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Ultrasound in speech therapy with adolescents and adults

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Abstract
The present paper comprises an overview of techniques using ultrasound in speech (re)habilitation. Ultrasound treatment techniques have been developed for English lingual stops, vowels, sibilants, and liquids. These techniques come from a series of small *n* studies with adolescents and adults with severe hearing impairment, residual speech impairment or accented speech at the Interdisciplinary Speech Research Laboratory at the University of British Columbia. Ultrasound allows excellent visualization of tongue shape features, which is especially useful for feedback during speech (re)habilitation. Further research is needed to evaluate the efficacy of ultrasound in speech (re)habilitation.

Keywords: *Ultrasound, speech habilitation, visual feedback technology*

Research has shown that visual feedback technologies can be effective tools for speech (re)habilitation, whether the feedback is acoustic (e.g., Maki, 1983; Bernstein, 1989; Volin, 1991) or articulatory (e.g., Fletcher, Hasegawa, McCutcheon, & Gilliom, 1980; Shawker & Sonies, 1985; Gibbon, Hardcastle, Dent, & Nixon, 1996; Michi, Yamashita, Imai, & Yoshida, 1993; Bernhardt, Fuller, Loyst, & Williams, 2000). Following in this tradition, the current research team at the University of British Columbia's Interdisciplinary Speech Research Laboratory (ISRL) has been conducting speech therapy studies with adolescents and adults with feedback from dynamic two-dimensional ultrasound. Participants with the following backgrounds have been included in the studies: severe hearing impairment (Bacsfalvi, Bernhardt, & Gick, 2003; Bernhardt, Gick, Bacsfalvi, & Ashdown, 2003; Bernhardt, Bacsfalvi, Gick, Radanov, & Williams, 2004), persistent speech impairment (Adler-Bock, 2004), and accented English (Gick, Bernhardt, Bacsfalvi, & Wilson, 2004). The current paper describes techniques for ultrasound use in speech therapy that have been developed across those studies.

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General methods and equipment in speech therapy using ultrasound

Speech therapy with ultrasound that is followed in the ISRL, and described in the present paper, follows standard principles and techniques of articulation and phonological intervention (Bernhardt & Stemberger, 2000; Bernthal & Bankson, 2004). In the present paper, the focus is on the use of ultrasound in that treatment process. The equipment and general therapy process are described below.

The equipment

During ultrasound, an ultrasound probe or transducer is placed beneath the speaker's chin, just above the larynx. Ultrasonic waves from the transducer are reflected back towards the probe when they encounter the air in the oral cavity that is just above the tongue surface. This reflection is converted into images that show the shape and location of the tongue at a given point in time. The transducer is longer in one dimension than the other. By holding the transducer so that the longer surface is oriented in a front-back plane relative to the head (i.e., parallel to the body), a mid-sagittal view of the tongue's surface and movement patterns is displayed as in Figure 1. The sagittal image shows the tongue's surface and movement patterns in a front-back plane from the tip to the root (although sometimes the tip or root are not completely visible). By holding the transducer so that the longer surface is oriented in a side-to-side plane relative to the head, a cross-sectional (coronal-oblique) view of the tongue is displayed as in Figure 2. The coronal view displays the tongue's surface from one side to another at a given point along the front-back dimension of the tongue. The coronal view shows any mid-line tongue grooving (Figure 2), or elevation (Figure 2) or depression of the sides of the tongue. By moving the transducer back and forth in a front-back plane under the chin, the relative depth of the groove or height of the sides of the tongue at various locations can be observed.

