The Tense-Lax Question and Intraoral Air Pressure in English Stops[*]

Dae-Won Kim[**]

ABSTRACT

Measurements were made of pressure rise time (PoRT), voice cessation time, flattened peak intraoral air pressure (Po), pressure static time (PoST), pressure-fall time and the duration of oral closure as four English speakers uttered isolated nonsense V_1CV_2 words containing /b/ and /p/ ($V_1 = V_2$ and the V was /ɑ/), with stress on either V_1 or V_2 alternately. The hypothesis tested was: The tense stop consonant will be characterized either by a higher Po or a longer PoST, and/or by both against lax. Findings: (1) PoRT was significantly greater in /b/ than /p/, (2) the voiceless stop /p/ produced generally greater mean Po, averaged across five tokens, than its voiced counterpart /b/, but statistically insignificant, and (3) altogether, across stress, tokens and subjects, the difference in the calculated pressure static time (PoSTc), i.e., PoST + PoRT, between /p/ and /b/ was highly significant ($p \leq 0.003$). Although further investigations remain to be taken, the results strongly supported the linguistic hypothesis of tense-lax distinction, with /b/ being lax and /p/ tense. Airflow resistance at the glottis and supraglottal air volume are assumed to be responsible for much of difference in PoRT between /p/ and /b/. The PoSTc reflecting, although indirectly, the respiratory efforts during the oral closure of a stop, was a convincing phonetic parameter of the consonantal tenseness based on respiratory efforts. The effects of stress on Po and PoSTc were inconsistent, and the shorter PoRT than consonantal constriction interval was always accompanied by Po and PoST.

Keywords: Tense-Lax, Intraoral Air Pressure, English Stop

---

[*] This work was supported by Korea Research Foundation Grant (KRF-2001-041-A00249) and was presented at 17th International Congress on Acoustics (Sep 2-7, 2001), University of Rome, Italy and at 1st International Conference on Speech Sciences (May 10-11, 2002), Korea University, Korea.

[**] Department of English Language Education, Pusan National University

1. Introduction

The feature 'tensity' is a familiar concept in phonetics although the phonetic parameters of consonantal tenseness are not easily found. The consonants the study is concerned with are stops. In this study, the feature tensity is defined as the amount of muscle action (or energy) used in the articulation of a phoneme, and the phonetic correlates of the feature tensity are considered to be time or amplitude and/or both. Most of the previous electromyographic studies, associated with labial closure gestures, reveal that there have been generally insignificant or unstable EMG data for a phonemic distinction based on muscular efforts in English (e.g., Lubker and Paris, 1970; Malecot, 1966; Fromkin, 1966; Sussman, et. al., 1973; Harris, et. al., 1965; Tatham, et. al., 1985). Lubker and Paris (1970, p.626), for example, stated that "the variability in the EMG data is an inherent characteristic of the data". Kim (1995), however, reported that in Korean the duration of muscle action and the peak EMG amplitude exerted by the orbicularis oris superior muscle were valid measures for the tense-lax opposition.

In a study of time and pressure characteristics of stop consonants in relationship to glottal activity, Warren and Hall (1973) have concluded that the difference in intra-oral air pressure among voiced-voiceless cognate pairs results from an intra-oral air volume difference and that voicing is responsible for much of the difference in pressures. In other words, differences in intra-oral air pressure among cognate pairs are attributed mainly to differences in the vocal fold activity and supra-glottal air volume, but not in respiratory efforts. This claim is supported by the findings (Netsell, 1969) showing insignificant differences in subglottal air pressure between the cognate pairs (for similar results, see also McGlone and Shipp, 1972, p.665; for data in Swedish, see Lofqvist, 1975). However, Warren and Wood (1969) reported that respiratory volumes are consistently larger for voiceless sounds and proposed that respiratory effort and intraoral volume are important factors which may influence consonantal pressures. The increase of supra-glottal air volume during the phonologically voiced stops is caused by various factors, such as an active pharyngeal expansion due to the depression of the hyoid bone (Kent and Moll, 1969; Perkell, 1969), lowering larynx, raising the soft palate, advancing the tongue root, drawing the tongue dorsum and blade down toward the mouth floor (Westbury, 1983), and a passive expansion of the supra-glottal cavity due to the compliance of the walls (e.g., Stevens, 1998, p. 328; Catford, 1977; Svirsky, et al., 1997).

On the basis of the lack of convincing phonetic data for consonantal tense-lax distinction, it has been claimed that although there are languages (e.g., Korean) for which a precisely defined parameter of consonantal tenseness may be postulated, English is not one of them and that we are entitled to describe the difference between English /b, d, g/ and /p, t, k/ in terms of voicing (e.g. Catford, 1977; Lisker and Abramson, 1964; Fromkin, 1966; Lubker and Parris, 1970): the former being actually or potentially voiced – that is, always involving some degree of glottal constriction not present in /p, t, k/ (Catford, 1977, p.204).

However, the usability of the feature [voice] as a phonetic cue for the phonologically voiced stop is almost negative both in production (for intervocalic stops, see Kim, 1989; for utterance-initial, intervocalic and final stops, see Flege and Brown, 1982) and in perception (Port, 1979; Lisker, 1957). In a study (Kim, 1989) with British English speakers using bisyllabic /'CVC̲VC/ words (i.e., 'mobbing', 'heeding', etc.) in pairs of natural sentences where the C̲ was a lax (i.e., phonologically voiced) stop, the feature [voice] was observed to be one of potential phonetic parameters of a lax stop. The period of vocal fold vibration as percentage of the oral closure interval of a lax stop ranged from 9% to 100%, giving a mean 64% (± 31.085). The amount of variability (± 31.08) in voicing suggests that the feature [voice] is not very helpful in distinguishing [p,t,k] from [b,d,g] in English (Kim, 1989, p. 242). The amount of variability in voicing was 3.3 times greater than the case with VOT for word-initial bilabial stops of Korean in which aspiration is one of phonological parameters.

