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Physiological investigation of dysarthria: Recent advances

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Recent years have seen the development and introduction of a range of new physiological instruments for investigating various aspects of articulatory function in persons with dysarthria. Included among these techniques are electromagnetic articulography (EMA), electropalatography (EPG), and pressure-sensing EPG. The aim of this paper is to describe and evaluate these techniques, highlighting their relative advantages, disadvantages, and specific applications in assessing articulation in speakers with dysarthria associated with a variety of neurological disorders. Emphasis will be given to those instruments that enable researchers and clinicians to examine articulatory functions in 3-dimensions, such as 3D-EMA (AG500) and 3D-EPG. In addition the application of pressure-sensing EPG and ultrasonography will be outlined. Each of these physiological techniques will be fully described in terms of their component hardware and underlying principles of operation. The use of each technique in the assessment of dysarthria will be illustrated wherever possible by reference to specific case examples, and especially cases drawn from various neuropathological groups. Research findings reported to date based on each of the above physiological instruments will be reviewed and the research summarized.

Keywords: *Dysarthria, speech impairment, motor speech disorders.*

Introduction

Although perceptual evaluations remain the benchmark for the assessment of dysarthria and contribute valuable information to the process of diagnosing and interpreting neurological speech disorders, instrumental observation and measurement of speech and its physiological correlates offers significant advantages over unaided perceptual judgements. The so called "physiological approach" to the assessment and treatment of motor speech disorders as espoused by Hardy (1967), Netsell (1986), and Murdoch (1996) evolved from the concept that the assessment of the individual motor sub-systems of the speech production mechanism (respiratory, laryngeal, velopharyngeal, and articulatory sub-systems) was crucial in defining the underlying speech pathophysiology and consequently for enabling the development of optimal treatment programmes (Abbs & DePaul, 1989; Murdoch, 1996). By including the use of instrumental procedures in the process of diagnosing speech disorders, clinicians are able to extend their senses and objectify their perceptual observations. In particular, instrumentation has given the clinician the ability to determine the contributions of malfunctions in the various components of the speech production mechanism to the production of disordered speech. Indeed, modern instrumentation enables the clinician to assess and obtain information about the integrity and functional status of the muscle groups at each stage of the speech production process from respiration through to articulation. It is not surprising, therefore, that clinicians are beginning to appreciate the considerable advantages of instrumental analysis which provides quantitative, objective data on a wide range of different speech parameters far beyond the scope of an auditory-based impressionistic judgement. Instrumental assessment can enhance the abilities of the clinician in all stages of clinical management, including:

- increasing the precision of diagnosis through more valid specification of abnormal functions that require modification;
- the provision of positive identification and documentation of therapeutic efficacy; and
- the expansion of options of therapy modalities, including the use of instrumentation in a biofeedback modality.

Unfortunately, until recently the application of the physiological approach has been hampered by a lack of appropriate instrumentation. For instance, the unavailability in past years of instruments capable of recording, in a safe and non-invasive manner, the

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dynamics of articulatory movements during speech production has seriously restricted the use of physiological instrumentation in the assessment and remediation of articulatory impairments associated with various types of dysarthria. In particular, the methodological difficulties encountered in viewing and tracking movements of the tongue due to its confinement in the oral cavity has presented a major obstacle to assessment of articulatory dynamics in speakers with dysarthria.

Advances in technology have seen the introduction of several physiological instruments capable of assessing articulatory dynamics in a non-invasive and safe manner. Notable among these instruments are the electropalatograph (EPG), capable of recording in real time tongue-to-palate contacts during speech, and electromagnetic articulography (EMA) which is able to record real time movements of the tongue, lips, and jaw during speech production. Both EPG and EMA have made significant contributions to our understanding of the nature of articulatory breakdown in motor speech disorders. The aim of the current review is to provide an update of the progress in development of new techniques to quantify articulatory function, with emphasis on three dimensional (3D) technologies to highlight the relative advantage/disadvantages of each method. Some of the problems encountered in the development and application of new technologies for assessing the dynamics of articulation, including 3D techniques, will be outlined. Specifically three new instrumental techniques will be described and discussed, including: three dimensional electropalatography (3D EPG), pressure-sensing palatography (PPG), and three dimensional electromagnetic articulography (3D EMA).

