Application of Cine Computed Tomography to the Assessment of Velopharyngeal Form and Function

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The mechanism of velopharyngeal closure is clearly three-dimensional in nature. Numerous attempts have been made to obtain a comprehensive picture of velopharyngeal movement, with varying degrees of success. A computed tomography scan system has recently been developed that may be used for real-time motion study of various body systems. This preliminary study was designed to assess the applicability of multi-level cine computed tomography scanning as a tool in the three-dimensional analysis of the velopharynx. One normal speaker and one speaker with an unrepaired palatal cleft were asked to phonate while serial sections were taken at 650-millisecond intervals through a number of transverse sections in the velopharyngeal region. This paper includes an explanation of cine CT technology, examples of scans on two speakers with clearly different velopharyngeal mechanisms, and discussion of the potential use of cine computed tomography as a tool in the analysis of both normal and disordered velopharyngeal function.

Information regarding structure and function of the velopharyngeal mechanism in normal individuals and those with velopharyngeal dysfunction is important to our understanding of the mechanism, and to our ability to recommend treatment.

The mechanism of velopharyngeal closure has been well documented. It is evident that movements in both the sagittal and coronal planes contribute to separation of the nasal and oral cavities (Skolnick et al, 1975; McWilliams et al, 1984). Movement in the sagittal plane may be documented using still lateral view radiography (Hixon, 1949), lateral view cineradiography (Karnell et al, 1985), or lateral view videofluoroscopy (McWilliams and Girdany, 1964). However, the velopharyngeal valve is three-dimensional and, as such, a comprehensive picture of its movement cannot be obtained by viewing only the midsagittal plane.

Numerous attempts have been made to document movement in the coronal plane. Of particular interest has been the documentation of movement of the lateral pharyngeal walls. Nasal endoscopy (Ibuki et al, 1983) allows for direct observation of the velum and pharyngeal walls during speech or nonspeech tasks. However, quantification is a problem. Further, assessment of lateral pharyngeal wall movement using nasal endoscopy is not reliable (Ibuki et al, 1983). Multiview videofluoroscopy (Skolnick, 1970) permits visualization by obtaining independent lateral, frontal, and basal views of the velopharynx. According to Skolnick (1975), the vertical location of lateral pharyngeal wall movement would be evident from the frontal view. Soft palate and posterior pharyngeal wall movement would be evident from the lateral view. Finally, all but the vertical location information would be seen in the basal view. Since multiview videofluoroscopy technique involves a separate procedure for each plane of viewing, the assumption must then be made that the patient is doing the same thing during all three procedures. Further, this technique involves three separate exposures to radiation by the patient. While not applicable to assessment of velar movement, ultrasound has been proposed as an instrument of some potential use in the evaluation of lateral

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pharyngeal wall movement (Hawkins and Swisher, 1978). However, the technique is not commonly used, perhaps since visualization of movement is difficult. In an effort to obviate the masking effect of structures overlying the pharynx on frontal view radiographs, Kuehn and Dolan (1975) proposed the use of frontal tomography. Although the technique was proposed to enable the investigator to "measure the degree and level of mesial displacement of lateral pharyngeal wall in relation to the soft palate, tongue, and other structures observable on lateral view radiographs" (p 208), the technique is not in common use today.

Given that the velopharyngeal mechanism is a three-dimensional valve, an evaluative system that allows for visualization of the mechanism in three dimensions would be of distinct value to the diagnostic process. A system that allows for three-dimensional visualization of the mechanism in motion would be of additional value. Three-dimensional imaging of bone surfaces has been accomplished (Marsh and Vannier, 1983). These three-dimensional images are constructed from a series of between 30 and 64 non-overlapping conventional axial computed tomography scans obtained at 2-mm intervals. While this technique is useful in describing normal and abnormal anatomy and in the planning and evaluation of surgical procedures for craniofacial anomalies, it is not readily applicable to imaging of dynamic events. Three-dimensional imaging of dynamic events has been attempted in the form of multiview videofluoroscopy (Skolnick and McCall, 1972). However, the latter technique involves some significant liabilities as described earlier.

Recently, a computed tomography scan system has been developed that is capable of three-dimensional real-time motion study of various body systems. The purpose of this paper is to present this new technique for the simultaneous and three-dimensional assessment of dynamic activity in the velopharynx.

