Interactive Computer Program for Biomechanical Analysis of Videoradiographic Studies of Swallowing

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During the past decade, substantial interest has developed in videoradiographic studies of oral pharyngeal swallowing for evaluating oral pharyngeal function in normal subjects and in patients with swallowing disorders. Recent investigations of oral pharyngeal swallowing in normal subjects have examined duration of cricopharyngeal opening and movement patterns of the hyoid bone as they are affected by bolus volume [1, 2]. These studies concluded with hypotheses regarding the relationship of biomechanical factors in the oral pharyngeal area to selected events in the oral pharyngeal swallow. Specifically, anterior and superior movement of the hyoid bone and the larynx are now hypothesized to be important biomechanical contributors to the opening of the cricopharyngeal region. This hypothesis and others regarding the biomechanics of the operation of the laryngeal and cricopharyngeal valves during the pharyngeal stage of swallowing need to be supported by further quantitative experimental evidence [3].

Measurement of movements of oral pharyngeal structures from videoradiographic studies is extremely time-consuming and difficult. Each video frame must be traced, and specific points of interest must be identified. Measurements from a single frame can take 30–60 min, making such analyses infeasible. To facilitate the biomechanical analysis of the pharyngeal swallow, the Video Analysis Laboratory at Northwestern University, Department of Communication Sciences and Disorders, developed an interactive computer program to digitize, enhance, and plot the movement of anatomic structures in the oral cavity and pharynx from the onset through the termination of the swallow. This report describes the application of this program to the biomechanical analyses of swallowing.

Hardware

Video digitization uses a video cassette recorder (VCR), capable of freeze-framing and of advancing single fields or frames, coupled to a video monitor. Digitizing of images from the VCR requires a personal computer (PC), a video digitizer board (frame grabber), and control software. We use an IBM PC-AT, a Data Translation frame grabber, and custom control software. Our system also contains two Sony 10" video monitors and a Mitsubishi video printer to display conveniently or print the current contents of the frame grabber, as shown in Figure 1. A Hewlett Packard laser printer produces data plots from the analyses.

The Process of Analysis

The process of biomechanical analysis of the oral pharyngeal swallow can be divided into five major steps: (1) digitization of desired images; (2) identification of reference points permitting corrections for head motion, magnification, and postural angle; (3) identification of anatomic points of interest; (4) computer calculation of the x and y coordinates of each anatomic point on each digitized frame, relative to

Received February 15, 1989; accepted after revision April 21, 1989.

This work was supported by U.S. Public Health Service grant PO1-CA-40007.

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AJR 153:277–280, August 1989
0361–803X/89/1532–0277

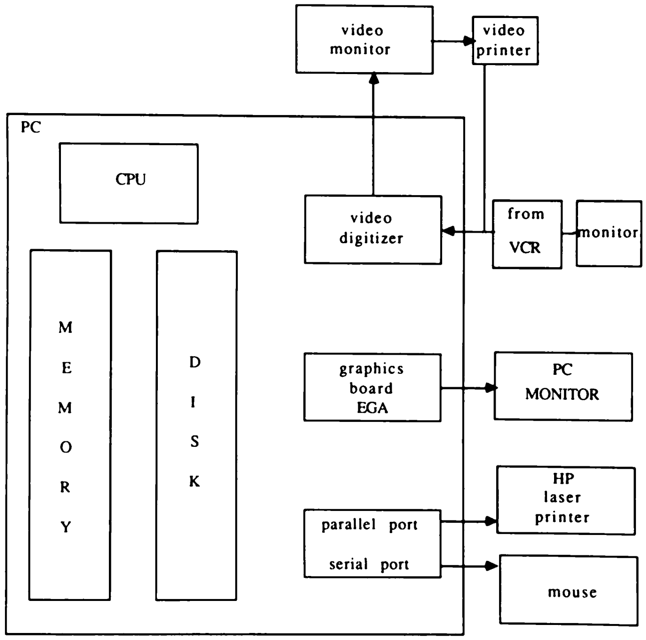

Fig. 1.—Hardware schema used in biomechanical analysis of swallowing. PC = personal computer, CPU = central processing unit, VCR = video cassette recorder, HP = Hewlett Packard, EGA = extended graphics adapter

an anchor point, corrected for postural angle and magnification; and (5) computer generation of plots of the spatial position of anatomic points vs time. The investigator defines the time base of these plots and selects the combination of points to be displayed, choosing between absolute and relative distance measures and selecting among horizontal distance, vertical distance, or total distance for each anatomic point. Each of these steps will be described in detail.