Prior to describing and discussing these techniques, however, it is of relevance to outline the origins of the author's current interest in quantitative investigation of dysarthria. Early in 1982 I was fortunate to be able to attend the inaugural Clinical Dysarthria Conference held in Tucson, Arizona. This conference was a landmark event for two reasons. First, it laid the foundation for what was to become the highly influential Motor Speech Disorders/Control Conference which is now held bi-annually. Second, the Tucson conference was a landmark meeting for me personally as it introduced me to the world of quantitative analysis of motor speech disorders. In particular, a paper presented by a young English speech-language pathologist named Pam Enderby was the first occasion on which I became aware of the potential for careful clinical observations of the speech production mechanism to be used to produce a standardized profile of dysarthria. The paper presented by Pam Enderby, of course, went on to be published as the now famous Frenchay Dysarthria Assessment (Enderby, 1983), an assessment that I and my research team have frequently used in combination with various physiological assessments to determine the pathophysiological basis of dysarthria associated with a variety of neurological conditions. In short, Pam Enderby was largely responsible for igniting my interest in quantitative, physiological assessment of dysarthria, an interest that I have now pursued for some three decades. It is a privilege to contribute to this Festschrift for Pam as a tribute to her enormous contribution to our understanding of neurogenic speech/language disorders and for leading the way in the development of quantifiable and standardized assessments of dysarthria.

Electropalatography

Electropalatography (EPG) is a technique for examining tongue function, which provides the clinician with information on the location and timing of tongue contacts with the palate during speech. In this technique, the client wears an acrylic palate with an array of contact sensors (varying from 32, 62, or 124) implanted on the surface (Hardcastle, Morgan-Barry, & Clark, 1985) (see Figures 1 (*a*) and (*b*)). When contact occurs between the tongue and any of

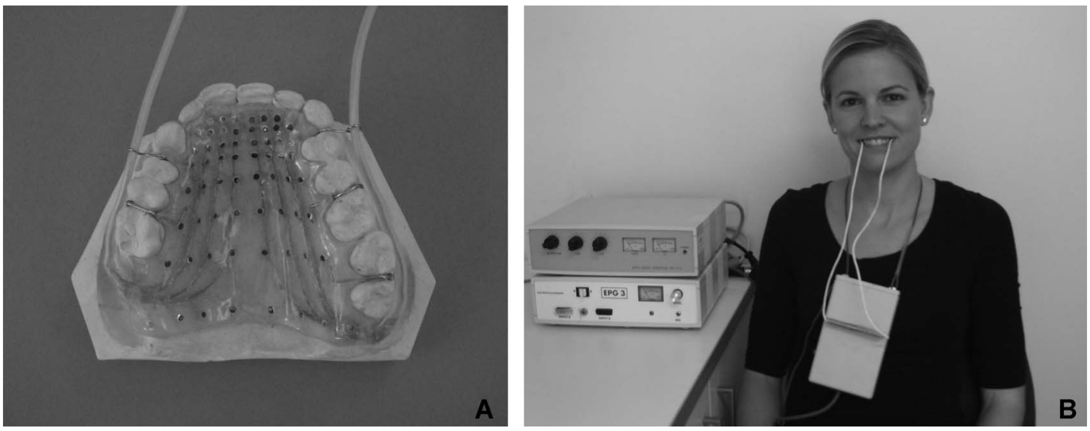

Figure 1. (*a*) Acrylic electropalatography (EPG) palate with touch sensitive electrodes. (*b*) Client fitted with electropalatography (EPG) palate.

the electrodes, a signal is conducted via lead-out wires to an external processing unit, which then displays the patterns of contact on a computer screen (see Figure 2).

Traditional two dimensional electropalatography (2D EPG) is a well-established technique being used in many speech science laboratories and clinics (Hardcastle, 1996) for both the assessment and treatment of speech disordered populations, including individuals with motor speech disorders (Goozée, Murdoch, & Theodoros, 1999; Goozée, Murdoch, Theodoros, & Stokes, 2000; Hartelius, Theodoros, & Murdoch, 2005; McAuliffe, Ward, & Murdoch, 2007; Murdoch, Gardiner, & Theodoros, 2000), structural abnormalities such as cleft palate, hearing impairment, and children with developmental speech disorders (Bacsfalvi, Bernhardt, & Gick, 2007; Fuchs, Brunner, & Busler, 2007; Fujiwara, 2007; Gibbon, Yuen, Lee, & Adams, 2007; Guzik, & Harrington, 2007; Hardcastle, 1996; Howard, 2007; Lee, Gibbon, Crampin, Yuen, & McLennan, 2007; Martin, Hirson, Herman, Thomas, & Pring, 2007; Moen, & Simonsen, 2007; Schmidt, 2007;