COMPUTED TOMOGRAPHY TECHNOLOGY

Computed tomography involves the mathematical, computer-assisted reconstruction of an image of a "slice" of anatomy. The input to the mathematical reconstruction process is a series of x-ray transmission measurements made in a number of different directions around the patient, all located in the tomographic plane or "slice" of interest (Trefler, 1985).

Conventional computed tomography produces images that reflect the varying attenuation of x-ray photons by body tissue of various densities. A conventional x-ray tube is used to generate the x-ray beam. Sensitive x-ray detectors are mounted on a gantry (Fig. 1) opposite the x-ray tube and measure the x-ray beam at different points after it has been transmitted through the patient. The section or slice is viewed from a number of angles as the gantry rotates around the patient. A typical scan requires 2 to 4 seconds to complete.

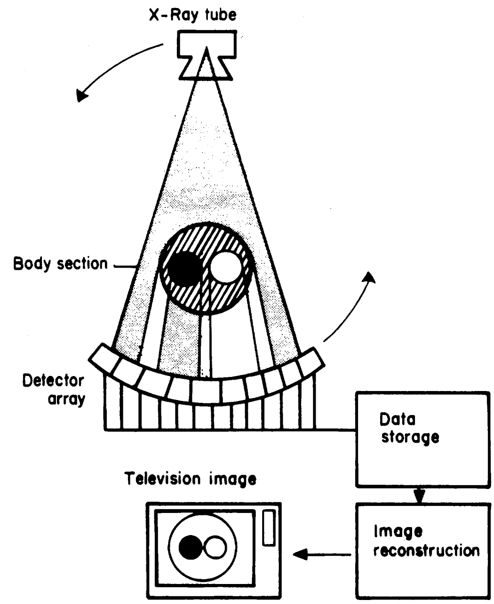

FIGURE 1 Conventional computed tomography system (Reproduced with permission from: Baddeley H, Davies E. Radiological investigation: a guide to the use of medical imaging in clinical practice. Australia: John Wiley & Sons, 1984.)

The cine computed tomography scanner (Imatron)[1] shown in Figure 2 is designed so that all mechanical motion is eliminated. After leaving the x-ray tube, the electron beam expands owing to mutual repulsion of the electrons and is focused by a magnetic lens. A bending magnet deflects the converging beam through a fixed angle, as may be seen in Figure 2. A time variation of the deflection magnet currents causes the plane of bending to rotate. At the base of the conical section, the focused beam strikes one of four target rings. The target ring is curved, forming a 210-degree arc below the patient (Fig. 3). As the beam is deflected along the target rings it is bounced off the ring, through a collimator to restrict beam size, and through the patient. Opposite the target rings is a series of detector rings, also arranged in an arc. Each detector ring con-

[1]Imatron Incorporated, South San Francisco, CA.

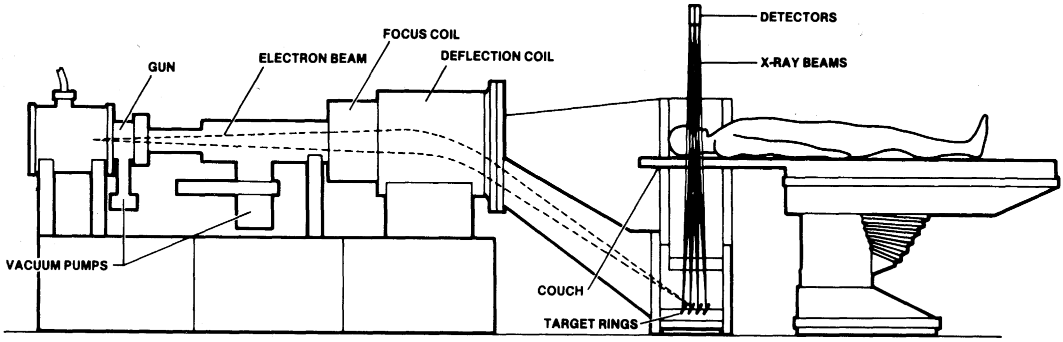

FIGURE 2 Cine computed tomography (Imatron) system.

