CHEST WALL MOVEMENTS PRIOR TO PHONATION

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Movements of the chest wall during the interval between an acoustic stimulus and the subject's vocal response were examined and timed in eight normal males. The reaction-time interval was divisible into two phases, a latency period with duration independent on chest wall status at the time of stimulus and an adjustment period during which the rib cage and abdomen usually moved oppositionally to achieve a prephonatory postural set. The time required for this adjustment varied significantly with lung volume, but was independent of the ventilatory phase previously in progress.

The chest wall dynamics underlying phonation and speech have been examined by numerous authors. A significant portion of this research has focused on the roles assumed by specific respiratory muscles during speech production (Stetson, 1951; Draper, Ladefoged and Whitteridge, 1959; Hoshiko, 1960; Hoshiko and Berger, 1965), while other studies have concentrated on the lung volumes or pressures necessary for speech (Draper, Ladefoged, and Whitteridge, 1960; Bunn and Mead, 1971). Investigations into the speech-supportive dynamics of the chest wall have primarily explored thoracoabdominal movements after the initiation of phonation. The papers of Hixon et al (1973, 1976) and Forner and Hixon (1977) are examples of such efforts. The preparatory "set" of the chest wall has been the object of far less attention.

There is a paucity of information concerning chest wall kinematics just before vocal onset. Gutzmann, cited by Luchsinger and Arnold (1965, p. 13) and by Lenneberg (1967, p. 78), identified "physiological asynchronism" of the components of the chest wall at the time of vocal onset. This same observation was made by Wilder (1972) and Wilder and Baken (1974) in infants and by Gould and Okamura (1974) in adults during singing.

Some preliminary investigations of voice-onset reaction time also have been undertaken. Izdebski and Shipp (1977) for example, reported on a study that measured neural, mechanical, and total reaction times using aerodynamic, acoustic, and electromyographic techniques, while Starkweather, Hirschman, and Tannenbaum (1976) have evaluated the reaction times of normal speakers and stutterers.

The chest wall is a complex, two part system with two degrees of freedom of movement (Konno and Mead, 1967), implying a high potential for movement-pattern complexity. With the exception of the results reported in the studies cited above, little information is available concerning chest wall mechanics prior to the initiation of voice. The need exists to examine more closely the way in which the chest wall sets up for phonation and to determine what effect the status of the ventilatory apparatus has upon the preparatory movement patterns and the time required for their achievement.

The purpose of this study, therefore, was (1) to observe the displacement of the chest wall as it prepared for phonation in order to assess patterns of thoracoabdominal displacement at varying lung volumes and respiratory phases, and (2) to obtain measures of the reaction times involved.

METHOD

Subjects

Eight males ranging in age from 20 to 27 years (mean 23.0) served as research subjects. All presented negative histories with respect to pathology of respiratory and vocal tract structures with the exception of EM, who had sustained multiple rib fractures several years earlier. None of the subjects had special training in speech or voice. Subject characteristics are summarized in Table 1.

TABLE 1. Subject characteristics.

Subject	*Age (yrs)*	*Height (cm)*	*Weight (kg)*	*Vital Capacity (liters)*	*Tidal Volume (liters*	*Minute Volume (liters)*
JC	22	184.5	73.5	5.8	0.37	7.9
TC	25	176.0	68.0	4.8	0.44	8.1
JE	22	191.0	83.0	5.2	0.27	4.9
MJG	21	166.5	70.3	3.9	0.39	7.6
MSG	21	170.0	54.9	4.0	0.42	8.0
EM	27	187.0	78.5	5.5	0.46	8.9
EN	20	179.0	72.6	4.4	0.47	10.1
MS	26	182.0	90.7	5.2	0.55	12.2

Instrumentation

The instrumentation array used in this experiment is diagrammed in Figure 1. Rib cage and abdominal movements were tracked using Whitney gauges as described by Baken and Matz (1973). The subject's vocal response was monitored with a contact microphone positioned just lateral to the thyroid ala. A special feedback system was provided to help the subject maintain constant vocal intensity. The amplified microphone sig-