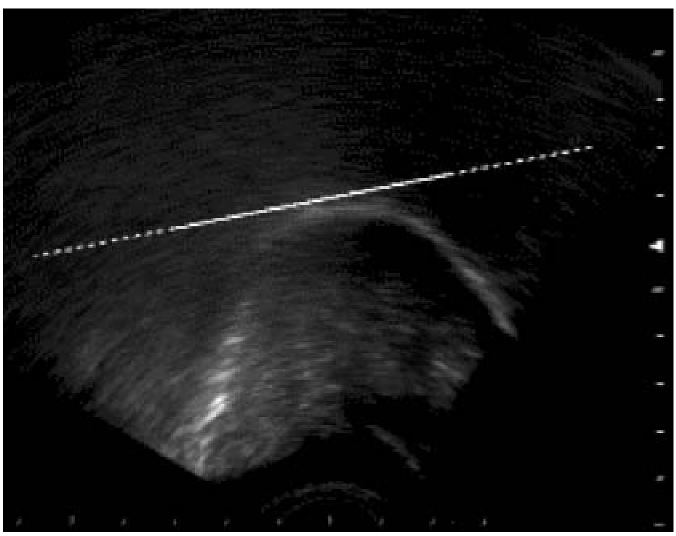

Figure 1. A sagittal ultrasound display of a typical adult /k/ showing an elevated tongue body. The tongue tip is on the right in all sagittal images. The reference line shows the target height for tongue back raising (and in this case, approximates the palate).

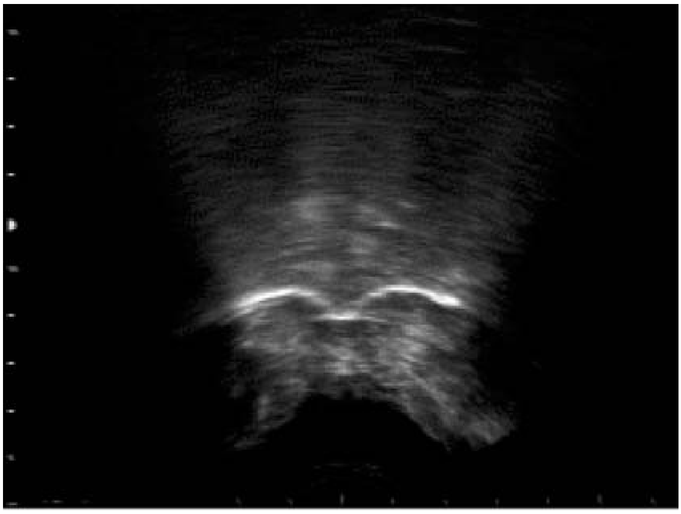

Figure 2. A coronal ultrasound display of a typical adult /s/ showing a mid-line tongue groove and raised lateral margins of the tongue.

Both sagittal and coronal views can provide feedback for speech (re)habilitation. The sagittal view has been utilized more often in the ISRL treatment studies, because it shows the tongue from the tip to its root. Backness and relative height of the tongue are visible in that mode, and also the slope or angles of various sections of the tongue (which can be important for the liquids). The coronal view has been used primarily for showing tongue grooving, vowel height and vowel tenseness.

It has sometimes been helpful to provide additional reference information on the display, e.g., for palate location or tongue backness, height or slope. On some of the ultrasound machines, it is possible to generate reference lines that can be moved around the screen with a cursor. These reference lines have not been designed for speech research, but have been exploited as references for target phones, i.e., showing target locations for the tongue tip, body or root (as in Figure 1 or 3, and as discussed further below for velars and alveolars).

Another technique for presenting additional reference information (not yet tried in the ISRL studies) is to present an image of the speaker's palatal contour. To derive a palatal contour from the ultrasound machine, ultrasound images of a water bolus can be captured. The speaker holds water in his or her mouth, moves the tongue tip backwards along the palatal surface and then against the teeth, and then swallows. (Note that measurements are taken after the bolus of water has passed by, to avoid recording the bolus/air interface.) The water allows the ultrasound to pass through the oral cavity (which previously had impenetrable air), and the sound waves then are reflected back from the palatal surface, resulting in the display of a palatal image. From the water bolus images, the palate contour can be sketched onto an overhead transparency, which can then be taped onto the ultrasound screen, giving feedback on tongue position relative to the palate. (The palatal contour is only approximate of course, because the position of the probe for the water swallow may be different from the position of the probe for speech practice, depending on the client's head position, and whether or not a fixed position is used for the transducer.) Alternatively, one could provide the client with a pseudopalate, and use both

