Computerized measurement of tongue dorsum movements with pulsed-echo ultrasound[a)]

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A computerized system for the measurement of tongue dorsum movements with pulsed echo ultrasound is described. The presentation focuses on technical and methodological considerations in the on-line acquisition of vertical tongue movement information, its digital processing and display. Problems associated with transducer placement, peak detection, data averaging, and curve fitting are considered, and validation procedures based on x ray and indicators of measurement reliability are reported. The discussion centers on advantages and disadvantages of the technique and its applications.

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INTRODUCTION

The measurement of the position of less accessible articulatory organs, such as the tongue, the velum, and the larynx, has been particularly difficult for speech researchers. Noninvasive ultrasound techniques have recently been applied to this problem to study laryngeal activity (Hamlet and Reid, 1972; Holmer and Rundqvist, 1975; Hamlet, 1980), pharyngeal wall displacements (Skolnick *et al.*, 1975; Ryan and Hawkins, 1976), and tongue movements (Minifie *et al.*, 1971; Sonies *et al.*, 1981; Watkin and Zagzebski, 1973; see Kelsey *et al.*, 1969, for review). In this paper we present an extension to these ultrasound procedures, a computerized measurement technique to monitor tongue dorsum movements with pulsed ultrasound.

Among the more-established techniques for the study of tongue movements are (1) x-ray cineradiography (e.g., Perkell, 1969), (2) computer-controlled x-ray microbeam (Kiritani *et al.*, 1975), (3) dynamic palatography (Hardcastle, 1972), (4) fiber optic viewing techniques (Sawashima and Hirose, 1968), and (5) electromyography with surface or fine wire electrodes (Hirose, 1971). Advantages and disadvantages of most of these techniques have been reviewed elsewhere (e.g., Hardcastle, 1974). Some of the advantages are extent of display (x ray), or proximity to the neural signal (electromyography). Some disadvantages are tissue invasion, the presence of interfering or unpleasant apparatus in speech tract cavities, possible radiation hazard, or limitations in measurement radius and/or precision. Echo ultrasound techniques share certain limitations in measurement radius and precision. However, they are noninvasive, and when augmented by a computerized data acquisition and analysis system, can provide reliable information concerning tongue dorsum position over time. Furthermore, there have been no reported bioeffects in humans at diagnostic intensities of ultrasound.

Two types of echo ultrasound equipment can be used to monitor tongue movements in speech, A scan and sector scan. In the A-scan method, ultrasound pulses are passed from a transducer positioned below the chin, through the skin and the muscular tissue of the tongue, and are reflected in proportion to changes in acoustic impedance, at transitions in tissue density in the tongue body, at the interface between the tongue dorsum and the ambient air, and at the oral cavity walls (see McDicken, 1981, for review of ultrasound technology). The interval between the emission of the signal and the reception of the greatest amplitude echo estimates the distance between the transducer and the surface of the tongue.

Measurements are collected in a comparable fashion when using sector-scan technology. Here the ultrasound beam repeatedly scans a sector of predetermined extent (typically 60°–90° of arc) to produce a two-dimensional image that can be displayed on a video screen. Typical scanning durations for the commonly used mechanical types of transducer are approximately 25 ms per sector. An advantage of sector scan is that it allows the display of either midsagittal or transverse sections of the tongue. However, with the mechanical transducer, data from the initial portion of each scan is temporally offset with respect to the final portion of the scan, so that a single image displays information obtained at different moments in time.

The following discussion focuses on technical and methodological considerations for a computerized system to measure tongue dorsum movement with A-scan ultrasound. It considers issues in data acquisition, analysis, and interpretation, limitations of the A-scan technique when applied to tongue dorsum movements, and some possible applications of the technique. The issues will be introduced in the context of an operational apparatus, and some characteristic data will be presented.

I. DATA ACQUISITION AND ANALYSIS

A. System overview

The present system (Fig. 1) consists of: (1) a Picker model 104 A-scan ultrasonoscope with a 3.5-MHz pulsed echo transducer, (2) an ultrasound-to-computer interface, (3) an

[a)] Order of authorship was determined randomly.