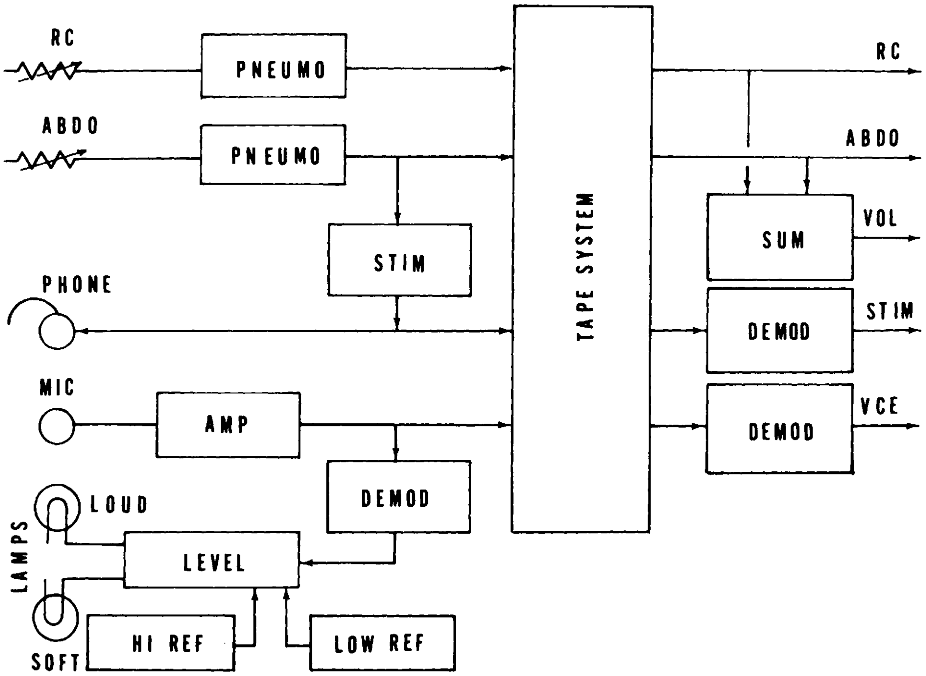

FIGURE 1. Block diagram of the experimental instrumentation.

nal was fed to a level discriminator which compared it to two reference voltages. When the voice signal exceeded the higher reference, a light in front of the subject labeled "loud" went on. Conversely, when the signal amplitude dropped below the lower reference a "soft" lamp was lit. The reference levels were adjusted for each subject to permit phonation in a limited range (less than ± 2.5 dB) about a self-selected comfortable loudness.

Stimulus tones of 1 sec duration at 150 Hz were triggered by a circuit that tracked abdominal movements. The circuit could be set to trigger a stimulus during either inspiration or expiration. After being activated by the experimenter the circuit waited until the selected ventilatory phase began and, after an additional delay randomly varied by the experimenter, generated a stimulus tone. The variable time lapse following the triggering of the circuit insured that the stimuli were delivered at different lung volumes rather than simply at the instant the ventilatory phase began.

Stimulus tones and vocal responses were tape recorded, together with rib cage and abdominal hemicircumferential data, on a H-P 3955 tape system. Data were derived from a paper readout prepared on a Narco Biosystems Physiograph-6 pen recorder running at a paper speed of 10 cm/sec. Stimulus-response time was measured from the point of stimulus onset to the point at which the vocal signal produced an observable pen deflection.