As long as airflow out of the glottis continues during the oral closure of a stop, there will be a certain amount of airflow resistance at the glottis, and the airflow resistance will delay pressure rise time (i.e., the pressure rising interval from the moment of oral closure to the onset of static pressure on the pressure signal in Figure 1). All else being equal, the amount of the airflow resistance at the glottis may vary with the state of the glottis of a stop. It has been claimed that much of differences in intra-oral air pressure among cognate pairs are attributed mainly to differences in airflow resistance at the glottis (e.g. Warren and Hall, 1973; Malecot, 1955; Arkebauer et al., 1967; Isshiki and Ringel, 1964; Lubker and Parris, 1970; Kohler, 1984).

Once intra-oral air pressure levels out during the consonantal constriction, no airflow will occur, and then plateau will necessarily take place if the pressure rise time is shorter than the duration of oral closure. The flattened peak intraoral air pressure (i.e., distance Hs on the pressure signals in Figure 1 corresponding to comparatively flattened peak intra-oral air pressure) will occur when the pressure rise time is the same as or shorter than the duration of oral closure. The flattened peak intraoral air pressure is an output of the equalization of air pressure between supraglottal and subglottal cavities. The equalization of pressures below and above the glottis ceases airflow out of the glottis. The cessation of airflow brings about no airflow resistance at the glottis. Thus, the flattened peak intraoral air pressure must be independent of airflow resistance, and it would reflect the peak amplitude of subglottal pressure generated by the respiratory efforts during the oral closure of a stop. Thus, pressure static time (i.e, distance Ds in Figure 1 corresponding to static interval from the onset of plateau to the moment of rapid fall in pressure) would reflect, although indirectly, the amount of energy generated by the respiratory muscle activities during the period of static pressure. If the pressure static time is long, the respiratory activity must necessarily be long, and vice versa. All else being equal, the longer the duration of the respiratory activity, the greater the amount of energy used and vice versa. The greater the flattened peak intraoral air pressure, the greater the peak respiratory gesture, and the less the flattened peak intraoral air pressure, the less the peak respiratory gesture. Thus, the flattened peak intraoral air pressure and the pressure static time could be precisely defined phonetic parameters of consonantal tenseness if they present significant differences between the so-called voiced and voiceless stop consonants.

However, one may argue that much of the difference in the pressure static time between /p/ and /b/ was causative of differences in the pressure rise time determined mainly by the size of supraglottal cavity and the airflow resistance. This means that there remain further investigations into pressure characteristics of stop consonants for a convincing phonetic parameter of consonantal tenseness. Glottal function can not explain differences among the cognate pairs in the flattened peak intraoral air pressure and the pressure static time, and it is required to undertake an investigation to study pressure characteristics of stop consonants in relation to timing variables, such as the pressure rise time, the pressure static time, the duration of oral closure, voice cessation time and pressure fall time (i.e., pressure fall interval from the moment of rapid fall in pressure to the release of oral closure) during the consonantal constriction. This study was designed to determine (1) whether or not the flattened peak intraoral air pressure and the duration of flattened peak intraoral air pressure are reliable phonetic cues for the tense-lax distinction and to see (2) how the timing variables depend on each other.

The hypothesis tested was as follows:

Hypothesis (1): The tense stop consonant will be characterized either by a higher flattened peak intra-oral air pressure or a longer pressure static time and/or by both against lax.

As mentioned above, the feature tensity is defined as the amount of muscle action (or energy) used in the articulation of a phoneme, and the phonetic correlates of the feature tensity are considered to be time or amplitude and/or both. According to this conception, the tense stop should be characterized either by a longer respiratory activity (i.e., a longer pressure static time) or by a greater peak respiratory gesture (i.e., a greater flattened peak intra-oral air pressure), and/or by both against lax.

2. Method

2.1 Instrumentation

For sensing intra-oral air pressure, a 17 cm long catheter of approximately 2 mm internal diameter was connected to the transducer and inserted into the mouth. As the pressure varies in the mouth so the pressure of air in the catheter changes. This pressure variation is transmitted along the catheter to the manophone (F-J electronics A/S Holt Denmark) outside the mouth, the frequency range of which is 0 – 1 KHz ± 3dB. The derived electrical signals are fed to channel one of the seven-track tape recorder for a permanent record. A reference oral microphone signal, a larynx microphone (F-J electronics A/S Holt Denmark) trace, and a laryngograph (manufactured by Phonetics Laboratory, University College London) trace were recorded on channel two, three and four, respectively, of the same tape recorder, set to direct mode, with a frequency response of 45 Hz to 20 KHz ± 3dB. The oscilloscope was used to monitor the devices, such as the Manophone and laryngograph, to ensure there were good signals of pressure and the vocal fold vibration. The signals of the electro manophone, the oral microphone, the larynx microphone and the laryngograph then were recorded simulatneously on the Siemens Oscillomink Mingograf running at 100 mm/s with a frequency response of 0 to 700 Hz ± 3dB and paper speed accurate to within 5%.

2.2 Speech items and subjects

A set of isolated nonsense V_1CV_2 (where $V_1 = V_2$) words were constructed where the consonants were bilabial stops /p, b/ and the vowel was /ɑ/. The VCV items were produced with stress on either V_1 or V_2 alternately at the rate of normal or moderately slow speech. Thus, stress was one of the controlled experimental conditions to determine the effects of stress on the intraoral pressure. Four British English subjects, male college students, pronounced each item five times using the set-up described just above. All subjects were from England, and none of them had reported speaking problems.

2.3 Measurement

Measurements were made of five timing variables and one amplitude variable (i.e., distance Hs on the pressure signals in Figure 1 corresponding to comparatively flattened peak intra-oral air pressure). The flattened peak intra-oral air pressure is an output of the equalization of air pressure between supraglottal and subglottal cavities, and it reflects the peak amplitude of subglottal air pressure generated by the respiratory muscle activities. The timing variables are as follows: (1) voice cessation time (VCT), i.e., voicing interval from line C in Figure 1 indicating the onset of oral closure to line a in the Figure showing the offset of the vocal fold vibration on laryngogram during the oral closure phase of a stop, (2) pressure rise time (PoRT), i.e., the pressure rising interval from the moment of oral closure to the onset of static pressure on the pressure signal in Figure 1, (3) pressure static time (PoST), i.e, distance Ds in Figure 1 corresponding to static interval from the onset of plateau to the moment of rapid fall in pressure during the oral closure phase of a stop, (4) pressure fall time (PoFT), i.e., pressure fall interval from the moment of rapid fall in pressure to the release of oral closure, and (5) the duration of oral closure (DOC). For the timing variables, two vertical reference lines (C) and (R) were constructed on the mingogram. The line (C) corresponding to the onset of oral closure was constructed on the basis of the air pressure signal and the audio signal trace, and the line (R) corresponding to the release of oral closure was made on the basis of the intensity trace of the larynx microphone (see Figure 1).