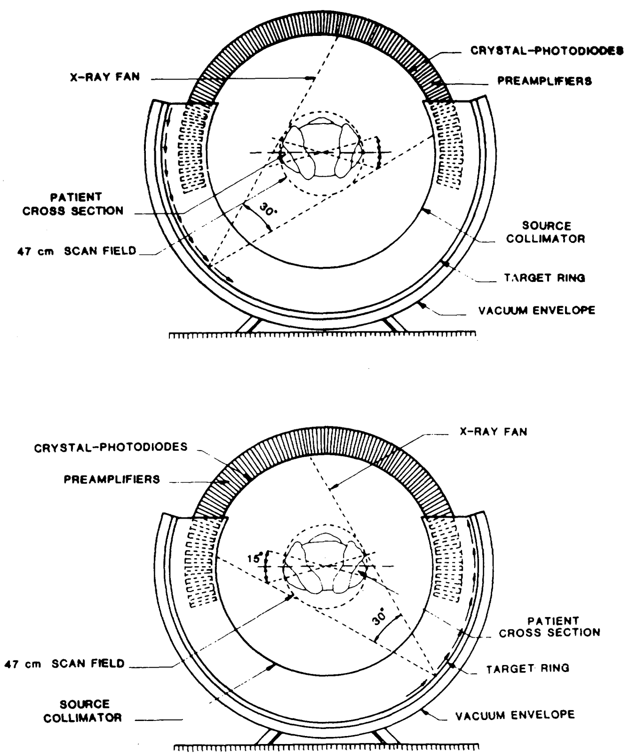

FIGURE 3 Orientation of electron beam in cine computed tomography system.

sists of a number of x-ray sensitive elements. Information from these elements obtained as the x-ray beam passes through the patient along the 210-degree arc is fed to the computer. Movement of the x-ray beam through the arc can be achieved much faster magnetically than mechanically. As a result, scan time has been reduced from 2 to 4 seconds to 650 milliseconds in the "flow" mode and 58 milliseconds in the "movie" mode.

Cine Computed Tomography Of The Velopharyngeal Mechanism

The patient to be evaluated is placed on a patient table (see Fig. 2) in a supine position. The head is stabilized to the table with a piece of surgical tape. The table is then positioned in the scanner such that the x-ray beams will pass through the "slices" of interest. A localization scan consisting of an exposure at each desired level is obtained in order to ensure correct positioning. Once this has been established, the actual cine study may be conducted.

The x-ray technique employed was 130KVp at 600 mA. The resultant dosage to the patient was 100 mrads per scan or frame. The upper radiation dosage limit was set to 2 rads. In order to remain under that limit, the scan rate of 650 milliseconds (flow mode) was chosen. That is, selection of the 58-millisecond scan rate (movie mode) would have allowed for the collection of 20 frames in only 1.16 seconds. In contrast, 20 frames could be collected over a period of 13 seconds in the flow mode.

Given this sampling rate, the choice of speech sample is limited. A 650-millisecond scan rate will not allow for an accurate depiction of movement during ongoing speech. The effective scan rate is less than 2 frames per second. By contrast, typical lateral view cineradiography is conducted at 24 frames per second. Therefore, we chose a simple task that would allow us to evaluate the extremes of movement (i.e., open versus closed) and that might allow some visualization of movement in between these extremes. The speech task involved alternation of (a) inhalation through the nose, and (b) a short 1- to 2-second prolongation of /s/. Sixteen to eighteen scans (frames) were then obtained simultaneously at each of four scan levels. The superior-most level was situated 8 mm above the palatal plane. The remaining three scan levels were situated at 8-mm intervals below the superior level. Eight millimeters represents the minimum "slice" separation of this system.