Digitization of Videoframes

The process of biomechanical analysis of swallowing begins with the investigator's selection of the sequence of frames to be analyzed. Usually, when studying the oral pharyngeal swallow, the onset point is selected as the first video frame exhibiting backward movement of the leading, or most posterior, edge of the bolus in the oral cavity. However, there may be instances in which the onset point is the beginning of movement of the hyoid bone, the soft palate, the larynx, or some other structure. The software is structured so that any onset point can be selected.

The Data Translation frame grabber (Model DT 2851, Marlboro, MA) accepts a standard National Television Standards Committee video signal and can display 256 shades of gray at a resolution of 512 × 512 pixels. To digitize an image, the VCR tape is positioned on a frame of interest, and the user initiates digitization through a software command. The user then enhances the contrast of, or filters, the digitized image to highlight anatomic structures, saving the result to disk. The process is repeated for all frames within a swallow. The digitized video frames are then stored on the hard disk. Each video frame requires 256K storage space if uncompressed. The digitized image can be compressed to reduce storage space. An almost unlimited number of video frames can be digitized and stored with a PC-compatible tape drive.

Because the pharyngeal swallow occurs in only 0.3 to 0.7 sec in normal individuals, we have digitized 30 frames/sec in our studies of normal subjects. However, frames or video fields can be digitized at any desired interval, for example, every third frame (1/10 sec), every tenth frame (1/3 sec), or every video field (1/60 sec). The time interval between digitized frames determines the time intervals to be labeled on the *x*-axis of the resultant plots of extent of structural movement (*y*-axis) against time (*x*-axis) for the swallow under analysis.

Determination of Reference Points and Postural Angle

The patient's head and neck posture usually is not absolutely vertical during the radiographic study. Yet, the *x-y* coordinate system used in digitization is based on true vertical and horizontal positions of the *x-y* axes. To correct for the angle of the patient's head, the head tilt forward or backward is calculated by entering two points on the digitized frame that are intended to define the desired vertical axis. The two points used can be the anterior/superior corner of the third cervical vertebra and the anterior/inferior corner of the fifth cervical vertebral bodies or the anterior/superior corner of two manometric sensors, if such a device is in place during the study, as shown in Figure 2. In either case, the resultant vertical axis approximates that of the pharynx. Interobserver and intraobserver reliability in identifying angle points from the manometric sensors are 98% and 97%, respectively. The maximum difference between establishing the postural angle from the manometric sensors and establishing it from the vertebral bodies was 2° in our experience. The computer uses the two points entered to calculate the angle at which the patient's head is tilted forward or backward from true vertical. The entire image is then rotated about the anchor point by this amount so that the desired vertical axis coincides

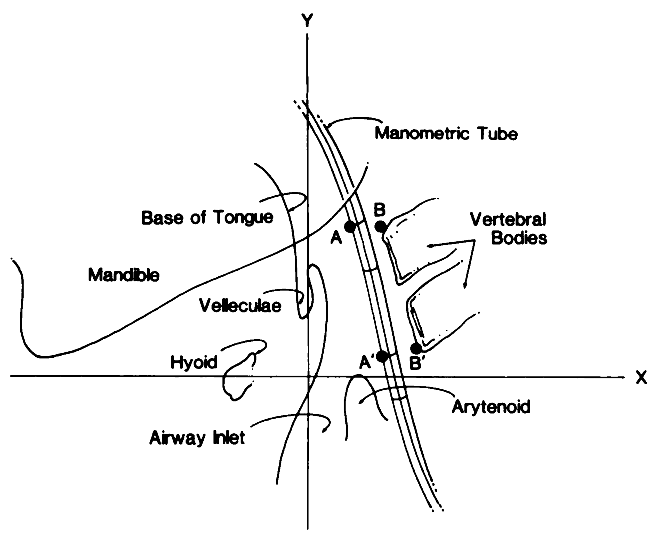

Fig. 2.—Reference points for postural correction may be manometric sensors (A–A') or anterior superior and inferior corners of two vertebral bodies (B–B'), as shown in tracing of a single videoframe.

with true vertical and the x-y coordinates of each selected point have been corrected for the effect of the patient's head posture.