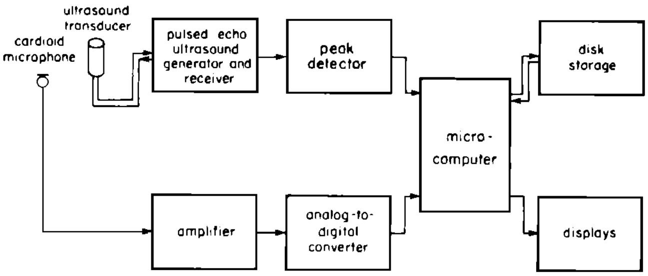

FIG. 1. Schematic diagram of computerized system for the measurement of tongue dorsum movements with pulsed echo ultrasound.

ElectroVoice 660 Dynamic cardioid microphone and audio amplifier, (4) a Cromemco CS-2 microcomputer with a digital input for the ultrasound channel and a 12-bit analog-to-digital converter for voice, and (5) a system control and data display terminal. The spatial average, temporal average intensity of the ultrasound signal is approximately 0.5 mW/cm^2, and the spatial peak, temporal average intensity, approximately 5 mW/cm^2. Recording facilities are currently being implemented for additional analog signals (e.g., EMG, lip and jaw movement).

The pulsed ultrasound transducer generates 3.5-MHz bursts at a 1-kHz rate. Each 1-ms interval contains an emission period of approximately 4 μs followed by an echo reception period of about 496 μs. The signal passes through soft tissue at an average speed of 1540 m/s (Goss *et al.*, 1978).

A large amplitude reflection from the tongue dorsum occurs between 58 and 84 μs after the emission of the burst, that is, at a distance of 4.5 to 6.5 cm from the transducer crystal. The time of occurrence of this large amplitude peak is measured by means of a peak-detection circuit in the ultrasound-to-computer interface. The value obtained provides an estimate of the position of the tongue dorsum. The observed values are recorded into computer memory at a 1-kHz rate. The acoustic signal is sampled concurrently.

Artifacts in the ultrasound record are suppressed by averaging and curve fitting operations. Analysis and display programs permit the presentation of the tongue dorsum position, its velocity and acceleration, and the corresponding voice signal.

B. Transducer placement and measurement orientation

In a typical experiment, the transducer (3.5 MHz, 13-mm diam, medium focus) is placed beneath the chin along the inferior midline of the mandible at an approximate distance of 1-cm anterior to the hyoid bone. The position of the transducer is maintained by means of an adjustable head harness which holds the transducer at a constant distance from the cranium, and thus from the hard palate (Fig. 2). Firm contact is achieved by the application of contact gel between the transducer surface and the skin. Contact between the subject and the apparatus is limited to the transducer surface and the cranial support of the head harness. The apparatus has no significant effect upon the extent of jaw movement (see Sec. H).

The exact orientation of the ultrasound transducer in

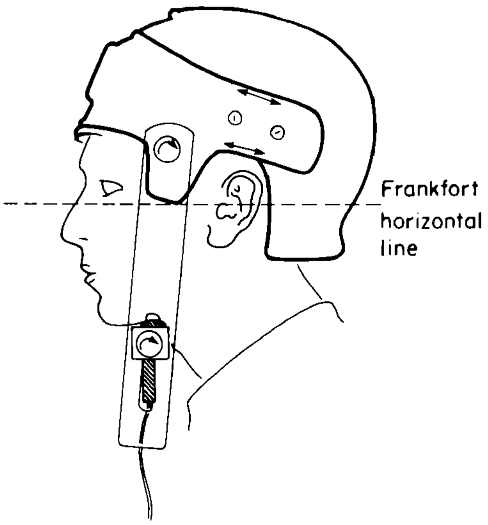

FIG. 2. Placement of ultrasound transducer for the measurement of vertical displacement of the tongue dorsum in the posterior oral cavity. The head harness (adjustable for head size) maintains the transducer at a constant distance from the cranium, and thus the hard palate. Adjustments for the placement of the transducer are indicated by arrows. A three-dimensional spatial coordinate system consisting of rulers and protractors (not shown) references the transducer position to the Frankfort horizontal line. The orientation of the transducer in the median plane is determined by rotation to a position appropriate to the measurement of posterior linguo-palatal constrictions (see text).