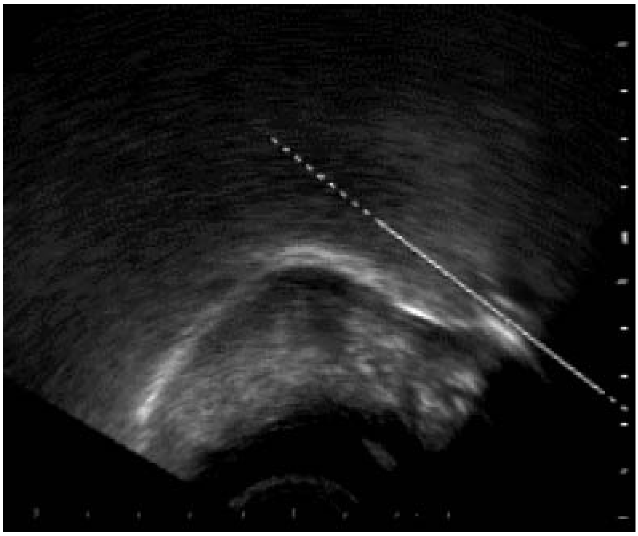

Figure 3. A sagittal display of a typical adult /t/ showing elevation of the tongue tip. The reference line approximates the alveolar ridge for tongue tip contact.

electropalatography and ultrasound simultaneously, something that has also not yet been tried in the ISRL studies.

A number of different ultrasound machines are currently available. Three different ultrasound machines have been employed in the ISRL treatment studies. Two have been used for both assessment and treatment: an Aloka SSD-900 portable ultrasound with a 3.5MHz convex intercostal transducer for Bernhardt et al. (2003), and more recently, an Aloka Pro-Sound SSD-5000 with a 6 MHz transducer. A portable Sonosite 180 Plus with a Sonosite C15/4-2 MHz MCX transducer has been used only for treatment. Clarity of the image is enhanced on all machines by adjusting the range and gain (e.g., range of 11, gain of 60 on the Aloka Pro-Sound) and coating the transducer with water-soluble ultrasound gel.

During assessment sessions, both audio and video data are collected so that the images of the tongue can be compared with the actual speech productions. With the Aloka portable, articulatory data were recorded to VHS tape at 30 frames per second from the ultrasound machine (JVC Super VHS ET Professional Series, SR-VS20), and the audio signal was simultaneously recorded on audiotape using a Pro-Sound YU34 unidirectional microphone amplified through the built-in pre-amplifier in a Tascam cassette deck, then simultaneously recorded to the same VHS tape as the video signal. With the Aloka Pro-Sound, ultrasound data have been recorded to digital videotape using a JVC Super VHS ET Professional recorder.

The three different machines have various advantages and disadvantages for speech therapy. With the portable machines, therapy can be conducted in a location convenient to the client. However, with portable instruments, it can be more difficult to ensure reliability of measurement across assessments, because of inconsistency in stabilization of the hand-held probe (although see Gick, Bird, & Wilson, 2005). Larger laboratory-based machines (such as the Aloka Pro-Sound) lack portability, but have larger, more diverse displays and can provide greater precision in measurement. With the ISRL set-up, for example, an ophthalmic examination chair allows stabilization of the speaker's head on a headrest, and a controlled position for the transducer, held in place with a mechanical arm attached to the chair. The angle of the transducer can also be recorded at each session, allowing verification of measurements later. In the clinical treatment process, small probe deviations may be insignificant. However, when measuring tongue movements, the error of within and between-sample measurement must be determined. The more constant the transducer position across samples, the less the error.