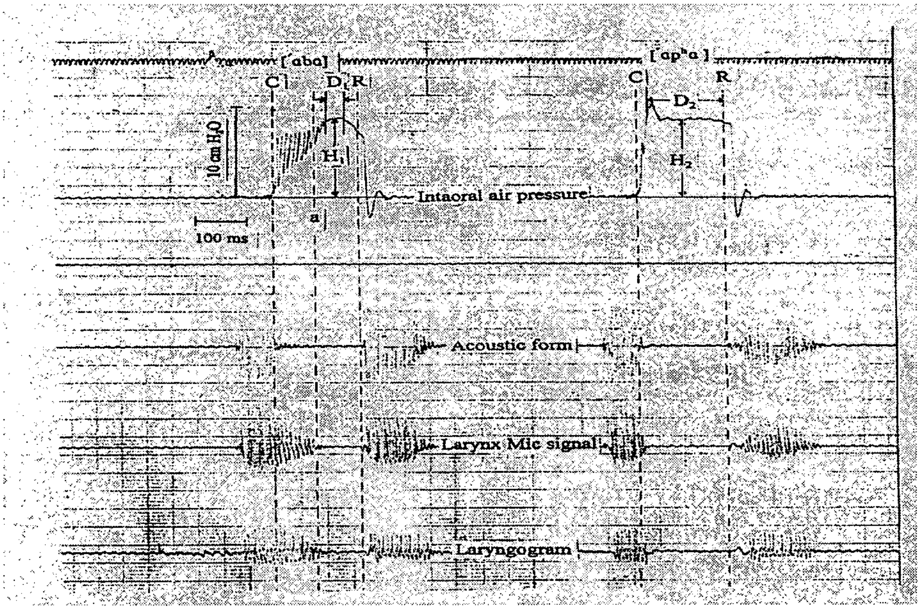

Figure 1. Mingograf print-outs of the isolated BrEng VCV words showing pressure rise time (PoRT), pressure static time (PoST), i.e., distance Ds, flattened peak intraoral air

pressure (Po), i.e., distance Hs, acoustic signals, larynx microphone signals, and laryngograms (where the line C and R indicate the onset/offset of the oral closure, respectively, and the line (a) the cessation of the vocal fold vibration on laryngograms.)

The onset of the intraoral air pressure rise indicating the onset of oral closure coincides always with the onset of the lowered amplitude of regular pulsing (i.e., the offset of the preceding vowel) on the audio signal trace (See Figure 1). The bursts of traces of the audio microphone and the larynx microphone always coincide, and they both indicate the onset of the release of oral closure. The duration of oral closure was measured from the line (C) to the line (R), and the voice cessation time was measured from the line (C) to the offset of the vocal fold vibration on the signal from the laryngograph. The pressure rise time (PoRT), i.e., the pressure rise interval, was measured from the line (C) to the onset of the (comparatively) flattened peak intra-oral air pressure (Po). The pressure static time (i.e., distance Ds on the mingograms as seen in Figure 1) was measured manually from the onset of flattened peak intraoral air pressure to the point where it starts to fall (case 1) or to the point where the burst of signal takes place on the audio microphone trace (case 2). Case 1 is usually for /b/ and case 2 for /p/. During the bilabial stop consonant /p/, the delay between the lip opening (i.e., the burst signal on the acoustic trace) and pressure drop varied from simultaneity to 15 ms. Pressure fall time (PoFT), falling interval of pressure from the beginning of pressure fall to the release of oral closure, was obtained by subtracting the pressure rise time and the pressure static time from the duration of consonantal constriction.

The flattened peak intraoral air pressure (Po) (i.e., distance Hs on the mingograms) was measured at a point approximating the mean value as seen in Figure 1, in disregard of the 'overshoot' at the onset of plateau and little ripples, having constructed a zero base line on the signal from the Manophone. Air pressure values were expressed in cmH_2O. A pulse on the abrupt rise in Po at the start of a voiceless stop is caused by the vocal fold vibration signaled on the laryngogram (see Fig. 1), and the 'overshoot' at the onset of plateau might have been caused by the inertia of the respiratory muscle activities (Ohala, 1990, p. 23). Air pressure falls below zero often after the release of stops. Inertia of pressure fall may be responsible for this. It can be presumed that the pressure is falling so rapidly after the release that it actually overshoots the zero baseline and momentarily goes negative. The air in the catheter is a part of the system, and so may distort the pressure recorded from the pressure in the oral cavity. Despite the limitations of small overshoots and undershoots, useful measurements could be made of relative timing variables and the amplitude variable, i.e., the flattened peak intraoral air pressure. However, aerodynamic simulations using a low-frequency model and a twomass model (McGowin, Koenig and Lofqvist, 1995) may be helpful to avoid the problem of distortion although a further refinement simulation model is needed.

2.4 Data analysis

A descriptive statistics was performed on SPSS for each dependent variable for each subject. Then, a series of paired-t-test were performed to determine if there is a significant difference between /b/ and /p/ in each dependent variable. And Pearson correlation coefficients were estimated to see the relationship between variables (voice cessation time : pressure rise time, flattened peak intraoral air pressure : static pressure time, etc.).

3. Results and Discussion

Table 1. Means, averaged across five tokens, and standard deviations of voice cessation time (VCT) in ms, pressure rise time (PoRT) in ms, flattened peak intraoral air pressure (Po) in cmH2O, pressure static time (PoST) in ms, the duration of oral closure (DOC) in ms during intervocalic bilabial stops of English and the calculated pressure static time (PoSTc) (=PoRT + PoST) (where − VCT indicates that voicing ceased prior to the onset of oral closure, S_1, S_2, etc. subject and ALL indicates across five tokens and four subjects).