the median plane is determined by rotating the probe to a position that (a) maximizes the measured displacement of the tongue dorsum from the position for /k/ to the position for /a/ and (b) preserves the traditional order of vowel heights /u, o, a/ in the tongue dorsum measurement. Condition (a) is satisfied by rotating the transducer until maximum displacement between /k/ and /a/ is observed on the ultrasonoscope screen. Condition (b) is tested by recording and examining trials of the sequence /kukoka/. If posterior vowel height order is not preserved, the transducer is rotated either in an anterior or a posterior direction [within the limits set by condition (a)], and the procedure is repeated.

Once satisfactory placement has been achieved, the transducer position is measured with reference to the cranium using a three-dimensional coordinate system. The horizontal and vertical coordinates of the center of the transducer surface and the transducer orientation are determined with reference to points on the Frankfort horizontal line by compasses and rulers attached to the harness. The Frankfort line connects the orbitale (lowest point of the inferior margin of the left orbit) with the porion of the left ear (upper margin of the external auditory meatus) (Zemlin, 1981, p. 388). The lateral position of the transducer is always along the axis connecting the nasion to the gnathion (the midsagittal line of the cranium). All points can be located either visually or by palpation. The coordinate system permits accurate replacement of the transducer from one recording session to the next.

Initial placement of the transducer at 90° to the Frankfort horizontal line usually satisfies both placement conditions described above (see Sec. H). Further, a sample of x-ray video recordings indicates that for repetitions of /ka/, this

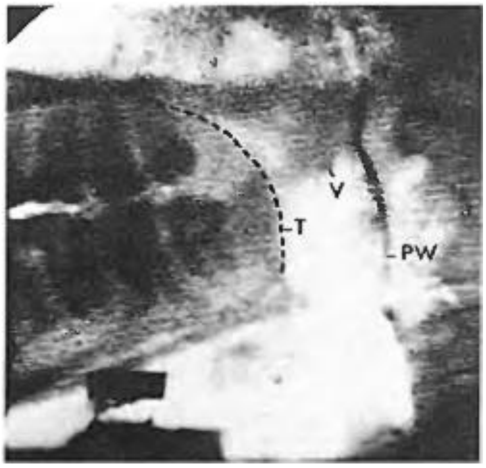

FIG. 3. X-ray video photograph of a lateral view of the posterior portion of the upper speech tract showing the tongue body at oral closure for the stop consonant /k/. The picture was taken during simultaneous recordings with ultrasound and x-ray video. The ultrasound crystal, seen as a dark rectangle at the bottom of the picture, is oriented towards the linguo-palatal closure. T: tongue body, V:velum, PW: posterior pharyngeal wall.

placement orients the transducer in the direction of the linguo-palatal closure for /k/ (Fig. 3).

Tongue dorsum displacements obtained with this procedure correspond to distances along the axis of the ultrasound beam, rather than to spatial coordinates of tissue points in the oral cavity. With this technique, the terms "displacement" and "velocity" thus refer to positions and rates of change along the measurement axis.

This type of measurement is desirable because it preserves the traditional vowel height order for back vowels (see Jones, 1956; Keller, 1978; Pike, 1947) and corresponds to the phonetically salient dimension of posterior linguo-palatal constriction, both articulatorily and acoustically.

In the articulatory domain, Harshman *et al.* (1977) applied factor analysis techniques to x-ray tracings of tongue positions in vowel production; one of the two factors they identified was a movement of the tongue in an upward and backward direction for the back vowels /u, ʊ, o, ɔ, and a/. Linguo-palatal or linguo-velar stops coarticulated with such back vowels may also be assumed to lie in this orientation.

From an acoustic point of view, posterior constrictions determine the relative sizes of the oral and pharyngeal resonator cavities which to a large extent determine the acoustic quality of the various vowels, and are likewise related to the acoustic characteristics of velar consonants (Minifie, 1973; Dew and Jensen, 1977).

