OPEN QUOTIENT AND SKEWNESS OF THE LARYNGOGRAPH WAVEFORM AS MEASURES OF PHONATION TYPES AND LARYNGEAL ARTICULATIONS IN WA[1]

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1 Introduction and objectives

This paper is a road-test of two methods, one established and one new, of assessing the relationship between the laryngograph (electroglottograph, EGG) waveform and phonation types and glottal consonants in the Wa language. The work is a pilot study carried out in the preliminary stages of a larger-scale research project into the pronunciation of Wa.

The new method of measuring the laryngograph waveform proposed here provides a means of quantifying phonation type for descriptive purposes, allowing vowels and laryngeal consonants to be treated identically. This study is a sneak preview of work in progress examining the phonetics of phonologically contrastive phonation types in Wa. Relatively few studies have been undertaken which make use of the laryngograph for linguistic phonetic purposes (e.g. Lindsey et al. 1992). It is hoped that this work may add to the growing repertoire of descriptive techniques available to the phonetician, given the current broad interest in the phonology, history and nature of tones and phonation types in Asian languages. For example, this work could serve as an alternative or complement to inverse filtering techniques or acoustic methods of investigating the linguistic use of phonation types.

2 The Wa languages

Wa belongs to the Palaungic branch of Northern Mon-Khmer (Diffloth 1980). Wa speakers number roughly one million, and are located in an area which Gérard Diffloth has described as the Waic corridor (Diffloth 1980:5), between the Salween and Mekong rivers in the Shan States of Burma and China's Yunnan province.

3 Register in Mon-Khmer

Mon-Khmer register is a binary phonological contrast which is associated with a variety of phonetic phenomena, among them pitch-based tone, as in Kammu (Svantesson 1983) and Blang (Zhou and Yan 1983); phonation type, as in Wa (Zhou and Yan 1984, Maddieson and Ladefoged 1985, Theraphan 1988, Svantesson 1993) and Mon (Theraphan 1987:161; 1990:12), or some combination of these features. Eugénie Henderson (1952:151), who was first to use the term register to refer to Mon-Khmer languages, describes the registers of Cambodian in terms of voice quality, pitch and larynx height.

A connection between Mon-Khmer register and tongue-root position was asserted by Kenneth Gregerson (1973). Register is described in terms of two contrasting 'laryngeal attitudes' by Jim Matisoff (1973:76), which he calls 'tense-larynx syndrome' and 'lax-larynx syndrome', which involve the tongue root and supra-glottal cavity as well as the larynx. But the articulatory domain of the Mon-Khmer register contrast is primarily, if not exclusively, the larynx.

4 Phonation types and laryngeal articulations in Wa

The phonological inventory of Wa speech sounds includes the following laryngeally articulated possibilities:

1) a four-way contrast in initial stop consonants

i)	unvoiced unaspirated	/p/
ii)	prenasalised voiced unaspirated	/^{m}b/
iii)	unvoiced aspirated	/p^h/
iv)	prenasalised voiced aspirated	/^{m}b^h/

2) the binary registral phonation type contrast

i)	'creaky' phonation	/a̰/
ii)	breathy phonation	/a̤/

3) syllable final consonants

i)	none (open syllable)	/ /
ii)	glottal stop /ʔ/	/ʔ/
iii)	glottal fricative /h/	/h/

The term 'creaky' is applied to Wa with some hesitation, since for many speakers, including the one used in this study, the phonation type of this register may be more accurately labelled as tense, pressed or even modal. The term 'creaky' is used throughout the paper nonetheless.