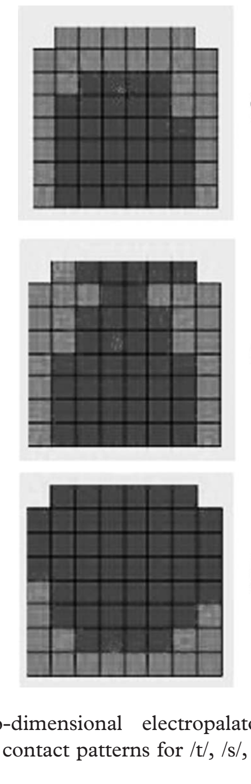

Figure 2. Two-dimensional electropalatography (2D EPG) tongue-to-palate contact patterns for /t/, /s/, and /k/.

Wrench, 2007). Despite this, traditional 2D EPG is limited by the nature of its display. The classic two dimensional (2D) tongue-to-palate diagrams (see Figure 2) that represent the output of the system fail to demonstrate either the unique anatomical characteristics of the individual palates or the relative spacing between the touch sensitive electrodes. Given that it is well accepted that palatal shape varies widely from individual to individual (some individuals have narrow, high-arched palates while others have broad, flat palates), and that shape influences tongue-to-palate contacts during speech (Hiki & Itoh, 1986), this failure may cause the data derived from traditional 2D EPG to be misinterpreted, especially when comparisons of the amount, location, and pattern of contacts are to be made between different speakers (e.g., narrow, high-arched palates are associated with an increased number of tongue-to-palate contacts due to closer proximity of the touch sensitive electrodes).

In an attempt to provide a solution to the limitations of traditional 2D EPG, researchers at the Centre for Neurogenic Communication Disorders Research, The University of Queensland, have recently developed a 3D EPG system aimed at improving graphic representation of tongue-to-palate contacts by way of computer generated, interactive 3D palatal models (Goozée, McAleer, Scott, & Murdoch, 2003). Although this latter system utilizes the same hardware and artificial acrylic palates as the traditional Reading EPG-3, it provides researchers and clinicians with the ability to visualize 3D images of their client's tongue-to-palate contacts during speech (see Figure 3).

The 3D system utilizes 3D laser scanning of the EPG palates combined with a custom-developed software package to enable simultaneous integration and display of the spatial geometry of the palate with details of tongue contact. Briefly, the dental cast of the client's hard palate required for moulding and manufacture of the artificial palate is scanned using a portable Polhemus Fast Scan hand-held laser profile scanner connected to a personal computer. The scanner scores 3D coordinates from the surface of the cast using a projected laser line and cameras mounted at an angle to the laser line to create a 3D mesh representation of the palate (see Figure 4). These coordinates are then uploaded into a custom-written software package (3D EPG viewer) to render a 3D

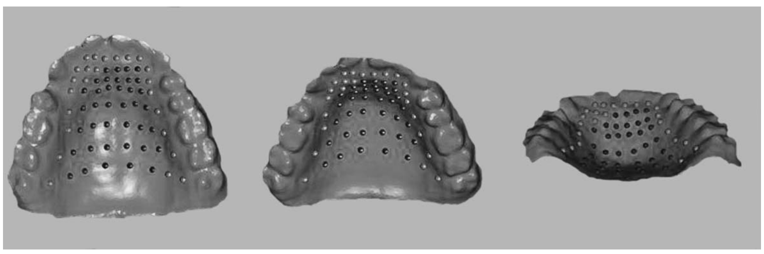

Figure 3. Three-dimensional (3D) image of the palate with virtual sensors showing tongue-to-palate contact.