The data obtained with this procedure preserve several types of information available with alternative techniques such as x ray. In particular, systematic displacement and velocity relations for different posterior vowels, speech rates, and stress levels, are comparable to relations obtained with other methodologies. For instance, greater displacements and peak velocities have been observed for lower vowels, slower speech rates, and greater stress levels[1] and congruent findings have been reported using x ray (e.g., Kuehn and Moll, 1976; Perkell, 1969). Furthermore, temporal relations between points in vertical lingual movement and other speech events can be assessed directly.

C. Tongue dorsum monitoring

When an ultrasound pulse is emitted from a transducer positioned below the jaw, it passes through the skin and muscular tissue of the tongue body (mylohyoid, geniohyoid, genioglossus, inferior and superior longitudinal, and lateral and transverse intrinsic muscles); the amplitude of the reflected signal corresponds to differences in acoustic impedance along the signal path. A large amplitude reflection can be measured at a distance of 4.5 to 6.5 cm from the transducer surface. It can be assumed that this reflection corresponds to the position of the tongue dorsum, since the maximum difference in acoustic impedance along the signal path occurs as the ultrasound signal passes from the muscular tissue into the ambient air.

Ultrasound echoes from the tongue surface can be gathered for tongue blade and tongue dorsum positions along the sagittal midline. In the anterior and lateral directions (below the tongue tip and the sides of the tongue), the signal is obstructed by intervening air pockets, and in the posterior direction, by the hyoid bone. Pulsed echo ultrasound with this placement is thus optimally suited for the study of oral cavity constrictions in the linguo-palatal to linguo-velar range.

Some proportion of the time, a large amplitude reflection not corresponding to the tongue dorsum arises as a result of tissue density changes within the tongue body or reflections within the oral cavity. As these observations typically differ in their time course from tongue dorsum positions, it is possible to remove almost all of these by specifying a range for acceptable measurements, and within that range, by excluding observations that lie beyond a given distance (e.g., 2 mm in either direction) from the preceding tongue dorsum measurement.

A further difficulty in attempting to track the movement of the tongue surface is that the ultrasound beam has a significant width at the tissue depth where recordings are made (the 3.5-MHz transducer used in our system has an effective beamwidth of about 13 mm at a focal length of 7 cm). This means that the resulting measurements are insensitive to the height of the tongue within the dispersion radius. In addition, relatively few points on the dorsum lie at right angles to the ultrasound beam. As a result, reflections from the surfaces which lie at oblique angles to the transducer are attenuated in amplitude. The latter difficulty is usually resolved by peak detection and digital processing techniques.

D. Peak detection and measurement resolution

The digital encoding of tongue dorsum reflections is achieved by means of a peak detection circuit. In each 1-ms measurement interval, the ultrasound pulse activates a timing circuit, as well as an envelope detector which follows the leading edge of the ultrasound echo. The timing circuit is stopped as the slope of the envelope changes from positive to negative at the peak of the echo, and the corresponding digital value is transferred to computer memory and added to a current ultrasound measurement file.

An amplitude threshold for peak detection is set by the operator to eliminate noise due to tissue interfaces within the tongue. The threshold is set so that one peak is detected in almost all measurement intervals.

The design of the circuit is such that when several reflections occur within a short time of one another, only the first of these is recorded. This has the effect of selecting a single large amplitude reflection in cases involving several related reflections.

The resolution of the peak detection system is affected by a number of factors. The ultrasound-to-computer interface operates on a 2-MHz clock, with a resulting temporal resolution of 500 ns, or 0.39 mm of tissue. In addition, the peak detection circuit has a constant phase lag equal to 0.39 mm and a variable error of ± 0.15 mm. The tracking error of the circuit is thus about 1.5% of the total displacement observed in repetitions of /ga/ by adults.

The resolution of the combined ultrasound-peak detection system was assessed by recording several trials in which the ultrasound signal was passed through a 6-cm block of Plexiglas. The average standard deviation of ten measurements of 3455 observations each was 0.58 mm.