The following set of syllables illustrates the size of the phonological burden borne by the larynx in Wa. Keeping constant the supralaryngeal articulatory sequence of bilabial plosive initial consonant plus open unrounded /a/ vowel, and changing only laryngeal activity though each syllable, the matrix of eighteen syllables shown Table 1 is generated. The registral contrast is not found in syllables beginning with aspirated consonants, after which vowel phonation is creaky.

pa̰	pa̤	^{n}ba̰	^{n}ba̤	p^{h}a̰	^{n}b^{h}a̰
pa̰h	pa̤h	^{n}ba̰h	^{n}ba̤h	p^{h}a̰h	^{n}b^{h}a̰h
pa̰ʔ	pa̤ʔ	^{n}ba̰ʔ	^{n}ba̤ʔ	p^{h}a̰ʔ	^{n}b^{h}a̰ʔ

Table 1: Eighteen possible Wa syllables, the phonological heterogeneity of which is preserved by laryngeal articulations alone.

For reasons of project size management, the effect on phonation type of initial consonant voicing contrasts is left outside the scope of this paper, which concentrates instead on the phonation type characteristics of the Wa vowel registers and laryngeal consonants.

5 A phonation type continuum

Despite some involved descriptive systems which have been developed to account for the complex agility of the vibrating larynx (see, for example, Catford 1964; Laver 1980:93-140), for descriptive purposes in a South East Asian linguistic context it is generally only necessary to define a three-way classification of phonation: creaky, modal and breathy (Theraphan 1988:321). In such an analysis, only two of these three categories are required to describe Wa vowels: creaky and breathy. Ladefoged points out that in Wa the difference between the phonation types is not as extreme as in other languages whose contrastive use of phonation type has been investigated experimentally, such as Jalapa Mazatec and !Xóõ (Ladefoged et al. 1988:314).

The Wa consonant inventory makes use of phonological oppositions which are laryngeally articulated: initial stop consonant voicing contrasts and final glottal consonants. In Wa, the glottal stop, which term properly describes the cessation of vocal fold vibration, is in fact realised as a short period (typically about 50ms) of true, aperiodic creaky phonation. In utterance-final position, vocal fold vibration may slow to an indistinct stop. The Wa glottal fricative is realised as a period of breathy phonation of similar length.

Breathy phonation in Wa is associated with breathy vowel register and with glottal fricative consonants, while relatively creakier phonation is associated with the creaky vowel register and glottal stops. The acoustic similarity in Wa of breathy phonation to glottal fricatives and of creaky phonation to glottal stops becomes apparent if spectral profiles are compared. The relative amplitudes of the first and second harmonics (H1, H2) have been shown to be an index of phonation type in Wa (Svantesson 1993:103) and in other languages which make phonologically contrastive use of phonation types (Ladefoged et al. 1988). The following illustrations derived from syllables in the corpus of recordings used for this study make this point clear:

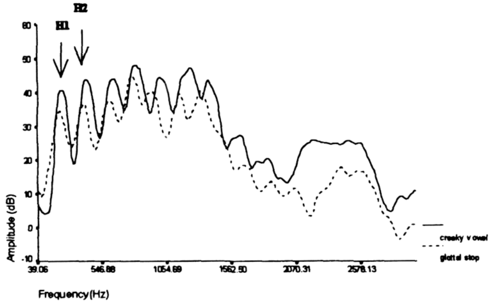

Figure 1 Overlaid spectral profiles (40 Hz b/w, 256-point, 20KHz sample rate, up to 3KHz shown) of Wa syllable-final creaky /a̰/ and of syllable final /ʔ/, realised phonetically as [a̰].

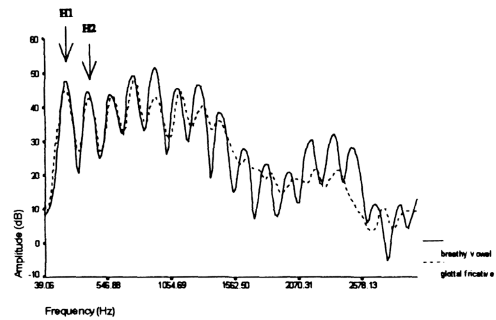

Figure 2 Overlaid spectral profiles (40 Hz b/w, 256-point, 20KHz sample rate, up to 3KHz shown) of Wa syllable-final breathy /a̤/ and of syllable final /h/, realised phonetically as [a̤].