The resultant images were then displayed on a computer terminal. By displaying successive images one after the other, visualization of the structures in a given tomographic plane could be seen in motion. Quantitative analyses could be

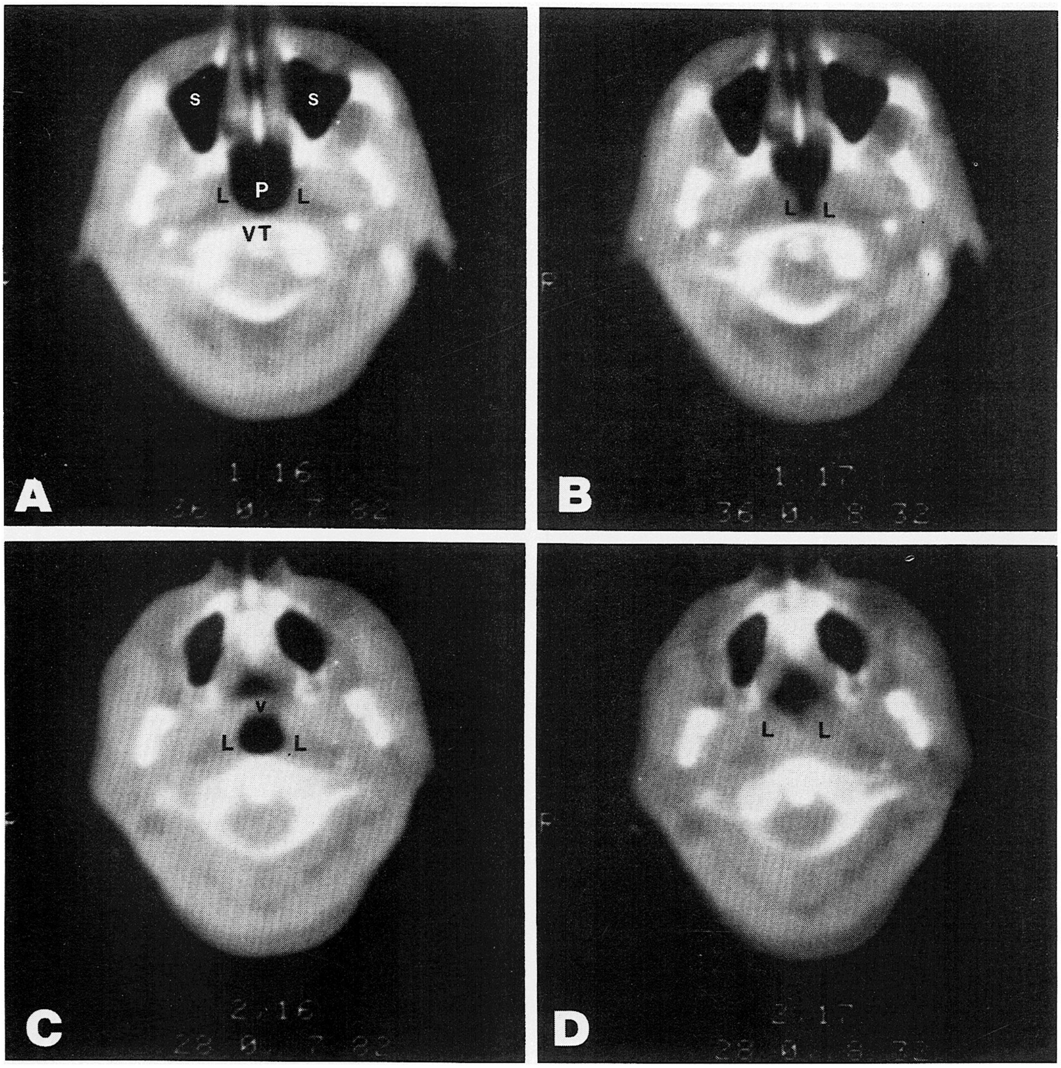

FIGURE 4 Scans obtained from a normal adult male: *A* and *B*, scans obtained at level 1; *C* and *D*, simultaneous scans at a level 8 mm lower (V = velum, L = lateral pharyngeal wall, VT = vertebra, S = sinus, P = pharynx). The velar prominence (V) is seen in Figure 4C as the velum is elevated during /s/ production.

conducted on individual scans using computer software in order to evaluate parameters, such as extent of movement.

For the purpose of this introduction of cine computed tomography technology, scans obtained on two patients are presented. Figures 4 A,B,C, and D show two successive scans obtained from a normal adult male. Only a two-level scan was performed on this subject, level 1 cutting through the palatal plane. Figure 4A was obtained during inhalation, and Figure 4B shows the velopharynx during production of /s/. Figures 4C and D show simultaneous scans at a level 8 mm lower. The horizontal "bar" of tissue passing through the velopharynx in the left hand scan of Figure 4C (labeled "V") represents a section of the velum that is positioned in this particular tomographic plane. Figures 4A, B, C, and D graphically depict lateral pharyngeal wall movement at both levels.