General speech therapy process

The speech therapy process with ultrasound has comprised the following components in the ISRL studies:

1. An initial speech assessment including:
   a. Audio-taped recordings of a standard word list (in the current studies, from the Computerized Articulation and Phonology Evaluation System (Masterson & Bernhardt, 2001)) and connected speech utterances
   b. Ultrasound and audio-recordings of sets of monosyllabic words repeated ten times in a standard phrase, e.g., "I'm a ___"
   c. An oral mechanism evaluation
   d. Other data relevant to participant diagnosis or previous treatment, e.g. hearing levels, EPG tracings, average pitch as determined by an acoustic analysis program.
2. An introduction to ultrasound through demonstration, written material, and practice with speech sounds and tongue movements.
3. A comparison of participant and target (SLP, parent) productions using "frozen" ultrasound images.
   a. The ultrasound machine allows the user to freeze the screen image at any particular point, giving a static image for discussion. Participants are asked to identify key elements of target productions in comparison with their own, both through drawings and in words. This perspective follows in the tradition of awareness and self-monitoring training approaches to phonological intervention (Bernthal & Bankson, 2004). Although the SLP initially has more information about phonetics through his or her training, the client also develops phonetics expertise through the treatment process. The ultrasound images provide the client with more information about tongue shapes and movements than can be gained with other types of feedback (the mirror, acoustic analysis, touch, electropalatography).
   b. Initially in treatment, tongue shape and movement patterns of normal speakers (usually the SLP) are used as templates for the client to emulate. As the client progresses through treatment, the SLP gives verbal feedback on the client's attempts. The client's tongue shape and movement patterns that result in the best acoustic productions then become the template for future productions. These may or may not be identical to the templates of the normal speakers.
4. Multiple practice opportunities at increasing levels of complexity, and using multiple cues (primarily visual and auditory, but sometimes also tactile).
   a. The treatment proceeds from articulatory gestures without voice, to gestures with voice for the target phones in isolation, then in syllables (in different

phonetic contexts, from most to least facilitative for the target in question, as in Kent, 1982), then in words, sentences, and conversation.

b. The SLP provides feedback on accuracy at all stages of the process, but from the beginning, the client is also asked to judge their own productions (whether tongue movements and location, or speech productions). For clients with hearing impairment, auditory self-monitoring can be challenging (depending on their hearing levels), but they can make judgments on visual displays and through tactile feedback (putting their hand under their chin, for example).

5. Clinic and home practice activities without ultrasound.
6. Ongoing evaluation of effectiveness (see the following section).

Evaluating effectiveness

The current paper focuses on treatment techniques with ultrasound, a discussion that would not be complete without a brief overview of methods used in evaluating treatment effectiveness. The ISRL studies have utilized standard single subject design procedures (as discussed in for example, Doehring, 1996): no-treatment and multiple baselines, alternating treatments, and short- and long-term post-treatment assessments or probes. Both quantitative measures (perceptual, acoustic, and ultrasound measures) and qualitative interviews (as in Denzin & Lincoln, 2003) have been utilized in evaluating outcomes, in accordance with the World Health Organization's (2001) recommendations for evaluation of (dis)ability at levels of the body (impairment), activities, and participation. The majority of methods have focused on changes in the body or impairment, i.e., phonetic transcriptions (Bacsfalvi et al., 2003; Bernhardt et al., 2003; Adler-Bock, 2004) and acoustic and ultrasound measurements (Adler-Bock, 2004). In addition, everyday listener judgments have been used to assess the speakers' potential for change in daily activities (Bernhardt et al., 2004) and interviews are being used to evaluate potential changes in the client's activities and participation in society (qualitative data).

Methodology for ultrasound measurement varies across researchers (see e.g., Gick, 2002; Whalen, 2003; Stone, 2005) in terms of the degree of automaticity, parameters selected for measurement, and type of values calculated (linear, non-linear, quadratic, ratio, etc.). To date, only one study has included ultrasound measurements in the ISRL treatment studies (Adler-Bock's 2004 treatment study of /r/ for two adolescents with residual speech impairments). Although a detailed description of the methodology is beyond the scope of the present paper, several key aspects of the measurement techniques are described for purposes of illustration. Still ultrasound images of the /r/ productions in various contexts were digitized from the ultrasound movies. Measurements were made at the maximum point of the articulatory gesture for each /r/ target (following standard practice for EPG measurement, e.g., Gibbon et al., 1996). Distances from the centre of the transducer (displayed at the bottom of the image in Figure 4) to the maximum points for tongue root retraction, tongue body height and tongue tip elevation were measured for each image. In addition, tongue heights were measured for the tongue body and tip.