Notice in the spectra of a Wa vowel with modal phonation and of a Wa glottal stop shown in Figure 1 that the amplitude of the first peak representing the first harmonic (H1) is higher than the second peak, indicating that the amplitude of H1 is greater than the second harmonic (H2). The reverse is true in Figure 2, which depicts the spectral profiles of a vowel with breathy phonation and of a glottal fricative. The overall formant structure of all four spectra in these illustrations is similar because they are all associated with an /a/ vowel produced by the same speaker.[2]

Potentially conflicting phonation types may be found within a single syllable, and it is with the aim of describing this that this paper explores a hypothetical phonation type 'continuum' which may be invoked to describe the range of phonation types found in Wa, be they associated with vowels or consonants. For instance, breathy vowel /a̤/ and creaky consonant /ʔ/ adjoin one another in the syllable /pa̤ʔ/, while in the syllable /pa̰h/, creaky vowel /a̰/ is followed by breathy consonant /h/.

Creaky and breathy phonation types are placed at opposite ends of the continuum, the extremes of which are not absolutes, since no absolute measure of phonation type is possible, but rather defined by the measurements which emerge from the study. This is a descriptive device conceived for maximum ease of application, exploiting the acoustic and articulatory similarity which pairs glottal stops with creaky phonation and glottal fricatives with breathy phonation in Wa. Such an apparently simplistic treatment of the complex phenomenon of phonation type is justified on two grounds. Firstly, the simplicity of the method mirrors the simplicity of the limited palette of phonological phonation type oppositions in Wa which underlies the phonetic reality. Secondly, the simplicity of this method is an advantage if it is consistently reliable and provides useful information, even though it the precise relationship between the measurement and the physiological reality has not yet been investigated.

6 Data collection information

The data presented in this paper are from recordings made in May 1996 of one male 56-year-old Wa speaker from Anshuai village, Cangyuan county, Yunnan, near the Burmese border. The speech of this village is recognised, understood and spoken as standard by many speakers of other forms of Wa throughout the wider Wa-speaking area. The informant was presented with a list of sentences in the Wa writing system used in China. This script, unlike other muddled Wa scripts in use, is phonologically accurate. In this system, phonation type and final glottal consonants /ʔ/ and /h/ are all indicated consistently. The informant is highly competent in this writing system, having published a number of books and articles in it and being involved in the development of Wa language teaching materials which are used in Cangyuan county and in Wa speaking communities further afield in Burma and Thailand. He was happy to read syllables in this script regardless of whether they occurred as words in the Wa language or not. However, it must be stressed that any conclusions about Wa phonetics drawn in this article are inferred from the speech of this single speaker.

The word list prepared contained all eighteen of the syllables mentioned in section 4 above, placed in the frame sentence (1):

(1) ʔeʔ ʔah lɔk ... nan (Wa)
we call like ... that way.
'We say ... like that.'

Simultaneous digital audio and laryngograph recordings were made onto stereo digital audio tape in a quiet office in Cangyuan. The informant read the list twice at a similar tempo during a single recording session, which thus yielded a set of 36 tokens. The following equipment was used: Sony TCD-D7 Digital Audio Tape-corder, Sony ECM-717 Electret Condenser Microphone, Laryngograph Ltd Field-model Fourcin-type laryngograph. The recordings were analysed using the PCLx Laryngograph Analyser (version 2.00) software package.

7 The laryngograph and it uses

The Fourcin laryngograph (Abberton et al. 1989) is a simple and portable device which allows non-intrusive investigation of movement within the larynx. Two electrodes are placed externally on the neck on either side of the thyroid cartilage as near as possible to the position of the vocal folds within. The resistance to the current passed between the electrodes changes as the vocal folds and other parts within the larynx vibrate or move. The changing resistance to the current which passes between the electrodes may be plotted graphically - the resulting image is known as the *laryngograph waveform*[3] or *Lx*. The resistance to the current decreases as the surface area contact between the vocal folds increases, in a relationship which has been shown to be inversely proportional by studies such as the gruesome experiment carried out by Scherer et al. (1988, and references), which tell us that the amplitude of the laryngograph waveform is very closely correlated to the area of vocal fold contact.