Subjects Items Variables		S_1		S_2		S_3		S_4		ALL	
		$\bar{X}$	SD	$\bar{X}$	SD	$\bar{X}$	SD	$\bar{X}$	SD	$\bar{X}$	SD
´aba	VCT	8.6	3.2	31.0	5.5	33.7	18.9	65.2	20.6	34.6	23.2
	PoRT	26.0	2.9	50.0	0.0	53.7	12.5	90.0	12.7	54.9	26.4
	Po	6.3	0.6	11.4	0.7	8.1	1.2	8.5	0.2	8.5	2.1
	PoST	66.0	11.4	52.0	4.5	27.5	5.0	40.0	10.0	46.3	16.4
	PoSTc	92.0	12.9	102.0	4.4	81.2	8..5	130.0	15.5	101.3	20.9
	DOC	124.0	8.9	124.6	7.8	127.5	6.4	148.0	17.9	131.0	11.4
´apa	VCT	−3.6	4.9	4.1	3.7	2.4	4.2	10.0	3.5	3.2	5.6
	PoRT	17.6	2.5	25.0	3.5	20.4	0.9	18.0	2.7	20.3	3.3
	Po	7.0	0.7	11.9	0.7	7.2	0.7	9.8	1.3	8.9	2.2
	PoST	96.8	8.4	129.4	13.0	115.0	11.2	142.0	12.0	120.8	19.4
	PoSTc	114.4	7.1	154.0	16.4	135.4	12.2	160.0	12.2	140.9	20.5
	DOC	114.4	7.1	154.0	16.6	135.4	12.2	160.0	12.2	140.9	20.5
abá	VCT	9.6	1.7	31.2	5.0	35.2	9.3	32.0	8.36	27.0	11.7
	PoRT	39.0	4.2	59.0	8.2	62.6	9.8	66.4	13.2	56.7	12.2
	Po	5.7	0.5	10.9	1.2	8.2	0.8	9.6	0.5	8.6	2.3
	PoST	36.0	9.6	65.0	7.1	36.0	13.9	67.0	13.9	51.0	17.3
	PoSTc	75.0	10.6	124.0	10.8	98.6	5.8	133.4	26.5	107.8	26.3
	DOC	106.0	9.6	139.0	8.2	117.0	17.5	170.0	7.9	133.0	28.2
apá	VCT	1.6	2.3	4.2	5.3	15.0	5.0	2.2	4.4	5.7	6.3
	PoRT	20.8	1.1	24.0	4.2	28.4	6.5	18.0	2.7	22.8	4.5
	Po	5.9	0.2	12.1	0.6	9.9	0.2	9.7	0.4	9.4	2.6
	PoST	90.0	8.7	123.0	10.4	114.4	7.0	160.0	17.7	121.9	29.0
	PoSTc	110.8	7.4	147.0	8.4	142.8	4.9	178.0	10.6	144.7	27.5
	DOC	110.8	7.4	147.0	8.4	142.8	4.9	178.0	10.6	144.7	27.5

Table 2. The results of paired t-test between /p/ and /b/ in voice cessation time (VCT), Pressure rise time (PoRT), flattened peak intraoral air pressure (Po), pressure static time (PoST), the duration of oral closure (DOC) during intervocalic bilabial stops of English and the calculated pressure static time (PoSTc = PoST + PoRT) (where S_1 S_2, etc. indicate subject and ALL indicates across five tokens and four subjects.

		´ɑCɑ /bːp/					ɑĆɑ /bːp/				
		PoRT	Po	Post	Postc	DOC	PoRT	Po	Post	Postc	DOC
S_1	t	4.070	−3.87	−2.79	−2.79	2.514	8.73	−1.63	−14.6	−12.1	−3.20
	Sign	.015	.018	.018	.049	.056	.001	.178	.000	.000	.033
S_2	t	15.81	−1.49	12.57	−8.20	−4.93	8.36	−2.27	17.9	−3.91	−1.71
	Sign	.000	.173	.000	.000	.001	.001	.053	.000	.004	.124
S_3	t	5.400	.403	−13.4	−24.5	−2.51	6.49	−9.55	−20.5	−15.2	−3.21
	Sign	.012	.714	.000	.000	.087	.000	.001	.000	.000	.032
S_4	t	13.71	−3.87	−11.9	−2.45	−2.22	10.1	−2.07	−18.9	−6.88	−2.09
	Sign	.000	.012	.000	.070	.077	.000	.093	.000	.001	.091
ALL	t	2.604	−.859	−4.83	−4.99	−1.24	5.49	−2.03	−7.77	−7.29	−2.44
	Sign	.042	.453	.017	.015	.303	.012	.135	.004	.005	.093

Table 3. Pearson correlation coefficients between variables (VCT : PoRT, Po : PoST and Po : PoSTc) during bilabial stops in isolated VCV words produced by four adult BrEng speakers.

Subjects		S_1		S_2		S_3		S_4	
Stops		/b/	/p/	/b/	/p/	/b/	/p/	/b/	/p/
□ɑCɑ	vct:PoRT	.748	.336	.604	.606	.878	−.250	.878	.612
ɑĆɑ	vct:PoRT	.643	.040	.876	.786	.565	.317	.988	.660
□ɑCɑ	Po:PoST	.402	.088	.075	.145	.456	.907	.208	.164
	Po:PoSTc	.491	.018	.393	.674	.181	.891	1.00	.710
ɑĆɑ	Po:PoST	.553	.518	.075	.147	.302	.060	.170	.097
	Po:PoSTc	.330	.590	.761	.512	.187	.613	.712	.431