These points of measurement were selected to capture key tongue shape constrictions for the target /r/: tongue tip raising, tongue body lowering, tongue root retraction (see more about /r/ in the next section). Key issues in ultrasound measurement are variable placements of the transducer and head movements of the speaker. Although the transducer was in a fixed position in the pre- and post-treatment assessments, there were small

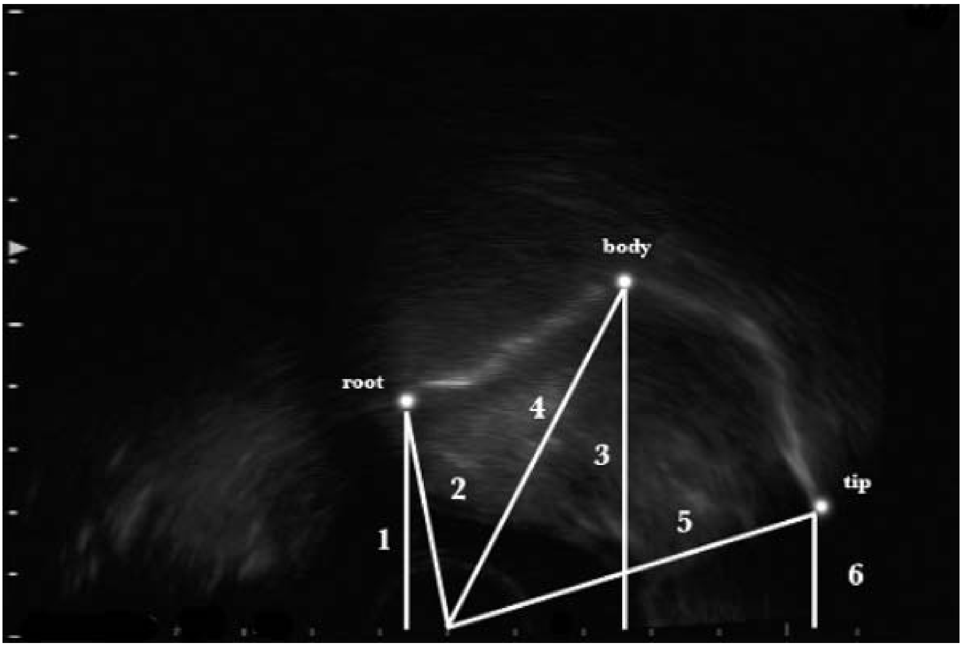

Figure 4. Locations of tongue measurement for /r/ in Adler-Bock (2004). 1=Height root (HR), 2=Distance to root (DR), 3=Height of body (HB), 4=Distance to body (DB), 5=Distance to tip (DT), 6=Height of tip (HT).

differences in transducer angles relative to the head between sessions, and slight head movements across tokens. Although there was no exact way to correct for head movement, a correction factor was worked out to minimize differences in transducer angle. This correction factor was based on pre- and post-assessment inter-speech tongue resting positions, with the clinical observations that rest positions can be stable and consistent postures that occur within speakers just before the onset of speech. The inter-speech tongue rest positions were captured and measured between repetitions of the phrases (e.g., "say ____ again" rest position "say ____ again"). The measurements were then used as benchmarks for comparing the transducer positions between the two sessions; pre-treatment measurements were adjusted (vertically, horizontally, and in terms of rotation) to correct for any difference in transducer positioning between the pre- and post-treatment sessions.