The laryngograph waveform gives a clear indication of the periodicity or aperiodicity of vocal fold vibration. If the waveform is periodic, one period T of the waveform is inversely proportional to the frequency f of the vocal fold vibration it depicts. This relationship enables the fundamental frequency F_0 to be calculated more easily and reliably than from a speech pressure waveform, as illustrated in Figure 3.

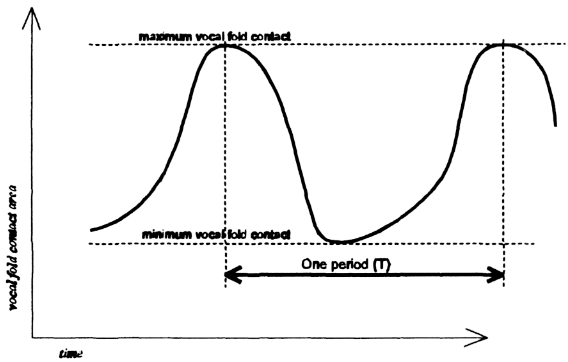

Figure 3 Laryngograph waveform showing period of vocal fold vibration (T). The frequency f of the vibration is calculated as $f = (1/T)$.

The information about phonation type, which is the concern of this paper, is encrypted in the shape of the laryngograph waveform. A visual impression of how the waveform shape can vary is given by the four laryngograph waveforms of this Wa speaker's voice, shown in Figures 4 and 5.

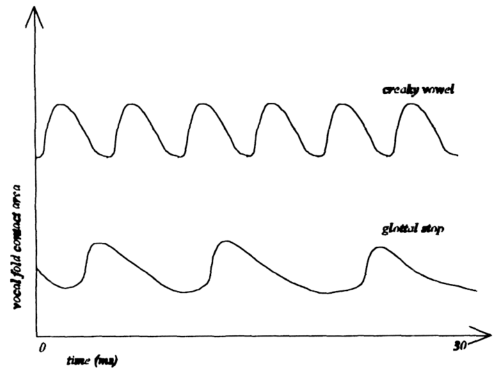

Figure 4 Laryngograph waveform shapes of 'creaky' phonation type and glottal stop (realised phonetically as [a̰]) from the Wa syllable /pa̰ʔ/.

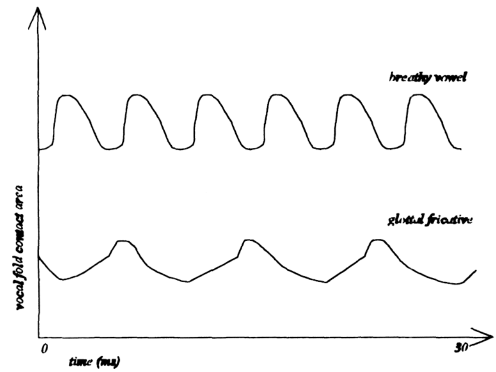

Figure 5 Laryngograph waveform shapes of breathy voice and glottal fricative from the Wa syllable /pa̤h/