3.1 Pressure rise time (PoRT)

Across four subjects, stress and tokens, PoRT was observed to be a significant ($p \leq 0.039$) discrimination between /p/ and /b/ although there were remarkable between-speaker differences (for statistic results of each speaker, see Table 1, Table 2 and Figure 2). The mean ratios of the PoRT for /b/ to /p/ were 1.7 (32 ms) : 1 (19 ms) for S1, 2.2 (55 ms) : 1 (25 ms) for S2, 2.4 (58 ms) : 1 (24 ms) for S3, and 4.3 (78 ms) : 1 (18 ms) for S4. Altogether the mean ratio of the PoRT between /b/ and /p/ was 2.6 (55.7 ms ± 18.8) : 1 (21.5 ms ± 3.5). The PoRT of the stop /b/ was composed of the voiced and voiceless periods. The overall mean ratios for voiced period to voiceless one was 1 : 1.6 in unstressed position and 1 : 2.1 in stressed position (see Table 1). As seen in figure 1, the rate of pressure rise increases when voicing ceases, and then plateau occurs, followed by rapid fall in pressure. Each subject showed devoiced periods prior to the onset of plateau during the articulation of /b/ (for a similar result, see Warren and Hall, 1973, Fig. 3, p. 124). However, the speed of pressure rise during the devoiced period of /b/ involving some degree of glottal constriction was about two times less than the speed of pressure rise in /p/ involving glottal openness. All else being equal, the amount of the airflow resistance at the glottis may vary with the state of the glottis of a stop. The glottal vibration in the stop /b/ with the narrow or closed glottis would increase the airflow resistance, which in turn decreases the amount of airflow out of the glottis. The reduced airflow delays the onset of plateau on the pressure signal. Thus, voicing and the narrow or closed glottis for /b/ are responsible for much of the difference in PoRT among the cognate pairs, and the PoRT cannot be one of the reliable phonetic parameters for the feature tensity based on the respiratory muscle efforts. The PoRT in the stop /b/ was positively related with the voicing interval, i.e., voice cessation time (VCT), irrespective of subjects and stress placement (see Table 3). On the other hand, the VCT during the articulation of the stop /p/ ranged from –3.6 ms (where – indicates prior to the onset of oral closure) to 15 ms, and the relationship between PoRT and VCT in the stop /p/ was not only insignificant but also inconsistent (Table 3).

3.2 Flattened peak intraoral air pressure (Po)

As seen in Table 1 and 2, the voiceless stop /p/ produced generally greater Po (mean 9.1 cmH_2O) than its voiced counterpart /b/ (mean 8.5 cmH_2O), but this was statistically insignificant across speakers. Although it is not directly comparable with the findings in the existing literature due to various factors, including the conceptual ambiguity of peak intraoral air pressure, differences in subject and speech materials, etc., the results disagreed with the previous findings (e.g., Lubker and Parris, 1970; Arkebauer, et al., 1967; Malecot, 1968; Lofqvist, 1976; Stathopoulos, 1986) in which the peak intraoral air pressure provided significant discrimination between /p/ and /b/, irrespective of consonantal position and vocalic stress. It also has been claimed that voicing is responsible for much of differences in the peak intraoral air pressure among the cognate pairs (e.g. Warren and Hall, 1973; Malecot, 1955; Arkebauer et al., 1967; Isshiki and Ringel, 1964; Lubker and Parris, 1970; Kohler, 1984). If this is the case, the term 'peak intraoral air pressure' cannot be identical with the flattened peak intraoral air pressure. The peak oral pressure, measured at a point on the pressure rise where airflow out of the glottis continues, should be under the influence of the airflow resistance at the glottis. However, the flattened peak intraoral air pressure is independent of the airflow resistance. The peak oral pressure under the influence of airflow resistance cannot reflect the peak amplitude of subglottal air pressure during the oral closure of a stop, and therefore cannot be a precisely defined phonetic parameter of consonantal tenseness.

Table 1 and 2 show that the effects of stop types and stress on Po were inconsistent, owing to the between-speaker variabilities. S_1 produced a significant discrimination in Po between /p/ and /b/ in unstressed position, but not in stressed position. S_2 and S_3 presented opposite results to the case with S_1. S_4 yielded insignificant difference in Po between the two types of bilabial stops. Because of the statistically insignificant results, Po alone was insufficient to support the linguistic hypothesis of tense-lax distinction, although the Po in /p/ was generally greater than in /b/.

3.3 Pressure static time (PoST)

Across tokens, stress and subjects, the PoST presented a highly significant discrimination ($p \leq 0.009$) between /p/ and /b/ (for statistic results of each speaker, see Table 1, Table 2 and Figure 2). The mean ratio of PoST, averaged across tokens and subjects, between the cognate pairs was 2.6 (/p/) : 1 (/b/) in unstressed position and 2.4 (/p/) : 1 (/b/) in stressed position. If the PoST reflects, although indirectly, relative amount of energy generated by respiratory muscle activities during the pressure static time, the PoST obtained and the insignificant difference in the flattened peak intraoral air pressure among the voiced-voiceless cognates may suggest that the hypothesis that the tense stop consonant will be characterized either by a higher flattened peak intraoral air pressure or a longer pressure static time, and/or by both against lax has been verified, and the results supported the linguistic hypothesis of tense-lax distinction. As mentioned in the introduction, however, one may argue that much of the difference in PoST between /p/ and /b/ was causative of differences in pressure rise time attributed to the expanded supraglottal cavity and the airflow resistance in /b/. Detailed discussion of this will follow on in the general discussion section. The correlation of flattened peak intraoral air pressure with PoST and the effects of stress on PoST were generally inconsistent, owing to inter-speaker variabilities (see Table 1 and 3).

3.4 Pressure fall time (PoFT)

The mean PoFT as percentage of the duration of oral closure, averaged across tokens and subjects, was 21.9% (28.7 ms) for /b/ in unstressed position and 19.5% (25.9 ms) in stressed position, while the stop /p/ was produced with no PoFT in both stressed and unstressed positions (see Figure 2). In general, the flattened peak pressure in /p/ began to fall either at release or after the release. This pressure fall was highly variable between subjects.