Treatment techniques for various sound classes

Across the studies, therapy techniques have been developed for the following categories: velar and alveolar stops, the approximants /l/ and /ɹ/, sibilants /s/, /ʃ/, and affricate /tʃ/, and vowels (tense-lax contrast, height and backness contrasts). Ultrasound displays give clearest feedback on tongue shape and place of articulation. Some information on manner of articulation is also visible. A caveat for the following discussion concerns intra- and inter-speaker variability in terms of exact tongue positions for targets, and relative amplitude of the various gestures. The goal of treatment with any method is an acceptable target in terms of acoustic parameters. Thus although the SLP or family member may model for the client, it is the client's own attempts that result in the SLP saying, "Yes. That's /s/. Now make that tongue shape/movement again."

Velars and alveolars

The velar-alveolar place difference is highly visible with the sagittal view of the tongue. The tongue tip movement and height for the alveolars contrast visibly with tongue body movement and height for the velars. (Figures 1 and 3 contrast /k/ and /t/.) Because stops also require articulator contact, it can sometimes be helpful to provide information relative to those contact points in order to enhance manner of articulation. This may be particularly important if the client has weak or no stop contacts. In the ISRL studies, reference lines were sometimes inserted onto the displays to provide target tongue positions for relative backness and tongue height (as shown in the figures), and/or to provide a visual reference for the hard palate (with a semi-horizontal line).

Sibilants and affricates

All alveolar and post-alveolar sibilants and affricates in English have lateral tongue-palate contact and a central groove (depression). The narrow central groove for /s/ at the point of alveolar constriction is shown in Figure 2. By tilting or dragging the transducer along under the base of the chin antero-posteriorly, the depth and width of the tongue groove can be portrayed at various locations. To give more information on tongue-palate contact patterns, diagrams of tongue-contact positions can be presented as an additional clinical support, e.g., from EPG diagrams or textbook drawings of the tongue (with the caveat that the client's own tongue contact patterns may differ from the diagram presented). The sagittal view shows the relative backness of the tongue tip and blade and helps distinguish alveolar from post-alveolar fricatives. Inserted lines or transparencies can provide stable reference information for tongue height, backness or grooving. The client attempts to move his or her tongue to the line provided.

The affricates have both stop and fricative components. The tongue has to move rapidly from an ungrooved tongue shape (the stop portion), to a grooved tongue shape (the fricative portion). For at least some speakers, it has been found in the ISRL studies, that the tongue also moves from a more forward (generally alveolar) position to a more clearly post-alveolar position for the affricate /tʃ/ (/t/ to /ʃ/). (Note that Hardcastle, Gibbon, & Scobbie, 1995, have not observed backwards movement for affricates; for their subjects, the stop portions of the affricate were in the same post-alveolar place as the fricatives.) Because displays are real-time, the therapist can model the tongue trajectories at different speeds to demonstrate the changing articulation. Additionally, a hard palate reference (via overlaid-transparency or on-screen reference lines) can be used show the difference in manner of articulation in terms of palate contact for the stop versus fricative portion of the affricate.

Vowels

The sagittal view for vowels shows relative tongue advancement and height for the various vowels. For example, the sagittal view for the vowels in Figure 5 displays a more advanced position of the tongue for one speaker's tense vowel /u/ relative to his cognate lax vowel /ʊ/, and in addition, shows a higher tongue body position for the tense vowel. Tongue trajectories for diphthongs in terms of backness and height are also clearly visible in the sagittal view (see also Gick & Wilson, in press).

Relative tongue height for the various vowels and tense-lax cognates can be similarly displayed using the coronal view (although that view was used only infrequently in the intervention studies).