8 Closed quotient (CQ)

8.1 Calculating laryngographically derived closed quotient

Closed quotient is one measurement which has been used in the fields of speech pathology (Abberton et al. 1989) and other vocal research (Howard 1995), but seldom in a linguistic context (see, however, Lindsey et al. 1992). Closed quotient is defined as the percentage of the waveform period *T* for which the glottis is closed. This raises the further question of how to define when the glottis is closed, and when open. One of the mathematically most simple and most common is to divide the overall amplitude of the Lx waveform in a fixed ratio[4]. The method outlined here is the method which the Laryngograph Analyser software package uses, in which the ratio is 7:3. So the upper 70% of overall peak-to-trough amplitude is defined as the closed phase and the lower 30% is the open phase. This ratio, like the parameters involved in any of the methods for measuring CQ, is arbitrary, but has been found convenient and reliable in previous studies using the Fourcin laryngograph (Davies et al. 1986). The closed phase CQ is calculated as a percentage of the waveform period. Figure 6 illustrates the what this calculation means in terms of laryngograph waveform shape:

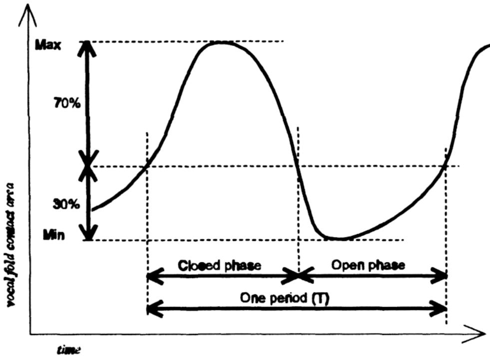

Figure 6 Illustration of closed quotient measurement. Closed quotient (CQ) is calculated as CQ = closed phase / T.

In two-dimensional graphic terms, the closed quotient is a measure of the relative pointedness and/or breadth of the waveform peak and troughs. The closed phase, and therefore also the closed quotient, is greater when the peaks are broader relative to the troughs; it is less when the troughs are broader or fuller relative to the peaks. We can expect the Lx waveforms of speaker's creaky and breathy vowels (in the upper halves of Figures 4 and 5 above) to display a difference in CQ even from a hasty visual comparison of the two shapes. Looking at the shapes of the Lx waveforms of his glottal stop and glottal fricative (in the lower halves of Figures 4 and 5 above), it is easy to see why both of them yield similar closed quotient measurements, since both are relatively far more broad-troughed.

Abberton et al. (1989) and Howard (1995) examine what the CQ measurement can tell us about the phonation represented by the laryngograph waveforms from which it is derived. Assessing the relationship between what can be measured on paper (or by a computer) and the physiological reality of movement in the larynx is beyond the scope of the present paper.

8.2 Measurements of closed quotient in Wa

The recordings were stored onto the lab computer's hard disk and the Laryngograph software was used to calculate closed quotient from the laryngograph traces at two points in each of the 36 tokens, the first half-way through the vowel and the second at syllable end, defined as the last cycle of vocal fold vibration for which the computer could derive F_0 and CQ form the laryngograph trace. Figures relevant to observations made below are in bold type. The closed quotient measurements from all 36 syllables (see Table 1) included in this study are summarised below in Table 2. Fundamental frequency measurements from the same syllables are set out in Table 3 for comparison.

Table 2: Closed quotient

	mid-vowel		change to syllable-end		
	creaky[5]	breathy	creaky	breathy	**both registers**
open syllable	56.28 (3.30)	48.33 (6.55)	-1.25 (1.89)	+4.23 (3.96)	**+0.58 (3.72)**
/ʔ/ final	58.65 (1.48)	57.72 (2.54)	-20.02 (8.36)	-18.35 (5.84)	**-19.47 (7.38)**
/h/ final	59.04 (2.09)	51.2 (3.91)	-24.91 (3.92)	-18.25 (4.86)	**-22.69 (5.19)**
all finals	**57.99 (2.62)**	**52.42 (5.87)**			

Table 3: Fundamental frequency

	mid-vowel		change to syllable-end		
	creaky	breathy	creaky	breathy	**both registers**
open syllable	182.91 (11.92)	165.15 (6.94)	-6.43 (5.79)	-3.20 (3.88)	**-5.35 (5.29)**
/ʔ/ final	187.16 (8.07)	176.05 (12.37)	-95.53 (17.79)	-92.88 (20.23)	**-94.64 (17.74)**
/h/ final	198.19 (7.00)	182.25 (4.44)	-72.64 (17.25)	-62.15 (9.79)	**-69.14 (15.5)**
all finals	**189.42 (11.01)**	**174.48 (10.71)**			

Tables 2 and 3 Mean (with s.d. in parentheses) measurements of closed quotient (CQ in %) and fundamental frequency (F_0 in Hz) made at a point half-way through the vowel are shown on the left of the table, categorised by vowel phonation type.