Procedure

Subjects were seated in a quiet room and the instrumentation connected. Several minutes of quiet tidal breathing were recorded as the subject breathed via a face mask into a Cardiopulmonary Instruments model 220 spirometer. The spirometric signal later was used to calibrate the lung volume estimate derived from the torso hemicircumferences according to the procedure described by Baken (1977). After the face mask had been removed a second sample of tidal breathing was obtained from which the subject's mean tidal volume and minute volume were later derived. Functional residual capacity (FRC) was determined by finding the mean tidal end-expiratory level. The subject was then asked to produce the vowel /a/ at a comfortable level while the feedback circuitry was adjusted. The significance of the feedback lights was then explained.

Finally, the subject was instructed to say /a/ at a comfortable pitch as quickly as possible whenever he heard a stimulus tone through an earphone fitted to his left ear. He was informed that it would not be possible for him to predict when a tone would be presented, and was reminded that his production of /a/ should be just loud enough to prevent either of the feedback lights from turning on. An opportunity to practice the task was provided and periodic reminders of the need for the fastest possible response were given.

Sixty stimuli were presented to each subject. Thirty were initiated during inspiration and 30 during expiration. The order of stimulus presentation and the number of breaths (from 3 to 6) between presentations were completely randomized for each subject, as was the length of the delay period between stimulus triggering and generation.

For purposes of data analysis, lung volume at the time of stimulus presentation was considered to have been high if its value was more than midcapacity (50% of the mean tidal volume). Lung volumes below midcapacity were considered low.

RESULTS

Response distribution

Measurable responses were elicited for 476 (99%) of the stimuli. Table 2 summarizes the distribution of responses with respect to respiratory system status at the time of stimulus presentation. The skewed distribution of the sample is consistent with the documented asymmetry (Lenneberg, 1967; Peters, 1969; von Euler, 1974) of the tidal breathing cycle.

Pattern of chest wall movement

Figure 2 shows a typical chest-wall response to the audio stimulus. For approximately 250 msec after stimulus onset the ventilatory movement in

TABLE 2. Respiratory status at the time of stimulus presentation.

Respiratory status	*% of responses*
Lung volume	
above midcapacity	40.8
below midcapacity	59.2
Movement	
Static (between ventilatory phases)	13.2
Inspiratory	35.3
Expiratory	51.5

progress (in this case, the transition from inspiration to expiration) continued without noticeable modification. Suddenly, however, the respiratory cycle was broken by what is clearly an adjustment of the chest wall for the phonation to follow.