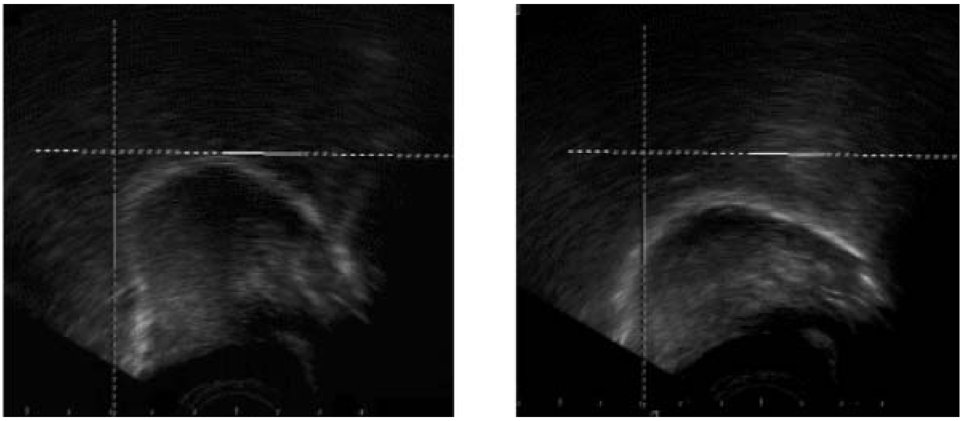

Figure 5. Sagittal displays of a typical adult tense vowel /u/ (left) showing a high tongue body and advanced tongue root position, and a typical adult lax vowel /ʊ/ (right), showing a retracted and lowered position compared with /u/ .

The approximants: English /r/ and /l/

The English /r/ and /l/ are complex articulations with multiple constrictions (both labial and lingual) that differ across word position and between speakers (Gick, 2003; Gick & Campbell, 2003; Oh, 2005). Ultrasound is a useful tool for showing the various lingual constrictions for the /l/ and /r/.

For /l/, the sagittal view shows extension of the tip and root, and a central dip (see Stone & Lundberg, 1996). The back constriction for /l/ is reduced in magnitude in prevocalic positions (Gick & Campbell, 2003; Figure 6, this paper). The dynamic sagittal view also shows relative timing of the anterior and posterior constrictions, with later anterior constrictions for the velarized [ł] (Sproat & Fujimura, 1993; Gick, 2003). The coronal view shows the lateral dip of one or both sides of the tongue for /l/, usually towards the posterior portion of the tongue body.

The English /r/ has several possible articulatory configurations, from a more retroflexed to a more bunched shape, and is generally articulated with three constrictions along the vocal tract (Delattre & Freeman, 1968; Alwan, Narayanan, & Haker, 1997; Westbury,

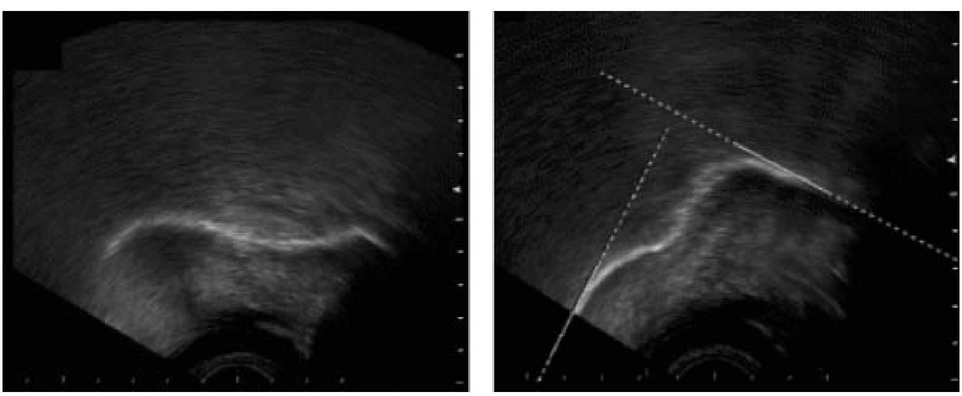

Figure 6. Sagittal displays of a typical adult prevocalic /l/ with posterior and anterior constrictions (left) and a typical retroflexed adult /r/ (right) with posterior and anterior constrictions.