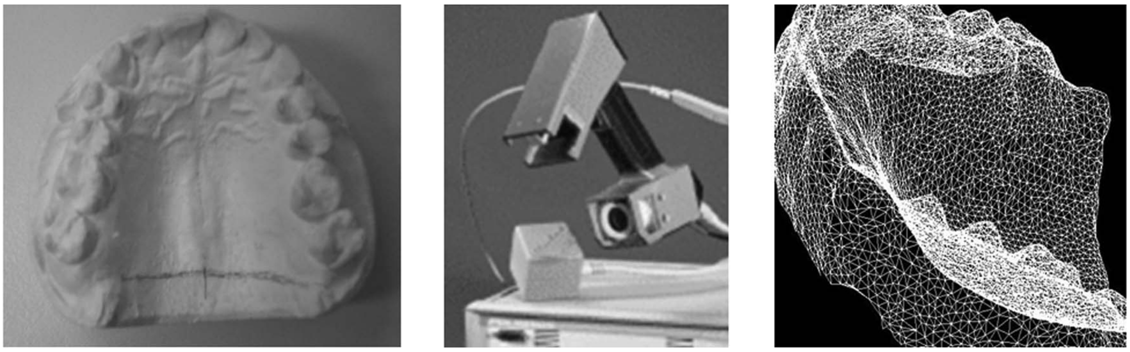

Figure 4. Laser scanning of the palatal cast to create a three-dimensional (3D) mesh image.

image of the individual's palate which includes virtual sensors representative of the touch sensitive electrodes in the artificial palate and which change colour according to the position and timing of tongue contacts with the artificial palate (see Figure 3).

Goozée et al. (2003) compared the effect of 2D vs 3D presentation on the interpretation of deviant EPG tongue-to-palate contact patterns by a panel of experienced speech-language pathologists. They reported that, based on presentation of the 2D diagrams, the panel of clinicians only provided a neurologically-based explanation for the deviant contact patterns recorded from a group of dysarthric patients post-traumatic brain injury, neglecting the possible influence of palatal geometry. In contrast, when provided with the 3D outputs, the panel provided both anatomically-based as well as neurologically-based explanations for the observed discrepancies in the EPG contact patterns. These findings highlight the potential for 2D EPG diagrams to be misinterpreted with possible flow-on consequences for the application of inappropriate therapy procedures. Clearly the findings of Goozée et al. (2003) demonstrated that the 3D EPG system was superior to the traditional 2D EPG in that it provided clinicians with a better basis on which to make judgements as to the potential factors that contribute to the discrepant EPG contact patterns in their clients, thereby enabling development of more appropriate treatment strategies.

Pressure-sensing palatography

As outlined above, EPG allows the timing, location, and patterns of tongue contacts against the hard palate to be examined during speech and, in doing so, provides important insights into the physiological disturbances that may underlie an individual's motor speech disorder. Indeed, both timing and spatial disturbances in tongue-to-palate contacts have been described in EPG studies of dysarthric speakers (Goldstein, Ziegler, Vogel, & Hoole, 1994; Goozée et al., 1999, 2003; Hardcastle et al., 1985; Hartelius et al., 2005; Morgan Barry 1993; Murdoch et al., 2000). The disturbances identified were posited to be responsible for, or at least to have contributed to, some of the deviant features perceived, including consonant imprecision and disturbances in speech intelligibility and rate. Aberrant EPG findings, like those reported in the various studies of dysarthric speech, lead to the question of "what physiological mechanism/s are responsible for those spatial and/or timing tongue to palate contact disturbances?" Answers to questions of this kind would help to further specify treatment goals and guide the development of even more effective physiologically-based treatment approaches. One possible mechanism underlying spatial and time disturbances might be aberrations in the pressure with which the tongue contacts the hard palate. Indeed, disturbances in the control of tongue pressure and tongue weakness have been commonly identified using static physiological measures in individuals with dysarthria (McNeil, Weismer, Adams, & Mulligan, 1990; Theodoros, Murdoch, & Stokes, 1995). Unfortunately, no instruments are currently commercially available to directly measure the dynamic tongue pressures generated during actual speech production. Consequently, the next step in the evolution of EPG is to extend its capabilities to dynamic pressure sensing. A device that records the spatial, timing, and pressure features of tongue contacts against the hard palate during speech would extend the capabilities of researchers and clinicians in determining the physiological bases of tongue dysfunction in a variety of speech disorders.