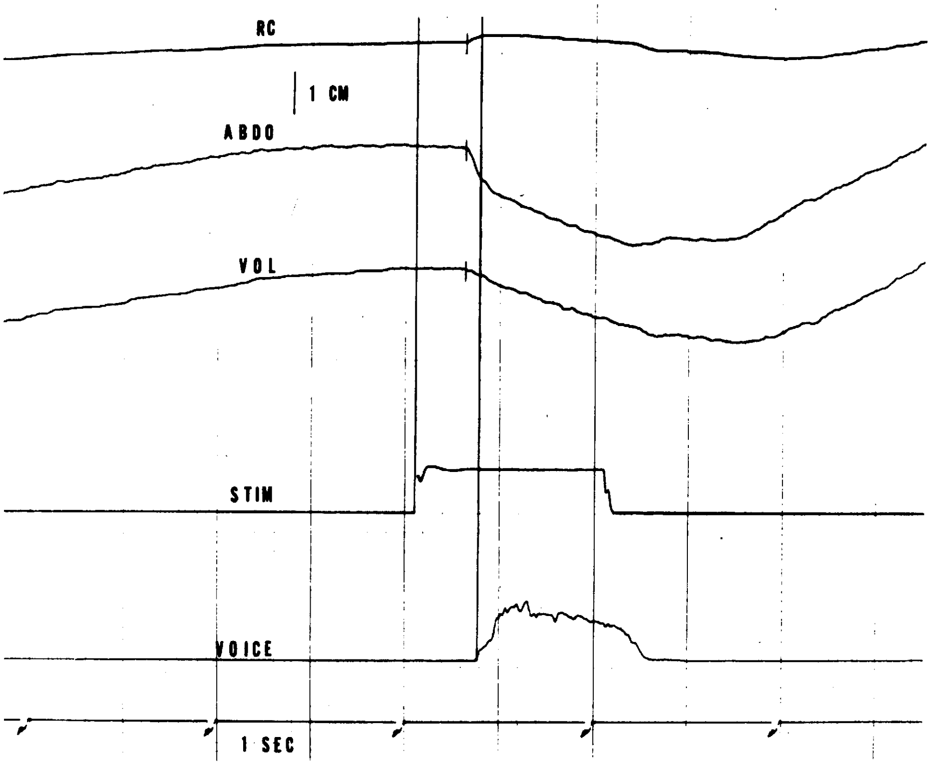

FIGURE 2. Typical chest wall response to a stimulus delivered at the end of inspiration. RC and ABDO denote rib cage and abdominal hemicircumference; VOL is estimated lung volume. Interval between vertical lines is total reaction time; short vertical markers separate latency and adjustment periods. Upward pen deflection indicates change in an inspiratory direction.

The adjustment manoeuvre shown involved directionally oppositional displacement of the chest-wall components: the abdominal wall moved inward while the rib cage expanded. Volume was thus transferred from the former to the latter. The net displacement, however, was not isovolume; the lung volume changed as a result of the chest wall adjustment. As shown in Table 3, directionally oppositional movement of the rib cage and abdomen characterized the adjustment in over 90% of the measurable responses, irrespective of the chest-wall status at the time of stimulus presentation. Three subjects, MJG, MSG, and MS, accounted for almost 90% of the cases in which the adjustment was non-oppositional, that is, in which both the rib cage and abdomen moved in the same direction. No distinct pattern could be found to account for these subjects' use of a clearly inspiratory or expiratory adjustment manoeuvre.

Irrespective of the type of chest wall movement observed, the stimulus-response interval (designated the reaction time, RT) was almost always clearly divisible into two portions: a continuation of ventilatory movement already underway, followed by a chest wall adjustment. The reaction time, then, may be partitioned into a *latency period* and an *adjustment period.*

TABLE 3. Relative frequency of adjustment movement patterns by subject.

Subject	*Adjustment Movement Type*		
	Oppositional (%)	*Inspiratory* (%)	*Expiratory* (%)
JC	98	0	2
TC	100	0	0
JE	100	0	0
MJG	71	12	17
MSG	87	0	13
EM	100	0	0
EN	98	2	0
MS	73	18	9
MEAN	90.9	4.0	5.1
S.D.	12.4	7.0	6.9

Reaction time characteristics

Table 4 summarizes the mean RT, latency time (LT) and adjustment time (AT) in milliseconds and as a percentage of the RT for each of the subjects. For the group as a whole, the LT accounted for 72% of the total response time, while the AT required only 28% of this interval.

Effect of chest wall status

Because the direction of chest wall movement and the lung volume at the time of stimulus presentation could be assumed to influence the re-

TABLE 4. Mean latency and adjustment times in milliseconds and as a percentage of total reaction time.

	Latency		Adjustment		Reaction
Subject	*msec*	*% of RT*	*msec*	*% of RT*	*msec*
JC	211.8	70	92.5	30	304.3
TC	249.7	77	73.7	23	323.4
JE	268.7	82	57.5	18	326.2
MJG	266.8	74	92.7	26	359.5
MSG	230.5	66	116.3	34	346.8
EM	241.7	75	81.8	25	323.5
EN	270.0	69	120.0	31	390.0
MS	218.8	66	112.0	34	330.8
MEAN	244.8	72	93.3	28	338.1
S.D.	22.9	5.6	22.0	5.6	26.7

sponse time, an analysis of the effect of these variables was undertaken. Table 5 presents the mean LT for each of the subjects under the several combinations of ventilatory phase and lung volume. Analysis of variance (Winer, 1962) failed to show any significant effect of chest wall status on the latency time.

