Fricative Noise in Human Speech," *Language and Speech* 3 (1960), 32-49 [Rpt. In: *Readings in Acoustic Phonetics*, ed. By Ilse Lehiste, 202-19 (Cambridge, MA: Mit Press, 1967)]. Cps stands for cycles per second (also known as Hertz) and is simply the measurement of frequency. For further discussion of acoustic measurements, see such textbooks as Keith Johnson, *Acoustic and Auditory Phonetics* (Oxford: Blackwell, 1997).

4. Indeed, this noise may mask the locus itself, possibly contributing to the widespread confusion between such "sounds" as [f] and [θ] – see, George A. Miller and Patricia E. Nicely, "An Analysis of Perceptual Confusions Among Some English Consonants," *Journal of the Acoustical Society of America* 27 (1955), 338-52, p. 347 [Rpt in: *Readings in Acoustic Phonetics*, ed. by Ilse Lehiste, 338-52 (Cambridge, MA: MIT Press, 1967), p. 310].

5. Thus, if we wish to observe the loud (dark) distributions more clearly, we could produce a "lighter" spectrogram (by enhancing black, subduing white, and/or increasing contrast). So long as the adjustment is made to the entire spectrogram, our observations would not be affected, only facilitated. Of course, such relativity is also quite important in phonology – see, for example, Roman Jakobson and Linda Waugh, *The Sound Shape of Language* (Bloomington: Indiana University Press, 1979), pp. 13-18.

6. Of course, for those languages that do not make use of such a scale, the spectra are in essence the same. The issue here is one of pertinence – whether or not the language under study utilizes this relationship in the functioning of the phonological system. Once again, compare Trubetzkoy, *Principles of Phonology*, and Jakobson, *The Selected Works of Roman Jakobson*, for issues of phonological pertinence.

7. Joseph S. Perkell, *Physiology of Speech Production: Results and Implications of a Quantitative Cineradiographic Study* (Cambridge, MA: MIT Press, 1969). The pertinent examination of the orifice of the larynx is found on pages 65 and 66.

8. For background information on cineradiography, see especially Sven E.G. Öhman, and Kenneth N. Stevens, "Cineradiographic Studies of Speech: Procedures and Objectives," *Journal of the Acoustical Society of America* 35 (1963), 1889; John M. Heinz and Kenneth N. Stevens, "On the Derivation of Area Functions and Acoustic Spectra from Cineradiographic Film," *Journal of the Acoustical Society of America* 36 (1964), 1037-38; Jana Óndročkavá, *The Physiological Activity of the Speech Organs* (The Hague: Mouton, 1973).

9. Note that the feature delimiting the position of obstruction is merely coarticulated. That the [t^h] is a dental and the [s] a sibilant has no bearing on the relative intensity of the aspirate prosody that is produced. Again, we must always be on guard against segmental thinking.

10. Antoine Meillet, *General Characteristics of the Germanic Languages*. Trans. by W.P. Dismukes. Coral Gables, University of Miami Press, 1970. P. 11.

11. Mermelstein, "Articulatory Model for the Study of Speech Production," p. 1082.