Figure 5 shows a series of scans obtained from an adult female with an unrepaired cleft of the hard and soft palate. The patient had been fitted with a palatal obturator, which was removed during this study. Figures 5A, B, E, and F were obtained during inhalation: Figures 5C, D, G, and H were obtained during production of /s/. This may be substantiated by the observation that, in Figures 5G and H the tongue has been elevated into the tomographic plane. The degree of velopharyngeal inadequacy demonstrated by this patient is clearly evident from evaluating these scans. Little if any movement of any structures is seen in Figure 5A, B, C, or D. Although there is some evidence of lateral pharyngeal wall closing movement in Figures 5E, F, G, and H, it falls far short of adequate.

Although Figures 4 and 5 clearly show the potential utility of this scanning system, it is impossible in a printed article to appreciate one significant benefit of the system. That is, the magnitude and pattern of velopharyngeal movement are observable when the structures are seen in motion.

The results of this investigation suggest that cine computed tomography technology may have some potential usefulness in the documentation of velopharyngeal form and function. In its

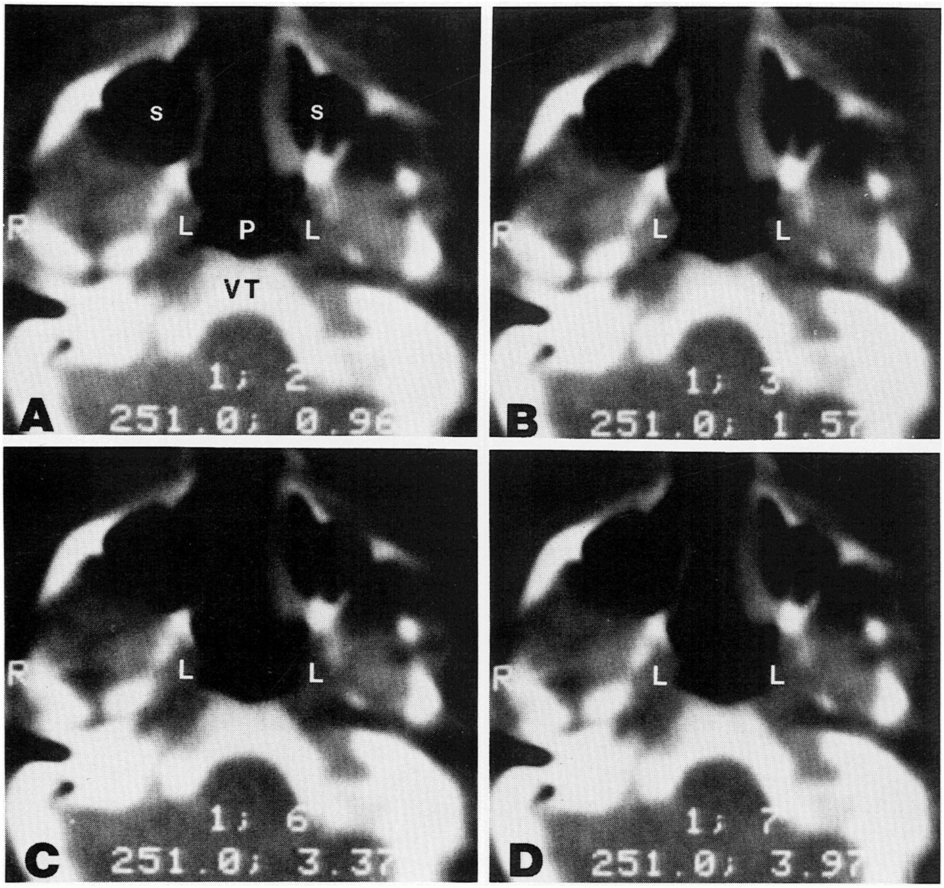

FIGURE 5 Scans obtained from an adult female with an unrepaired cleft of the hard and soft palate: *A, B, C,* and *D,* scans obtained at level 1.