TABLE 5. Mean latency time (in msec) as a function of chest-wall status.

	Chest Wall Status							
	Inspiratory		*Expiratory*		*Static*			
Subject	*High*	*Low*	*High*	*Low*	*High*	*Low*	*Mean*	*S.D.*
JC	200	235	217	224	165	230	211.8	26.0
TC	264	243	254	237	270	230	249.7	15.7
JE	284	258	253	255	267	295	268.7	17.2
MJG	228	275	258	294	240	306	266.8	30.5
MSG	229	234	238	221	—	—	230.5	7.3
EM	240	232	241	243	257	237	241.7	8.4
EN	280	270	270	260	—	270	270.0	7.1
MS	232	209	240	224	195	213	218.8	16.4
MEAN	244.6	244.5	246.4	244.8	232.3	254.4	244.8	—
S.D.	29.0	22.0	16.0	24.6	42.9	36.0	—	—

The parcellation of AT according to chest wall status is shown in Table 6. The significance of the observed differences in the means was assessed by a two-way analysis of variance (Winer, 1962), the results of which demonstrated that the adjustment time is significantly influenced ($F = 15.56$, $p < 0.001$) by the lung volume at the time of stimulus presentation. Neither the respiratory phase in progress nor the interaction of the phase and lung volume were significant contributors to the observed variation.

TABLE 6. Mean adjustment time (in msec) as a function of chest-wall status.

	Chest Wall Status							
	Inspiratory		*Expiratory*		*Static*			
Subject	*High*	*Low*	*High*	*Low*	*High*	*Low*	*Mean*	*S.D.*
JC	80	86	72	90	135	92	92.5	22.1
TC	65	99	50	78	50	100	73.7	22.6
JE	54	67	51	58	47	68	57.5	8.5
MJG	88	103	90	105	80	90	92.7	9.5
MSG	115	115	128	107	—	—	116.3	8.7
EM	80	110	83	77	63	78	81.8	15.4
EN	100	130	100	130	—	140	120.0	18.7
MS	101	127	77	107	100	160	112.0	28.4
MEAN	85.4	104.6	81.4	94.0	79.2	104.0	93.3	—
S.D.	20.0	20.9	25.7	22.7	33.8	33.6	—	—

DISCUSSION

Adjustment manoeuvre

It is clear from the findings of this study that there is a preferred "set up" manoeuvre by which the chest wall is prepared for phonation, at least in the context of the experimental task used. Just before phonatory onset, volume is usually shifted from the abdomen to the thorax, and there may be an accompanying change in lung volume.

Increasing rib cage size represents a reasonable strategy for maximizing the efficiency of the system as a source of the pressurized air needed to drive the vocal folds. The resultant elongation of the expiratory muscles increases their contractile efficiency and the expansion also stiffens the rib cage (Mead, 1974), making it less prone to displacement in passive response to the aerodynamic events of speech.

Hixon et al (1973, p. 113) believed that:

> the general distortion of the chest wall from its relaxed configuration constitutes a form of posturing of the system off of which the speaker then minimally distorts the chest wall to provide the rapid compressional volume changes needed to drive the larynx and upper airway. . . . It is tempting to speculate that speakers set the chest wall in this platform configuration so that certain of its muscles are placed at their optimal mechanical advantage.

The prephonatory chest wall displacement seen in the present study would seem to meet the requirements of this construct. It may also represent "tuning" of the diaphragm as suggested by Hixon et al (1976). The nature of the experimental task prevented the subject from achieving a preferred phonatory lung volume, and thus the results may represent compensatory adjustment which may be qualitatively indicative of the kind of setup generally absorbed into the integrated chest wall displacements through which the system reaches a target posture before a preplanned speech event.