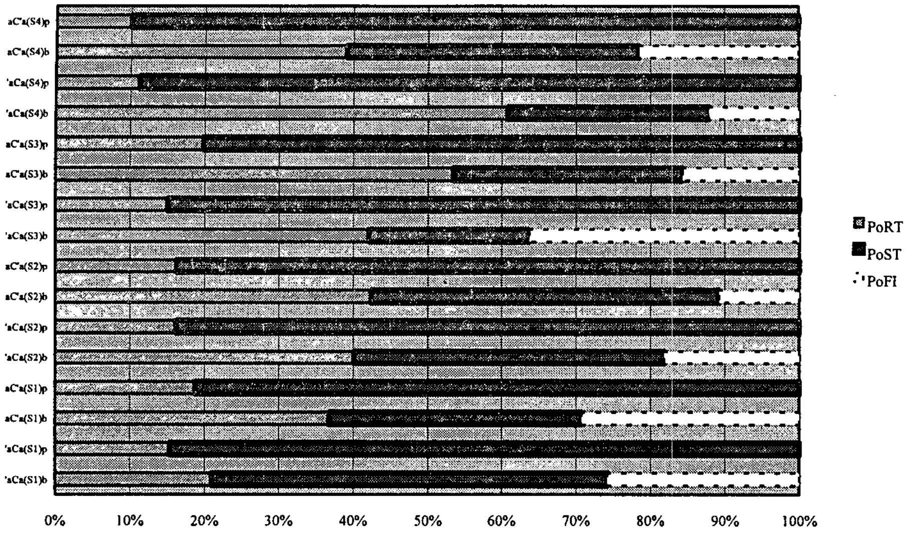

Figure 2. Mean pressure rise time (PoRT), pressure static time (PoST), and pressure fall time (PoFT) during the consonantal constriction, averaged across five tokens, as percentage of the duration of oral closure as four BrEng speakers uttered isolated aCa words containing /b/ and /p/ (S1, S2, S3 and S4 indicate subjects).

One of 4 subjects yielded pressure fall at release for most of the items (7 out of 10). But others showed pressure fall after release. The delay between the lip opening for the release of the /p/ and pressure drop ranged from 0 to 15 ms. This was in agreement with the existing findings that "the delay between lip opening and pressure drop varied from simultaneity to 15 ms" (Shipp, 1973, p.169). Aspiration is an important acoustic cue to distinguish /p/ from /b/ in intervocalic position. Thus, the pressure fall lag and the glottal openness at release are required to produce an acoustic cue with a puff of air, aspiration, for /p/. Phonologically /b/ involving some degree of glottal constriction is unaspirated, and the /b/ is not expected to produce aspiration at release, but voicing for vowels following /b/. Probably, this is why the speaker began to make the pressure fall an average of 27 ms prior to the release. High pressure, i.e., flattened peak oral pressure (mean 8.5 cm H_2O), would not necessarily be required to produce voicing for vowels following /b/. The vocal folds will continue oscillating as long as the pressure drop across them is greater than 2.039 cm H2O (i.e., 2,000 dyn/cm^2) if they are suitably configured (Ladefoged, 1964; Catford, 1977, p.29; Westbury and Keating, 1986, p.149; Westbury, 1983, p.1325).

3.5 The duration of oral closure (DOC)

As seen in Figure 2, the DOC of the intervocalic stop was always longer than pressure rise time, irrespective of speakers and stress placement (see also Table 1). The DOC was an average 2.3 times longer than pressure rise time in /b/ and 5.6 times longer in /p/. The pressure rise time may be determined largely by supraglottal air volume, airflow resistance at the glottis and respiratory efforts rather than the duration of oral closure. Table 2 shows that the statistical results of DOC among the cognate pairs were not only insignificant but also inconsistent due to inter−speaker differences. The DOC did not determine the distinction between the cognate pairs in intervocalic position although DOC was one of conditions for flattened peak intraoral air pressure and the pressure static time. It is well known, however, that phonologically voiceless word−final stops in such words as 'bat' and 'back' are longer than their voiced counterparts of 'bad' and 'bag', and that the vowel in the latter pair is longer than in the former (e.g. Catford, 1977, p.201; for production and perception, see Malecot, 1970, p. 1589). The vowel is shortened when the consonant is lengthened.

4. General Discussion

As seen in Figure 2, the significant difference in the pressure static time among the cognate pairs was attributed to differences in pressure rise time and pressure fall time during consonantal constriction. The pressure rise time for /p/ was remarkably shorter than that for /b/. The mean ratio of pressure rise time, averaged across tokens, subjects and stress, between the cognate pairs was 2.6. The mean pressure fall time during consonantal constriction in /b/ was 20.7 % (27.3 ms) of the duration of oral closure, while /p/ was produced with no pressure fall time during consonantal constriction. The vocal folds will continue oscillating as long as the pressure drop across them is greater than 2.039 cm H2O (i.e., 2,000 dyn/cm^2) if they are suitably configured (Ladefoged, 1964; Catford, 1977, p.29; Westbury and Keating, 1986, p.149; Westbury, 1983, p.1325). Thus, high oral pressure in /b/, i.e., flattened peak intraoral air pressure (overall mean 8.5 cmH_2O), is not necessarily required for the production of voicing for vowels following /b/. Probably, this is why Po in /b/ started to fall rapidly within mean 27.3 ms (20.7 % of the duration of oral closure) of release. In the production of /p/, on the other hand, the delay between lip opening and pressure drop ranged from 0 to 15 ms (for similar results, see Shipp, 1973, p. 169). For /p/ glottal openness and pressure drop lag are required to produce an acoustic cue with a puff of air, i.e., aspiration. In general, the aspiration is one of the principal acoustic cue to distinguish /p/ from /b/ of English, except for the word-final stops.