The right-hand part of the table shows the difference between measurements of CQ and F_0 at mid-vowel and syllable end, this time categorised by syllable final consonant (or lack of).

Two observations were made from the closed quotient measurements. Firstly, as might have been expected from applying the closed quotient calculation illustrated in Figure 6 to the laryngograph waveform shape of a creaky vowel shown in Figure 4, closed quotient is significantly (p=.008) greater in creaky Wa vowels than in breathy, irrespective of syllable final. In Figure 7, closed quotient can be seen to be increasing through the open breathy vowel. A greater difference in closed quotient would have been recorded had the comparison been made nearer the beginning of the vowel rather than at the mid-point. This pattern was observed only for open breathy vowels and not for those with laryngeal consonant finals.

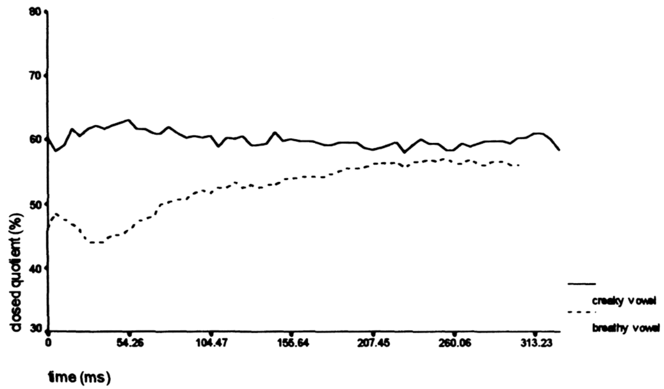

Figure 7 Comparison of closed quotient in Wa vowel /a/ with creaky and breathy phonation types. Taken from syllables /pa̰/ and /pa̤/

The second observation is more surprising. Given the similarity between Wa creaky phonation and glottal stops and between breathy phonation and glottal fricatives demonstrated in the laryngograph waveforms in Figures 4 and 5, it might have been predicted that the closed quotient of glottal stops and glottal fricatives might diverge yet further than do the mean closed quotient measurements of creaky and breathy vowels. In fact, the reverse is true: syllable final glottal stop /ʔ/ and glottal fricative /h/ are both characterised by a fall of around 20% in closed quotient, the slight difference between the mean fall being statistically insignificant. The similarity is illustrated in Figure 8.

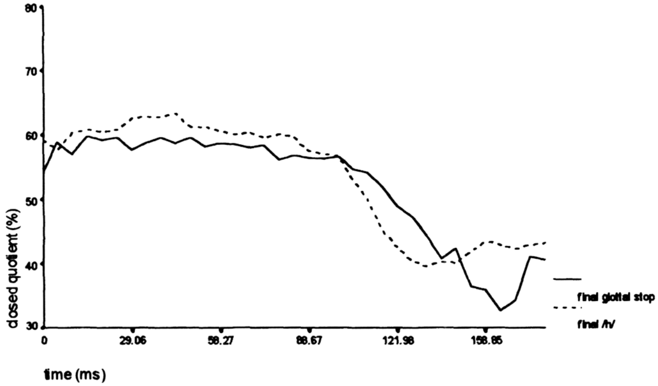

Figure 8 Comparison of closed quotient in Wa glottal stop and glottal fricative, following creaky /a̰/ vowel. Taken from syllables /pa̰ʔ/ and /pa̰h/.