E. On-line digital processing

Digital processing of the ultrasound file is accomplished first by means of a real-time path tracing program, and then by off-line averaging and the application of natural cubic spline functions (de Boor, 1978). The path tracing program attempts to find a smooth path through the data recorded in the 3.455-s trial (currently being upgraded to 4 s) by testing successive 1-ms measurement intervals for values within a ± 2-mm window. The program starts with a value for tongue dorsum position obtained during the first ms of measurement, and it tests successive intervals for values that lie within ± 2 mm of the current position. Trials are judged acceptable for further analysis if 98% or more of the measurement intervals provide data along the traced path. Within these bounds, occasional gaps in the data are not found to affect further analysis.

F. Data averaging and cubic spline functions

Analysis of the ultrasound data involves a pooling of displacement measurements, and the application of natural cubic spline functions to the averaged values. The purpose of these techniques is to reduce nonsystematic variation in the data, and to increase the clarity of the graphical presentation of the ultrasound records.

Data averaging procedures allow the user to select an optimal bandwidth for the analysis and display of tongue dorsum movements. This is accomplished by dividing the duration of the trial into equal intervals and averaging the measurements in each interval to provide knots for a spline fitting program. As an example, if 80 intervals are specified for a 3.455-s trial, interval midpoints, or knots, are separated by 43.2 ms, producing a bandwidth of approximately 11.5 Hz.

Natural cubic splines are piecewise polynomial functions that describe a curve connecting a set of data points.

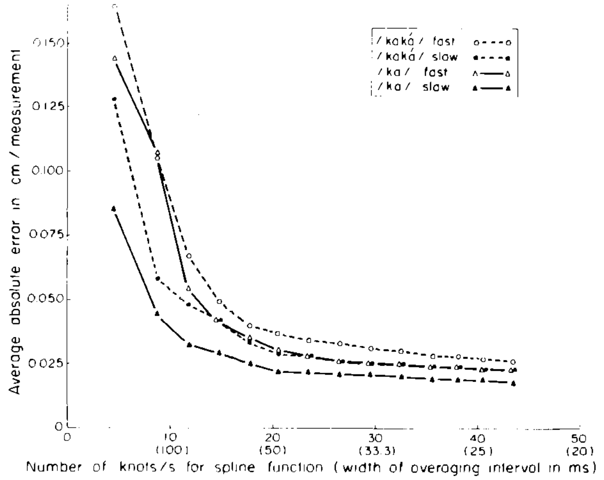

FIG. 4. Average absolute error per measurement as a function of the number of knots used to calculate the spline function. Corresponding widths of averaging intervals are given in parentheses.

The curve and its derivatives are continuous at the data points. An optimal spline function is one that minimizes the error between the raw data and the spline while capturing the overall trend of the measurements.

Numerical techniques were used to study the relation between interval width and the goodness of fit of the spline function. The procedure involved an iterative calculation of the average absolute difference between the cubic spline and the raw data, for interval widths between 20 and 165 ms. Cubic splines were computed for repetitions of /ka/ at two speech rates, either with alternate vowels stressed or with all vowels given equal stress (Fig. 4). Interval widths greater than about 45 ms were found to result in substantial increases in the average absolute error per measurement.