Evidence of the adjustment pattern consistently observed in the present study has been noted before, but its significance seems not to have been appreciated. Luchsinger and Arnold (1965, p. 13) and Lenneberg (1967) cite Gutzmann's 1928 observation of what he interpreted as a "physiological asynchronism" in speech breathing. The former cite Gutzmann as stating that, at the end of prephonatory inspiration, "the chest curve continues to rise with its inspiratory movement, while the abdominal curve is already descending with expiration." Rather than representing an asynchrony or mistiming of the chest wall components, it is likely that what was observed was a normal chest wall adjustment appearing at the end of the prephonatory inspiration.

Gould and Okamura (1974) noted a similar pattern just before singing phonation in trained and untrained singers. The pneumographic tracings they present show changes similar to the adjustment manoeuvre observed in the present study. They interpreted this finding to show that "the abdominal musculature plays an important role in the initiation, regulation, and production of voice (p. 285)." The present study indicates that the abdominal movement they observed is part of a complex posturing that is not unique to singing. Wilder (1972) and Wilder and Baken (1974) described similar movements during the crying and noncrying vocalizations of infants as young as two months of age. If, indeed, the movements represent chest wall adjustment, the pattern is very likely to be inborn and unlearned.

Latency and adjustment times

The presence of a latency period between stimulus onset and the initiation of an observable mechanical response is, of course, to be expected. Despite the superficial quiet, this portion of the stimulus-response interval is characterized by intense nervous system activity. The stimulus is detected and decoded, information from the periphery about the status of the entire speech system is analyzed and integrated, a set of upper motoneurone responses is formulated, and appropriate peripheral nerve impulses are transmitted to initiate a muscular response. Clearly the complexity of this portion of the response process is likely to be independent of the status of the vocal tract and ventilatory system and therefore would not be expected to vary as a function of the variables explored in this study. Presumably this period is absorbed into the inspiratory interruption preceding an utterance in running speech.

Given that there are minimal requirements that the air supply must satisfy if adequate phonation is to be achieved, it is reasonable to assume that a variable adjustment of the respiratory system will be needed, depending on how far from adequate the respiratory status is at the time of stimulation. By implication, the time required for chest wall adjustment would be expected to vary accordingly. In the present study the static/high volume and expiratory/high volume conditions most closely approximated the chest wall status that would prevail at the start of a normal speech utterance, while the inspiratory/low volume condition was the most radically different from the normal speech-onset situation. The difference in the mean adjustment times under these conditions was evaluated by a Scheffé contrast (Edwards, 1967) and found to be strongly significant ($t' = 4.34$; $\alpha < 0.01$) with the more normal postures requiring shorter adjustment times, as expected.

Low lung volumes always required more adjustment time, and presumably greater adjustment, than high lung volumes. Considering the pressure-volume characteristics of the respiratory system this is unremarkable. It is, however, surprising that the direction of chest wall movement at the time of stimulus presentation did not have a significant influence on the adjustment time. One would expect the different momentum characteristics (Josenhans et al, 1971) to influence the rapidity of adjustment. Further investigation of this point seems warranted.

Izdebski and Shipp (1977) have reported reaction time data on a task similar to the one reported here. They timed the delay from onset of an acoustic stimulus to the appearance of electromyographic activity of the interarytenoid and posterior cricoarytenoid muscles, and also measured the interval from emg onset to the first cycle of the phonatory response. No attempt to control for chest wall status was reported.

Izdebski and Shipp found a mean "mechanical time" of 80.62 msec; the present study's equivalent period, AT, had a comparable mean duration of 93 msec. The findings of the two studies differ, however, in the observed mean LT ("neural time" in the Izdebski and Shipp data). The present study found a mean of 245 msec, while Izdebski and Shipp reported 148 msec. This difference is probably attributable to the different observational techniques used.

The disparate results can be reconciled if consideration is given to the probable lag between onset of emg activity and the appearance of observable mechanical response (Atkinson, 1978) as well as to the interaction of vocal risetime characteristics (Koike, Hirano and von Leden, 1967) and different vocal-onset criteria.

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