Although the development of a device to measure dynamic lingual pressures represents the new frontier in EPG, the concept of measuring tongue-to-palate pressure during speech production is by no means a new one. In the 1960s and early 1970s a series of primarily phonetic-based studies were carried out to examine lingual pressures exerted during articulation in normal and alternate conditions (e.g., different rates of speech, intensity levels) and to investigate issues such as the usefulness of lingual pressure measures in physiologically differentiating speech sounds (McGlone, & Proffit 1967; McGlone, Proffit, & Christiansen, 1967; Proffit, & McGlone 1975; Proffit, Palmer, & Kydd, 1965). These studies were often limited, however, in regards to the instrumentation and the recording and analysis procedures employed with typically only one-to-three relatively bulky strain gauge pressures transducers, either embedded in an artificial palate or attached to the teeth, being used to record tongue pressures, with little or no rationale provided regarding choice of sensor position. Pursued by only a small number of researchers, primarily McGlone and Proffit, this line of research appeared to be abandoned before the 1980s.

Recently, there has been a resurgence in interest regarding tongue-to-palate pressures, with instruments being developed by researchers in Japan and in the US (Wakumoto, Masaki, Honda, Kusakawa, & Ohue, 1999; Yokoyama, Sonies, Michiwaki, & Michi, 2001), in Germany (Müller, Rose, Hohlfeld, Blechschmidt, Schuster, & Werthschutzky, 2002), in France (Jeannin, Perrier, Payan, Dittmar, & Grosgogeat, 2008), and by researchers at the Centre for Neurogenic Communication Disorders Research, The University of Queensland, Australia (Murdoch, Goozée, Veidt, Scott, & Meyers, 2004) for examining tongue pressures exerted against the palate during speech and/or swallowing. The development and features of the Australian prototype PPG are briefly outlined below. For a full description of the instrument, including calibration procedures, the reader is referred to Murdoch et al. (2004). A requisite for devising the Australian dynamic tongue-to-palate pressure-sensing instrument was that, in addition to measuring pressure, it would incorporate the important dynamic features and capabilities of the successful Reading EPG-3 system. That is, it would also be able to provide information regarding the timing and spatial characteristics of tongue contacts during speech.

In the initial PPG, five pressure sensors were embedded in an acrylic palate specifically moulded to an individual's hard palate using a replica cast, as per current EPG palates. A photograph of the prototype PPG is presented in Figure 5.

Figure 5. Photograph of prototype pressure-sensing palate, with five embedded pressure sensors (three in anterior region and two posterior).

On the basis of the findings of trials performed on both normal (Murdoch et al., 2004) and dysarthric speakers, it is evident that, although at the prototype stage, PPG represents the new generation of EPG, being capable of recording dynamic tongue-to-palate pressures with minimal to no interference to speech detected perceptually. Further, PPG has been shown to be sufficiently sensitive to detect tongue pressure differences between different consonants, and was reported to be able to register lingual pressures for all of the alveolar consonants examined by Murdoch et al. (2004). Despite this, as is expected in the case of instruments at the prototype stage of development, further refinements and improvements to the instrument are needed. For instance, the restricted number of pressure sensors in the prototype PPG has been reported to cause some problems in the optimal positioning of the pressure sensor to detect consonant lingual pressures (Murdoch et al., 2004). This problem, however, is expected to be largely overcome by increasing the number of pressure sensors in the palate, thereby increasing sensor coverage across the palate. Further refinements of the prototype PPG are also currently in progress, including optimization of the artificial palate using future polymer concepts, with the intended goal of producing a flexible palate sub-structure that can be reused and moulded to a person's hard palate.

Overall, despite the need for further development and refinement, the PPG has already proven to be a useful addition to the battery of instruments currently available to assess tongue function during speech. PPG has the potential to extend the capabilities of researchers and clinicians in determining the physiological bases of tongue dysfunction in a variety of speech disorders, thereby enabling more specific treatment goals to be devised that target the underlying physiological disturbance(s).