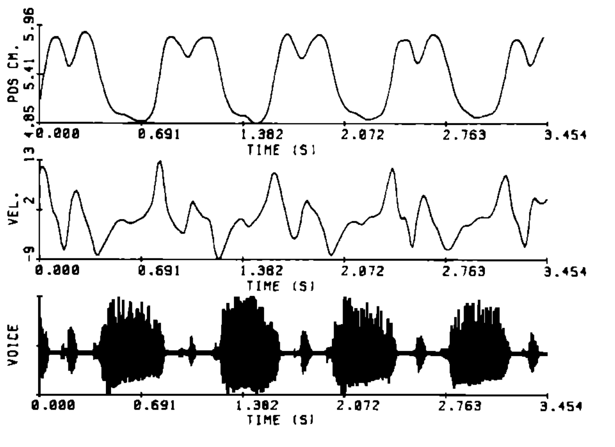

FIG. 5. Top: Ultrasound record of displacement of tongue dorsum during repetitions of /kaká/, shown at a bandwidth of 11.5 Hz. The upper peaks correspond to the position of the tongue dorsum for linguo-palatal closure, points at the bottom of the tracing give the position of the tongue dorsum for the open vowel /a/. Values on the ordinate correspond to the distance in cm from the crystal of the ultrasound transducer to the dorsum of the tongue (see Fig. 3). Middle: Velocity record showing the rate of tongue dorsum raising (positive values) or lowering (negative values). Bottom: Corresponding acoustic record. Short vowels are shown as the smaller of the two types of signal. Subject: male native speaker of English.

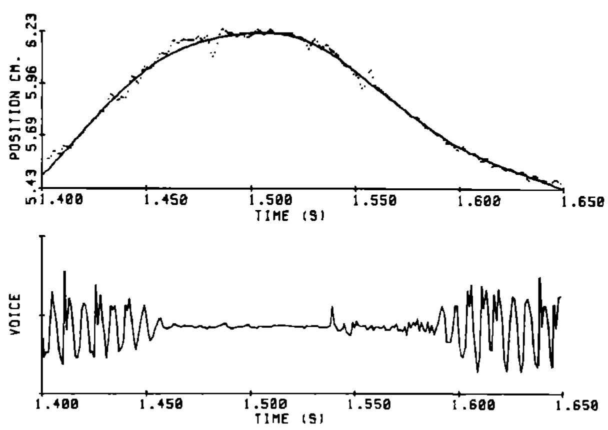

FIG. 6. Top: Ultrasound record of the displacement of the tongue dorsum during the production of /ka/ at a fast speech rate. Raw data points and the corresponding cubic spline function are given for a 250-ms segment involving a closure for /k/. The spline shown here represents a tongue displacement bandwidth of 11.5 Hz. Bottom: Corresponding acoustic signal.

Spline functions were selected for the present application because (a) the functions are differentiable and thus permit the calculation of the velocity and acceleration of the tongue dorsum, as well as its displacement over time, (b) a spline fit allows gaps in the data, i.e., it allows unequal spacing of points along the time axis, and (c) spline functions enable the calculation of numerical values corresponding to the height of the curve at any point in time.

G. Displays

The graphical display of ultrasound data currently involves the presentation of any of the following four parameters: (1) tongue dorsum position, (2) tongue dorsum velocity, (3) tongue dorsum acceleration, and (4) the corresponding acoustic waveform. Either the entire record (Fig. 5) or selected portions (Fig. 6) can be displayed. Numerical values corresponding to points in any of the records are obtained by a semiautomated program in which the user positions a cursor at a desired point along the time axis.

H. Measurement validation

In the present study, several approaches have been followed toward validation of the ultrasound measurements. These have involved simultaneous pulsed echo ultrasound and x-ray recording, an assessment of possible distortion of jaw movement, an evaluation of the mechanical stability of the head harness, a study of the effects on tongue dorsum measurements of variations in transducer orientation, and an analysis of indicators of the internal consistency of the ultrasound measurement.

Comparisons of ultrasound and x-ray techniques have previously been reported for the measurement of tongue dorsum position. Good correspondence was observed between measures obtained with x ray and through-transmission ultrasound, with nonsense bisyllables as stimuli (Watkin and Zagzebski, 1973) and between sector-scan and x-ray fluoroscopic measurements of tongue displacements in vowel-to-vowel and vowel-to-consonant transitions (Sonies *et al.*, 1981). A weaker correspondence was reported between separate recordings of pulsed echo ultrasound and x ray, using the sustained production of selected vowels and fricative consonants as stimuli (Minifie *et al.*, 1971).

In the present study, measures obtained with x ray were compared with those of the computerized pulsed echo ultrasound system. Three trials of 3.455-s duration were conducted using a single normal male subject who produced alternately stressed repetitions of the nonsense syllable /ka/. Lateral x-ray recordings of the posterior oro-naso-pharyngeal region were produced using a Picker Flouroscopic Imaging System and video recorder.