9 Skewness

9.1 Calculating Skewness

The new measurement involves assessing the symmetry of the laryngograph waveform by expressing the peak-to-trough time as a proportion of the waveform period. Note that this does not involve the use of any model-dependent set ratio or other parameter. The derivation of the skewness measurement from a hypothetical laryngograph waveform is illustrated in Figure 10.

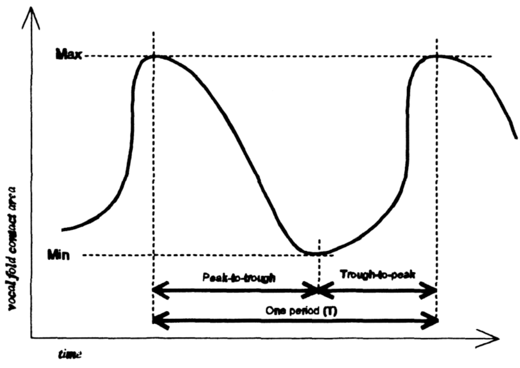

Figure 9 Illustration of skewness measurement. Leftward skewness is calculated as (peak-to-trough / one period) x 100%.

It is important to note that reference here is made not to open and closed phases but to the skewness of the wave as a whole, the simplest way of measuring which is by comparing the portions of the waveform period for which vocal fold area contact is decreasing from the maximum to the minimum (peak-to-trough) and increasing from the minimum to the maximum (trough-to-peak) respectively. No reference is made to the rate of amplitude change at difference stages of the waveform cycle other than pinpointing the peak and the trough, nor is it claimed that the peak or the trough correspond to significant points or phases during the cycle of vocal fold vibration.

Skewness is a measure of the waveform's degree of symmetry. Leftward skewness is measured here as the peak to trough time as a percentage of the waveform period. For a symmetrical waveform, when the closing and opening phases are equal, the skewness as measured here is 50%. Leftward rather than rightward skewness is chosen so that the creakier the phonation, the higher the numbers returned by the skewness measurement technique used here. The choice of leftward skewness over rightward is a matter of convenience only. What is significant is how skewness can help us describe the laryngograph data.

Attempts have been made to interpret the symmetry of the laryngograph waveform and the glottal pulse it represents. (Ní Chasaide and Gobl 1997:440, Titze 1990:7). Laryngograph waveforms are typically skewed to the left to some degree, though the skewness can be relatively more leftward or rightward. A more symmetrical glottal pulse, which boosts the lower harmonics, is a hallmark of breathy phonation (Ní Chasaide and Gobl 1997:440) and is observable in the spectra (Figs 1 and 2) and laryngograph waveforms (Figs 4 and 5) derived from these Wa recordings. Conversely, creakier phonation is associated with an Lx waveform shape skewed to the left.

Care has to be taken in interpreting the skewing of the laryngograph waveform, since skewing is indicative both of qualitative differences in phonation type and of the intensity of laryngeal excitation. (Ní Chasaide and Gobl 1997:441). However, for the purposes of this descriptive study, confusion or failure to distinguish between these two causes of skewness is likely to enhance, rather than blur the results, since creaky voice generally involves a sharper laryngeal pulse than breathy (Ladefoged 1988:301).

By comparing the waveforms in Figures 4 and 5 in this light, skewness emerges as an obvious way of quantifying the difference between the laryngograph waveform shapes of glottal stops and fricatives.

9.2 Measurements of Skewness in Wa

Leftward skewness was calculated at the same points in each of the syllables as closed quotient was in the section above. The figures are set out in Table 4 below.