Hashi, & Lindstrom, 1998; Tiede, Boyce, Holland, & Chou, 2004). The most anterior constriction (not visible with ultrasound) is labial, i.e., lip rounding, which is apparent particularly pre-vocalically. The middle constriction is made by the tongue tip or blade, as it stretches backward towards the palate (retroflexed /r/), or approximates the palate (in a more bunched /r/). The posterior constriction is made by the tongue root as it retracts towards the pharyngeal wall. Both of the tongue constrictions are visible with ultrasound. A posterior and relatively wide mid-line depression (channel) is another important component of /r/ articulation. The posterior part of the tongue body is "braced" against the back teeth on each side of the oral cavity. The depression is visible in the coronal view of /r/.

In the treatment studies, we have used a componential approach to teaching /r/ and /l/, focusing on the various lingual constrictions singly, and then in combination (Bacsfalvi, Adler-Bock, Bernhardt, & Gick, 2004). Reference lines have been sometimes added to the displays to help the clients focus on relative tongue tip or body height, and root retraction. Generally, retroflexed /r/ has been easier to demonstrate than bunched /r/. Contextual facilitation has also been utilized successfully for /r/. Most effective phonetic contexts across participants have been:

1. Alveolar stops in clusters /tr/ and /dr/: The raising of the tongue tip for the clusters appears to helps position the tongue for /r/ with the tip up, and the body and root retracted and low (the shape of a children's slide).
2. After /l/ (tongue tip up): When producing /l/, then sliding the tongue quickly back and forth along the palate, the participants sometimes produced an [r] in transit. Once identified, they learned to prolong the [r] part of the articulation, using the visual feedback to help focus the prolongation.
3. After /i/ or /ʃ/: These facilitated /r/ by focusing attention on the lateral tongue bracing and posterior mid-line groove common to both (in approximately the same location along the hard palate).
4. After the low back vowel /ɑ/: The /ɑ/ and /r/ share a similar tongue retraction, promoting the pharyngeal constriction of /r/.

Conclusions

Two-dimensional ultrasound has shown promise as a way to accelerate positive change in speech production in adolescents and adults with varying backgrounds (hearing impairment, persistent speech impairment, accented English). Advantages of ultrasound are as follows:

1. The tongue can be observed dynamically or statically with either sagittal or coronal-oblique views, providing alternative perspectives on configurations and movements. Images can be enhanced and extended through reference lines and the use of overhead transparencies.
2. Ultrasound is used external to the face, and is thus less invasive than other current visual feedback technologies (EPG, magnetometry, glossometry).
3. Ultrasound does not require individualized hardware, such as the artificial palate for EPG. Thus, it can be used immediately, without additional costs or delays per client.
4. The displays are relatively easy to explain to participants.

5. Portable ultrasound machines allow treatment to be provided in locations convenient for the client; stationary machines with fixed transducers allow consistency in data collection for evaluation purposes.

Ultrasound has not yet been systematically compared with other visual feedback tools, although both EPG and ultrasound were found to be effective in Bernhardt et al. (2003).

Some limitations of two-dimensional ultrasound, and possible ways to address those limitations are as follows:

1. It is not possible to monitor the sagittal view and the coronal view simultaneously with two-dimensional ultrasound. Three-dimensional dynamic ultrasound (currently a static display) or the simultaneous use of EPG and ultrasound could provide more multidimensional views, which might prove more facilitative.
2. Further, ultrasound does not provide tongue-palate contact information. Reference information can be added to the display, but the combined used of EPG and ultrasound again might be more illuminating than static reference lines or transparencies.
3. Ultrasound gives no acoustic information. A divided screen showing both tongue configurations and acoustic displays could provide additional information on pitch, intensity, voicing, manner of articulation and/or formants.
4. Methods for ultrasound measurement are time-consuming and still under development. It is not yet known whether the lack of consistency in probe positioning across utterances and sessions is a critical factor for treatment and outcomes evaluation, but the minimization of differences in probe angle across sessions is crucial for accuracy in research.

There is much yet do discover about speech production and speech (re)habilitation. Ongoing basic and clinical research with ultrasound will enhance our knowledge in those areas.

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