In the x-ray analysis, distances along the ultrasound transducer axis from the transducer surface to the tongue dorsum were measured on a frame-by-frame basis. The comparison between x ray and ultrasound revealed a similar displacement and time course for the two types of measures. However, the measure-to-measure variability was greater for x ray than for ultrasound. This is consistent with findings presented by Watkin and Zagzebski (1973, Fig. 4, p. 546) and may be attributed to the fact that in scoring x rays, the position of the tongue dorsum cannot always be established satisfactorily for reasons such as interference from cavity fillings or limited resolution of the video image.

Potential changes in jaw motion due to the head harness were assessed by video-taping jaw movement with and without the harness. Two subjects produced repetitions of posterior consonant–vowel pairs (/ka/, /ga/, /ko/, /go/) at two speech rates, in both an equal-stress and an alternate-stress condition. For each condition, measurements of the greatest vertical displacement of the gnathion were obtained. Jaw displacements with and without head harness were found to vary in a nonsystematic manner across conditions. Average differences in vertical jaw displacement of 0.32 and 0.29 mm were observed for the two subjects. The differences were not reliable, $t(15) = 1.35$, $SE = 0.24$ mm, $t(15) = 1.61$, $SE = 0.11$ mm, for the two subjects, respectively.

The mechanical stability of the head harness was evaluated by measuring the anterior–posterior movement of the anterior edge of the transducer in the same video recordings. Average transducer movements of 0.14 and 0.31 mm were observed for the two subjects. (Average error for an equal number of measurements of a video recording of a stationary edge was 0.15 mm.)

The effects of variations in transducer orientation were studied by recording, for three transducer placements, repetitions of /ga/, /go/, and /gu/ at a normal speech rate, with alternate vowels stressed. The sequence of stimuli was produced by two subjects with the transducer oriented at 90° to the Frankfort horizontal line, at 3° anterior and 3° posterior to the 90° orientation. In both subjects, the transducer center line was 5.3-cm anterior to the porion and aligned with the median plane. Measurements of tongue dorsum displacement and maximum lowering velocity are shown in Table I.

For both subjects, measurements of tongue dorsum displacements for /ga/, /go/, and /gu/, taken at 90° to the Frankfort horizontal, preserved traditional vowel height order. Similar displacement and velocity estimates were ob-

TABLE I. Effects on tongue dorsum measurements of variations in transducer orientation. Measurements were taken at 90° to the Frankfort horizontal line (vertical), at 3° anterior and at 3° posterior to the 90° orientation. Displacement values (in cm) are the averaged differences between the maximum and minimum distances of the tongue dorsum from the transducer surface. Maximum velocities are shown in cm/s. Averages are based on 20 values per condition.

	/gu/		/go/		/ga/	
	unstressed	stressed	unstressed	stressed	unstressed	stressed
Displacement						
Subject DO						
3° anterior	0.50	0.58	0.68	0.72	0.73	0.92
vertical	0.44	0.62	0.67	0.76	0.75	0.94
3° posterior	0.58	0.56	0.61	0.57	0.77	0.81
Subject EK						
3° anterior	0.19	0.32	0.26	0.84	0.23	0.95
vertical	0.20	0.31	0.27	0.69	0.27	0.88
3° posterior	0.24	0.34	0.22	0.65	0.20	0.93
Maximum velocity						
Subject DO						
3° anterior	5.52	5.50	7.55	6.75	8.62	7.44
vertical	5.25	5.88	7.71	6.69	8.60	7.57
3° posterior	7.06	7.80	6.17	5.84	7.48	7.31
Subject EK						
3° anterior	3.21	4.08	5.51	8.79	4.96	9.82
vertical	3.78	3.68	5.04	7.28	5.84	8.77
3° posterior	3.84	4.15	4.28	6.73	4.07	8.87

tained for subject DO in the anterior and vertical orientations and for subject EK in the vertical and the posterior orientations. Greater differences were observed for the remaining orientation. Vowel height order was preserved for both long and short vowels in all orientations for subject DO, and for long vowels in all orientations for subject EK. Thus measurements differ somewhat with small changes in transducer orientation; however, these differences do not substantially alter the pattern of the data.