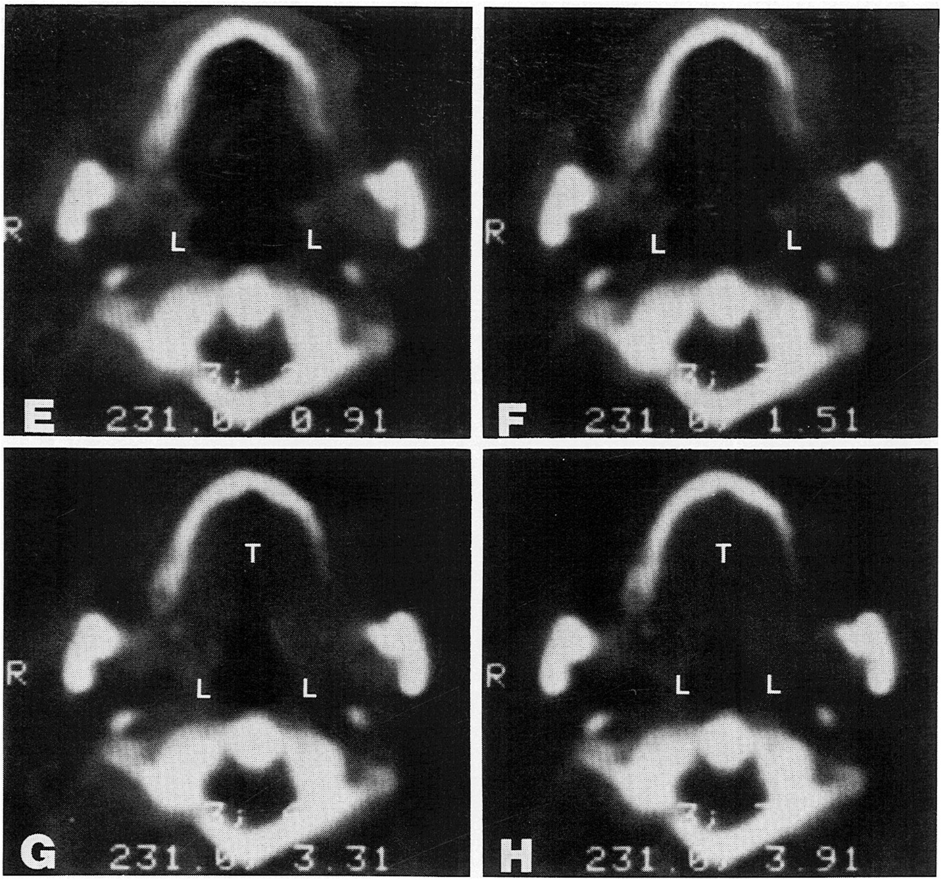

FIGURE 5 Continued *E, F, G,* and *H,* simultaneous scans at a level 16 mm lower (L = lateral pharyngeal wall, VT = vertebra, S = sinus, P = pharynx, T = tongue). The tongue (T) is elevated into the tomographic plane in *G* and *H* during /s/ production. The small medially directed flaps of tissue that appear just above L labels in *E* are palatal tags reflecting unjoined velar musculature.

present state of development, it allows for visualization of all sides of the velopharynx at different tomographic levels. It also allows, to some degree, visualization of the motion of velopharyngeal walls during phonatory and nonphonatory events. There are, however, some aspects of the system that must be considered liabilities at this time from the standpoint of assessing velopharyngeal function. Each "slice" is, at a minimum, 8 mm in thickness. This reduces the number of slices that may be used to visualize the inferosuperior dimension of the velopharynx and, hence, reduces the resolution in that dimension. An updated version of the system is expected to allow for 3-mm thick slices. The present system has effective scan rates of 1.67 and 17 frames per second. We chose the slower rate in order to limit radiation exposure to 2 rads while collecting about 10 seconds of data. This will obviously and significantly restrict the speech sample that may be used. Improvements in this area would be expected to provide for more detailed motion analysis. The patient must be supine during this procedure. Therefore, one must be concerned about possible gravitational effects on the physiology of the velopharynx. Although patients may be positioned at a 45 degree angle, this would alter the orientation of the images (i.e., they would no longer be in the transverse plane). Finally, images cannot presently be combined to get a composite three-dimensional picture. Advances here would also be expected to improve the applicability of this technology for the analysis of the velopharyngeal mechanism.

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