Electromagnetic articulography

Electromagnetic articulography (EMA) is a technique for tracking articulatory movements during speech using alternating electromagnetic fields. Specifically, the movements of miniature receiver coils, which can be fixed to various articulators, including the tongue, upper and lower lips, jaw, and velum, are detected and recorded over time. In the case of 2D EMA systems currently in most frequent use, these movements are recorded along the midsagittal plane (Hasegawa-Johnson 1998; Kaburagi & Honda 1997; 2002; Schönle, Grabe, Wenig, Hohne, Schrader, & Conrad, 1987; Wakamiya, Kaburagi, Honda, & Sawada, 2003). The first commercially available 2D EMA system, the AG100, was developed by Carstens Medizinelektronik in 1988. Since that time, an upgraded 2D EMA, the AG200, has also been released. In both the AG100 and AG200 2D EMA systems transmitter coils, housed in an assembly that fits around a person's head and positioned in the

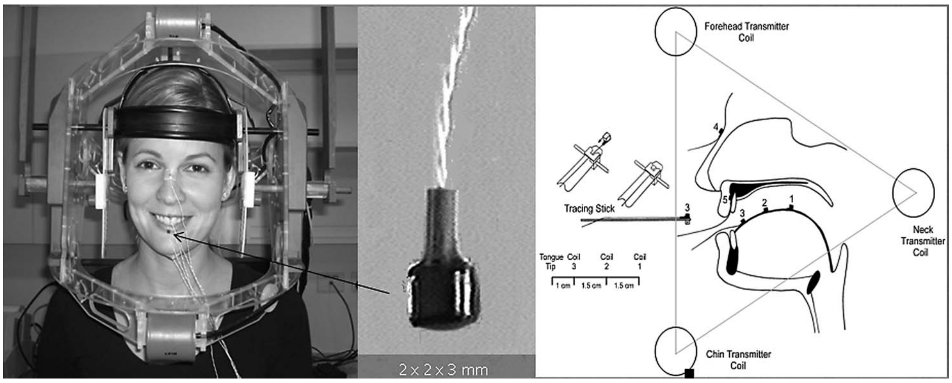

Figure 6. Two-dimensional (2D) electromagnetic articulograph showing the helmet and transmitter coils, miniature receiver coil, and typical placements for receiver coils on the articulators in the midsagittal plane.

midsaggital plane, generate alternating magnetic fields at different frequencies, which in turn induce alternating signals in a set of miniature receiver coils (see Figure 6). The distance between a single receiver coil and a transmitter coil can be determined by the magnitude (or relative strength) of the alternating electrical signal induced in the receiver coil, as it will be inversely proportional to the cube of the distance from the transmitter coil (Perkell, Cohen, Svirsky, Matthies, Garabieta, & Jackson, 1992; Schönle et al., 1987), provided the transmitter and receiver coil axes are in parallel alignment. The alternating signal induced in a receiver coil placed within the magnetic fields generated by the transmitter coils is comprised of signal components of differing frequencies that match the frequencies of the transmitter coils. By separating the signal components at each receiver coil and determining the distance between the receiver coil and each transmitter coil using the magnitude of each signal component, the location (x–y coordinates) of the receiver coil within the 2D representation of articulator movements along the midsagittal parameters can be computed, including the velocity, acceleration/deceleration, displacement, and duration of articulatory movements. To date 2D EMA has been used to study articulatory kinematics in a range of normal and disordered speakers including: children (Murdoch & Goozée, 2003) and adults (Kuruvilla, Murdoch & Goozée, 2007) with dysarthria subsequent to traumatic brain injury; adults with dysarthria post-stroke (Chen, Murdoch, & Goozée, 2008); and speech disordered children exhibiting differentiated and undifferentiated lingual gestures (Goozée, Murdoch, Ozanne, Cheng, Hill, & Gibbon, 2007a). The technique has also been used to investigate lingual kinematic strategies used to increase speech rate in younger and older adults (Goozée, Stephenson, Murdoch, Darnell, & LaPointe, 2007b). For a recent review of the use of 2D EMA see Van Lieshout (2006).

Despite the ability of 2D EMA systems to identify aberrant articulatory kinematics in speakers with motor speech disorders associated with a variety of neurological conditions, the greatest limitation of 2D EMA is its restriction to tracking movements in the midsagittal plane. A major consequence of this limitation is that 2D EMA is not able to monitor substantial lateral deviations of the tongue and jaw from the midline (e.g., as occurs in flaccid dysarthria associated with unilateral lesioning of the XIIth cranial nerve) without error. To overcome this limitation, Carstens Medizinelektronik has more recently developed the AG500 EMA, which is capable of tracking articulatory movements in three dimensions. The 3D EMA involves six transmitter coils housed within a plastic box-like helmet (see Figure 7). Importantly, unlike the 2D EMA systems, the 3D EMA helmet does not restrict movement of the individual undergoing assessment, which facilitates the use of the instrument with children (who are more prone to movement than adults) and persons with movement disorders (e.g., Parkinson's disease, Huntington's disease, etc.). Importantly, the 3D EMA system allows not only full spatial recording of sensor movement, but also measurement of the sensor orientation. Consequently, unlike 2D EMA, lateral tongue and jaw movements provide a source of information rather than error. Given that the AG500 can track articulatory movements in 3D raises the possibility that movement signals