Finally, internal consistency of the ultrasound measurement is demonstrated by the similarity in magnitude of tongue dorsum displacements in repetitions of a single syllable (Fig. 5). Standard deviations for repeated displacements from the linguo-palatal closure for /k/ or /g/ to the maximum opening for /a/ typically range from 0.5 to 1.25 mm [coefficients of variation ($s/\overline{X}$) of 0.07 to 0.18].

II. DISCUSSION

There are certain advantages to the use of pulsed echo ultrasound relative to other tongue movement measurement techniques; there are also certain limitations. Some of the limitations can be circumvented with appropriate recording and analysis techniques.

Recording tongue movements with ultrasound is noninvasive, and has not been shown to have any biologic effects in humans at diagnostic intensities. As a result, it is possible to record a substantial number of samples, each the duration of a typical utterance. Also, pulsed ultrasound is particularly amenable to on-line computerized measurement and analysis techniques. In comparison to x ray and sector scan, the unidimensional A-scan measurement provides a readily interpretable record of vertical tongue dorsum position and movement. The data are available for display and analysis immediately after recording, permitting in-session examination and rerecording if necessary.

The disadvantages of pulsed-echo ultrasound relate to measurement radius, precision, and the inability to measure the position of specific tissue points.

Because of the nature of ultrasound transduction, only recording locations and orientations where the signal passes entirely through tissue can be used. In practical terms, this limits pulsed echo ultrasound recording positions to posterior submandibular placements for the observation of palatolingual, velo-lingual, and upper pharyngeal constrictions. However, it should be pointed out that other ultrasound techniques can be applied to investigations of certain further speech structures (e.g., laryngeal activity, Hamlet, 1980).

Imprecision in ultrasound recordings results from a number of factors. Resolution is limited by the beam width of the signal, variable error associated with peak detection, the spatial resolution of the ultrasound-peak detection system, and by the fact that data acquisition captures only the first of several possible major ultrasound reflections in the area of the tongue dorsum. However, limitations in resolution do not substantially affect the validity of the measurement as long as the variation introduced is small relative to the overall extent of the movement.

The inability to measure the position of specific tissue points on the tongue dorsum results in the possibility that identical displacements can be recorded for quite different movements. For instance, a large movement in an anterior–posterior direction can produce measurements indistinguishable from those of a small movement in a vertical direction. Nevertheless, the unidimensional measurement axis can provide information that is monotonically related to the phonetically salient dimension of back tongue raising. In normal subjects, ambiguity regarding the interpretation of displacements is reduced by a placement procedure that preserved known relations in posterior vowel heights and by restricting the stimulus set to sounds involving posterior constrictions. In populations with articulatory abnormality, the absence of known patterns of movement limits the interpretation of A-scan measurements to statements regarding the single dimension of vertical tongue dorsum displacement.

There is a substantial literature on bioeffects associated with nonionizing radiation such as ultrasound (see Abdulla, 1978; O'Brien, 1978; Repacholi and Benwell, 1980, for reviews). To date, studies with humans have not shown any biologic effects at diagnostic intensities (typically below 10 mW/cm^2 spatial average, temporal average intensity). In view of reported bioeffects in animals and tissue cultures at these and higher intensities, attenuation of the intensity of the ultrasound signal source and limitation of the duration of testing is recommended. In our laboratory, 10-dB RF attenuators are installed on the signal source, effectively reducing the ultrasound intensities to approximately 1/10 of those found in diagnostic applications.

The measurement of tongue dorsum movements with a computerized pulsed-echo ultrasound system is of particular interest in investigations of lingual control, linguo-palatal interaction, and of relations between lingual movements and those of other articulators. It is potentially applicable in the research and diagnosis of speech motor dysfunctions, such as various forms of dysarthria, aphasia, and child language disorders, in deaf speech acquisition, and in stuttering. The system may also be of interest in studies of mastication and swallowing, and of the relationship between these vegetative functions and speech behavior.

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