Table 4: Leftward Skewness

	mid-vowel		change to syllable-end		
	creaky	breathy	creaky	breathy	**both registers**
open syllable	65.27 (4.42)	58.6 (4.65)	+0.56 (4.57)	+3.57 (2.31)	**+1.49 (4.13)**
/ʔ/ final	66.06 (4.87)	59.33 (0.77)	+3.48 (7.53)	+12.54 (0.66)	**+6.50 (7.49)**
/h/ final	65.56 (4.98)	63.78 (1.56)	-12.97 (3.57)	-13.12 (1.13)	**-13.02 (2.91)**
all finals	**65.63 (4.56)**	**60.57 (3.53)**			

Table 4 Mean (with s.d. in parentheses) measurements of the Leftward Skewness (in %) made at a point half-way through the vowel are shown in the left-hand part of the table. The right-hand part of the table shows the change by the end of the syllable.

Notice that, like the closed quotient measurement, the mean leftward skewness is 65.63% at the midpoint of creaky vowels and 60.57% in breathy vowels: the two are significantly (p=0.01) different by 5.06%, though the percentage difference is not of the order of the 15.04% difference observed between the closed quotients of creaky and breathy vowels recorded in Table 2. Miraculously, though, the mean change in leftward skewness between mid-syllable and syllable end is different for each type of syllable final included in the study. Leftward skewness increases slightly, but not significantly, in open syllables. A barely significant (p=0.55) mean rise is observed during a glottal stop /ʔ/ if the phonation type of the preceding vowel is not taken into account. The mean rise of 12.54% is rise is highly significant (p=0.003) for glottal stops following breathy vowels only. Leftward skewness is dramatically (p=0.000) less, by an average of 13.02% during the articulation of a glottal fricative syllable final /h/.

In terms of the Wa phonation type continuum proposed in Section 5 above, a high degree of leftward skewness denotes a position towards the creaky end; less leftward skewness indicates a position nearer the breathy end.

10 Implications and directions for further research

Closed quotient is sensitive to the differences in shape between the upper and lower regions of the plane on which the laryngograph waveform is plotted, while skewness takes into account symmetry in the left-to-right dimension of the same plane. In these Wa measurements there is a trade-off between the enhanced differentiation of creaky and breathy voice possible with closed quotient and the focus of the skewness measurement on the difference between glottal stop and glottal fricative. The two measurements offer complementary perspectives of the laryngograph waveform. The work that has been done relating closed quotient to the physiological activity within the larynx makes it an attractive tool. The practical usefulness of the skewness measurement for these Wa data is intriguing, however. Speculating momentarily, it seems likely that a measurement of laryngograph waveform skewness should be linked to the relative speed with which the vocal folds open and close during phonation, and perhaps also about the muscular activity and aerodynamic conditions in the glottis which would occasion such a difference. Closed quotient is based on the premise that the folds close more quickly than they open and defines instead open and closed phases, even though the vocal folds are in constant motion during phonation and the line dividing these phases has to be imposed artificially.

If the phonation type continuum model is tenable and there is a reliable experimental procedure which can assign speech sounds a position on it, then it should be possible to make some statement about the precise articulatory events within the larynx when sounds with conflicting phonation type characteristics come into contact with one another. This in turn might lead to new insights into the coarticulation of phonation types and laryngeal sounds.

Measuring skewness of the laryngograph waveform has proved undeniably useful for describing these Wa data. It remains to be applied to phonation type phenomena in other languages.

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Notes

1. Partial support for this research was provided by grants from the Scholarships Committee of the School of Oriental and African Studies and the Humanities Research Board of the British Academy.

2. There is a connection between vowel quality (in terms of formant frequencies) and registral phonation type in Wa (Wang and Chen 1981:50), as in many Mon-Khmer languages. This, and a suspected relationship between phonation type and spectral profile at higher frequencies, are the topics of work in progress.

3. In some studies, typically those which call the device an electroglottograph (EGG), the resistance to the current instead of the current itself is plotted. The resulting waveform is vertically flipped but otherwise identical to the waveforms shown in this paper.

4. A number of other methods of measuring the *open* and *closed phases* of the waveform are described in Howard 1995:164.

5. The registral phonation type contrast is neutralised in vowels following aspirated initials. These vowels have creaky phonation type.

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