All else being equal, much of the difference in pressure rise time among the cognate pairs might have been caused by some combination of differences in (1) the supraglottal cavity, (2) the airflow resistance at the glottis, (3) subglottal pressure generated by respiratory muscle activities, (4) the duration of oral closure. Considering, however, the insignificant difference between /b/ and /p/ in flattened peak intraoral air pressure reflecting subglottal pressure and the duration of oral closure, it can be postulated that much of the difference in the pressure rise time between /b/ and /p/ can be attributed largely to differences in supraglottal air volume and the airflow resistance and that much of the difference in the pressure static time was causative of the difference between /b/ and /p/ in pressure rise time. Overall mean pressure rise time was observed to be 55.8 ms in /b/ and 21.5 ms in /p/. Thus, it can be assumed that the expanded supraglottal air volume and airflow resistance delayed the onset of flattened peak intraoral air pressure by an overall mean 55.8 ms in /b/ (see PoRT, Table 1), which in turn reduced the pressure static time up to a mean 55.8 ms. In /p/, the onset of the flattened peak intraoral air pressure was delayed for a mean 21.5 ms

The flattened peak intraoral air pressure is a result of the equalization of air pressure between the subglottal and supraglottal cavities, and the flattened peak intraoral air pressure would reflect the peak amplitude of subglottal air pressure generated by respiratory muscle activities during the consonantal constriction. Accordingly, the pressure static time would reflect, although indirectly, the amount of energy generated by the respiratory muscle activities during the pressure static time. Netsell (1969) found insignificant differences in subglottal air pressure between the voiced-voiceless cognate pairs of English during the oral closure phase of stop consonants, regardless of the point of measurement (at oral closure and release) (for similar results, see McGlone and Shipp, 1972, p.665; for data in Swedish, see Lofqvist, 1975). This means that the pressures below the glottis are of essentially the same magnitude during production of voiced-voiceless cognates and that the most obvious cause for lower intraoral air pressure for /b and /d/ is due mainly to greater airflow resistance at the glottis during /b/ and /d/ phonation. If so, during the oral closure phase of the voiced stops, intraoral air pressure would continue to increase throughout the stops. The stops, of which the duration of oral closure is the same as or shorter than the pressure rise time, would produce intraoral air pressure continuing to increase throughout the stops. The intraoral air pressure continuing to increase throughout the stops must be under the influence of the airflow resistance.

As seen in figure 1, however, the stop phase of /b/ showed a substantial period of flattened peak intraoral air pressure and pressure fall mean 27 ms prior to the release. This result disagrees with the previous findings. It could be assumed that the air pressure fall prior to the release of /b/ reflects the fall of subglottal air pressure although the possibility has not ruled out that the pressure fall for /b/ may be a result of supraglottal air volume expansion during the consonantal constriction. The same magnitude of subglottal air pressure as in /p/ would not be required to produce vowels following /b/. Considering the assumption that the air pressure fall prior to the release of /b/ may reflect the fall of subglottal air pressure during the stop constriction and the existing claims that the pressures below the glottis among the voiced–voiceless stops are of essentially the same magnitude and that the airflow resistance is responsible for much of difference between /b/ and /p/ in pressure rise time, one can add the pressure rise time to the pressure static time for reliable differences among the cognate pairs in the pressure static time reflecting, although indirectly, the relative amount of energy generated by the respiratory muscle activities during the oral closure of a stop.

Across five tokens and four subjects, the difference among the cognate pairs in the calculated pressure static time (PoSTc), i.e., the pressure rise time + the measured pressure static time, was significant ($p \leq 0.015$ in unstressed position and $p \leq 0.005$ in stressed position (see Table 2). Considering the results and the fact that Po in /p/ was generally greater than that in /b/, although statistically insignificant, it can be said with confidence at the level of 1.5 % that the hypothesis that the tense stop consonant will be characterized either by a higher flattened peak intraoral air pressure or a longer duration of flattened peak intraoral air pressure, and/or by both against lax has been verified.

Flattened peak oral pressure fall lag in /p/ after the release of oral closure was observed to be a mean 6.8 ms (± 3.829), across tokens, subjects and stresses. The magnitude of pressure during the pressure fall lag, i.e., the interval of pressure from the release of oral closure to the onset of the pressure fall, was of the same as or similar to the flattened peak intraoral air pressure. Taking into account the pressure fall lag in /p/, the level of significance for the difference in drPoc among the cognate pairs will improve. Although further investigations remain to be done, the results strongly supported a linguistic hypothesis of tense–lax distinction, with /p/ being tense and /b/ lax. This is in contrast with the contention of a number of investigators (e.g. Malecot, 1955; Arkebauer et al., 1967; Issheki and Ringel, 1964; Warren and Hall, 1973; Lubker and Parris, 1970; Kohler, 1984) that much of the difference in intra–oral air pressure among cognate pairs are attributed mainly to airflow resistance at the glottis. The apparent discrepancy is due to the fact that the existing claims base their argument on air pressure under the influence of airflow resistance and we base ours largely on differences in the pressure static time, i.e, PoSTc (see Table 1 and 2). The pressure static time (PoSTc) which is independent of airflow resistance appeared to be one of the convincing phonetic correlates of the feature tenseness based on respiratory efforts during the consonantal constriction, although indirect, but the flattened peak intraoral air pressure alone was insufficient to support the linguistic hypothesis of tense-lax distinction. The peak pressure in /b/, measured at a point where air-flow continues, should be under the influence of airflow resistance. The peak oral pressure under the influence of airflow resistance would not reflect the peak amplitude of subglottal pressure. As a result, the peak oral pressure under the influence of airflow resistance cannot be a precisely defined phonetic parameter of consonantal tenseness as claimed in the existing literature.

In general, neither the pressure static time (PoST) nor the calculated pressure static time (PoSTc) was significantly related with the flattened peak intraoral air pressure (Po) (See Table 3). The shorter pressure rise time than the duration of oral closure is always accompanied by the flattened peak intraoral air pressure and the pressure static time. The British English subjects in this study yielded shorter pressure rise time than the duration of oral closure in /b/ and /p/, and no fully voiced /b/s were produced in isolated /VCV/ words where the vowel was /ɑ/.

References

Arkebauer, H. J., T. J. Hixon & J. C. Hardy. 1967. "Peak intraoral air pressures during Speech." *Journal of Speech and Hearing Research*, 10, 196-208.

Catford, J. C. 1977. *Fundamental Problems in Phonetics*. Edinburgh: Edinburgh University Press.

Flege, J. E. & W. S. Brown. 1982. "The voicing contrast between English /p/ and /b/ as a function of stress and position-in-utterance." *Journal of Phonetics*, 10, 335-345.