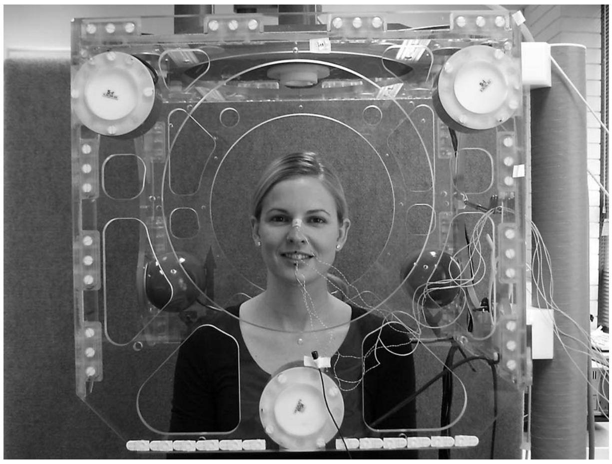

Figure 7. Three-dimensional (3D) electromagnetic articulograph (AG500).

(e.g., tongue movement) acquired by the AG500 may be able to be translated into visual representations (e.g., of tongue movement) that could be utilized in biofeedback therapy for the treatment of a range of articulatory disorders, as has been tested with 2D EMA (Katz, Bharadwaj, & Carstens, 1999; Katz, Carter, & Levitt, 2007a; Katz, Garst, Carter, McNeil, Fossett, Doyle, et al., 2007b).

The 3D EMA has the potential to provide, for the first time, the opportunity to quantify lingual, jaw, and lip movements during speech in three dimensions. In this way, 3D EMA will provide a greater understanding of the physiology of articulatory function in normal speech as well as the pathophysiology of articulatory breakdown in speech disorders associated with neurological diseases, orofacial abnormalities (e.g., cleft palate), etc. Further, 3D EMA would appear to offer an unprecedented opportunity to develop 3D visual models of the tongue for use in physiological biofeedback programmes for the treatment of a range of articulatory disorders. The AG500 EMA system therefore has potential to be used not only as a research tool but also clinically as a biofeedback device.

Conclusion

With the possible exception of studies based on x-ray microbeam and ultrasound techniques, in past years the secrets of tongue function in speech remained hidden within the confines of the oral cavity due to a lack of appropriate instrumentation. Only relatively recently have tools and instruments in the form of 2D technologies such as 2D EPG and 2D EMA provided a means of visualizing, in a limited way, the functioning of the tongue and other articulators during speech. The 3D technologies outlined above have the potential to provide unprecedented opportunities to quantify normal and disordered articulatory function from a more realistic 3D perspective with direct benefits for the development of more efficacious treatment approaches for dysarthria. Undoubtedly, the impetus for development of these technologies was based on the call for the development of more standardized and quantitative assessments of dysarthria made by Pam Enderby as far back as the early 1980s.

At the time of writing, the physiological instruments described and discussed above are primarily restricted to use as research tools, their use in clinical situations being somewhat limited by their relatively high cost and by the need for specialized training in their use. The adoption of these techniques into more widespread clinical use will be dependent on proof of their ability to provide a clearer understanding of the pathophysiological basis of the various forms of dysarthria, leading to more effective and efficacious interventions. In the event that such proof is forthcoming, the training of speech-language pathologists in the use of these methodologies will need to be incorporated into the relevant education programmes.

As further physiological techniques for the investigation of dysarthria are developed in the future, it is not suggested that the perceptual methods that have provided the gold standard for dysarthria assessment be abandoned. Rather, physiological instruments such as those outlined above should be used to complement perceptual assessments. Further, it is anticipated that in the near future developments in the fields of neurophysiology and neuroimaging such as transcranial magnetic stimulation and diffusion tractography will further enhance our ability to investigate the neuropathophysiological basis of dysarthria by providing information as to the status and integrity of the motor systems involved in the regulation of motor speech function.

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