Fromkin, V. A. 1966. "Neuro-muscular specification of linguistic units." *Language and Speech*, 9(3), 170-199.

Harris, Katherine S., Gloria F. Lysaught & Malcolm M. Schvey. 1965. "Some aspects of the production of oral and nasal labial stops." *Language and Speech*, 8, 135-147.

Isshiki, W. & R. Ringel. 1964. "Air flow during the production of selected consonants." *Journal of Speech and Hearing R*esearch, 7, 233-244.

Kent, R. D. & K. L. Moll. 1969. "Vocal-tact characteristics of the stop cognates." *Journal of Acoustical Society of America*, 46, 1549-1555.

Kim, Dae-Won. 1989. "The relationship between full voicing and the oral closure interval of a lax intervocalic stop." *Journal of Phonetics*, 17, 239–243.

Kim, DaeWon. 1995. "An EMG study of the feature 'tensity' with reference to English and Korean." In *Proceedings of the 15th International Congress on Acoustics* (ed. Mike Newman), Vol III, 77–80. Trondheim, Norway: TAPIR.

Kohler, K. J. 1984. "Phonetic explanation in phonology: the feature fortis/ lenis."*Phonetica*, 41, 150–174.

Ladefoged, P. 1964. "Comment on 'Evaluation of methods of estimating subglottal air Pressure'." *Journal of Speech and Hearing Research*, 7, 291–292.

Lisker, L. 1957. "Closure duration and the intervocalic voiced–voiceless distinction in English." *Language*, 33, 44–49.

Lisker, L. & A. S. Abramson. 1964. "A cross language study of voicing in initial stops: Acoustical measurement." *Word*, 20, 384–442.

Lofqvist, A. 1975. "A study of subglottal pressure during the production of Swedish Stops." *Journal of Phonetics*, 3, 175–189.

Lofqvist, A. 1976. "Oral air pressure in the production of Swedish stops." *Working papers*, Phonetics Laboratory, Lund University, 13, 41–57.

Lubker, J. F. & P. J. Parris. 1970. "Simultaneous measurements of intraoral pressure, force of labial contact, and labial electromyographic activity during production of the stop consonant cognates /p/ and /b/." *Journal of Acoustical Society of America*, 47, No. 2, 625–633.

Malecot, A. 1970. "The lenis–fortis opposition: Its physiological parameters." *Journal of Acoustical Society of America*, 47, 1588–1592.

Malecot, A. 1968. "The force of articulation of American stops and fricatives as a function of position." *Phonetica*, 18, 95–102.

Malecot, A. 1966. "Mechanical Pressure as an Index of 'Force of Ariculation'."*Phonetica* 14, 169–180.

Malecot, A. 1955. "An experimental study of force of articulation." *Studia Ling.*, 9, 35–44.

McGlone, R. E. & T. Shipp. 1972. "Comparison of subglottal air pressures associated with /p/ and /b/." *Journal of Acoustical Society of America*, 51, No. 2 Part (2), 664–665.

McGowin, R. S., L. L. Koenig & A. Lofqvist. 1995. "Vocal tract aerodynamics in /aCa/ utterances: Simulations." *Speech Communication* 16, 67–88.

Netsell, R. 1969. "Subglottal and intraoral air pressures during the intervocalic contrast of /t/ and /d/." *Phonetica*, 20, 68–73.

Ohala, J. J. 1990. "Respiratory activity in speech." In W. J. Hardcastle & A. Marchal (eds.), *Speech Production and Speech Modelling*. Dordrecht: Kluwer. 23–53.

Perkell, J. S. 1969. "Physiology of speech production: results and implications of quantitative cineradiographic study."*Res. Monogr*, No. 53 (MIT Press, Cambridge).

Port, R. F. 1979. "The influence of tempo on the stop closure duration as a cue for voicing and place." *Journal of Phonetics*, 7, 45–56.

Shipp, T. 1973. "Intraoral air pressure and lip occlusion in midvocalic stop consonant production." *Journal of Phonetics*, 1, 167−170.

Stathopoulos, E. T. 1986. "Relationship between intraoral air pressure and vocal intensity in children and adults." *Journal of Speech and Hearing Research*, 29, 71−74.

Stevens, K. N. 1998. *Acoustic Phonetics*. Cambridge, MA: MIT Press.

Sussman, H. M., Peter F. MacNeilage & Robert J. Hanson. 1973. "Labial and mandibular dynamics during the production of bilabial consonants: Preliminary observations." *Journal of Speech and Hearing Research*, 16, 397−420.

Svirsky, M. A., K. N. Stevens, M. L. Matthies, J. Manzella, J. S. Perkell & R.

Wilhelms−Tricarico. 1997. "Tongue surface displacement during obstruent stop Consonants." *Journal of Acoustical Society of America*, 102, 562−571.

Tatham, Marcel A. A., Raymond G. Daniloff & Paul R. Hoffman. 1985. "Electromyographic invariance of lip closure for /p/−/b/." In *Speech Science* (Daniloff, Raymond G. ed.). London: Taylor & Francis, 1985, 336−350.

Warren, D. W. & D. J. Hall. 1973. "Glottal activity and intraoral pressure during stop consonant productions." *Folia Phoniatric: International Journal of Phoniatrics*, Speech Theraphy and Communication Pathology, Gainesville, FL Vol. 25, 121−129.

Warren, D. W. & M. T. Wood. 1969. "Repiratory volumes in normal speech: a possible reason for intraoral pressure differences among voiced and voiceless consonants." *Journal of acoustical Society of America*, 45, 466−469.

Westbury, J. R. 1983. "Enlargement of the supraglottal cavity and its relation to stop consonant voicing." *Journal of acoustical Society of America*, 74 (4), 1322−1336.

Westbury, J. J. & P. A. Keating. 1986. "On the naturalness of stop consonant voicing." *J. Linguistics* 22. 145−166.

Received: October 27, 2002
Accepted: November 30, 2002

▲ Dae−Won Kim
Department of English Language Education, Pusan National University
Changjung−Dong, Gumjong−Gu, Pusan 609−735, Korea.
Tel: +82−51−510−2613
E−mail: dwokim@hyowon.pusan.ac.kr