If accurate measurements are to be made of anatomic points as they move during the course of the swallow, magnification caused by the fluoroscope must be corrected. This is accomplished by incorporating a reference distance (preferably in the sagittal plane) into the fluoroscopic image. Examples of such reference points are (1) two manometric sensors placed 3 cm apart at the midline of the pharynx, (2) a 1-cm-long lead letter taped to the neck, or (3) a coin taped under the subject's chin. In any case, these reference points are identified on each digitized image, and the corresponding reference distance is entered at the onset of the analysis process in response to a software prompt.

Identification and Storage of Anatomic Points of Interest on Each Frame

Once all desired video frames have been digitized, enhanced, and stored, the investigator determines the anatomic points to be marked on each video frame. The number of anatomic points to be marked on each video frame is entered into the program. We usually mark seven points, in addition to the two points on the manometric sensor or the vertebral bodies that mark posture: (1) the posterior/superior corner of the subglottic air column (representing laryngeal elevation), (2) the anterior/superior tip of the arytenoid cartilage, (3) the posterior point on the base of the tongue at the vertical level of the anterior/superior tip of the arytenoid cartilage, (4) the posterior wall of the cricopharyngeal region, (5) the anterior wall of the cricopharyngeal region, (6) the anterior/superior corner of the hyoid bone, and (7) the anchor point (either a lead marker placed on the side of the neck or a prominent point on a cervical vertebral body). The anchor point serves as the origin for the x-y coordinate system. Each anatomic point marked on each video frame is assigned x-y coordinate values relative to the anchor point. To mark anatomic points, the program places cross hairs on the video screen. By using a mouse connected to the system, the investigator moves the cross hairs to identify the desired anatomic point. By striking a computer key, this point is marked on the digitized image. The process is repeated for all points. When all points of interest are marked on the frame, the x-y coordinates of all points are placed in a digitized data file that is stored independently of the digitized images.

We have examined the interobserver and intraobserver reliability in identification of anatomic points from the video frames. Both interjudge and intrajudge reliability in identification of the aforedescribed seven anatomic points was less than 1 mm.

Calculation of the Vertical and Anterior Movement of Anatomic Points

The physical units of the frame grabber x-y coordinate system are pixels; however, we require information in millimeters. The reference points delineate a known distance, which has a corresponding distance in pixels. Therefore, a scaling factor can be computed after all of the desired anatomic points are marked on each of the digitized video frames. Software analysis then extracts positions or movements of anatomic points over time. First, the data from each frame in a swallow is corrected for head movement. Second, the data's dimensions are converted from pixels (device coordinates) to millimeters (physiologic coordinates). Third, the movement of each point in the vertical or anteroposterior plane is calculated relative to the anchor point of the coordinate system or other selected anatomic landmark.

Plotting the Movement of Selected Anatomic Points

A plotting subroutine is used to display graphically the vertical, anterior, total, or relative movement of the anatomic points of interest in a plot of distance vs time that can be printed on the laser printer.

Our observations suggest that the timing of events within the oral pharyngeal swallowing sequence do not have a constant relationship to each other among swallows or among subjects. For example, the oral phase of swallowing may persist for 0.5 sec in one swallow and 0.7 sec in another. This has the effect of staggering the occurrence of events later in the swallow, making it difficult to average values among swallows meaningfully. This problem can be controlled to some extent via a flexible time base that allows the user to define time 0. Time 0 can be indexed to any chosen event, such as the onset of the oral swallow, cricopharyngeal opening, or laryngeal vestibule closure. From the selected zero point, all other events and movements of interest can be plotted backward or forward in time. The effect is to synchronize the swallows around an event of interest, thereby enabling averaging of values among swallows. Because data are stored in a standard format, data across swallows of the same subject and various subjects can be compared.

Examples of plots generated by this computer analysis are shown in Figures 3 and 4. In Figure 3, the temporal relationship of vertical and anterior movement of the hyoid bone is

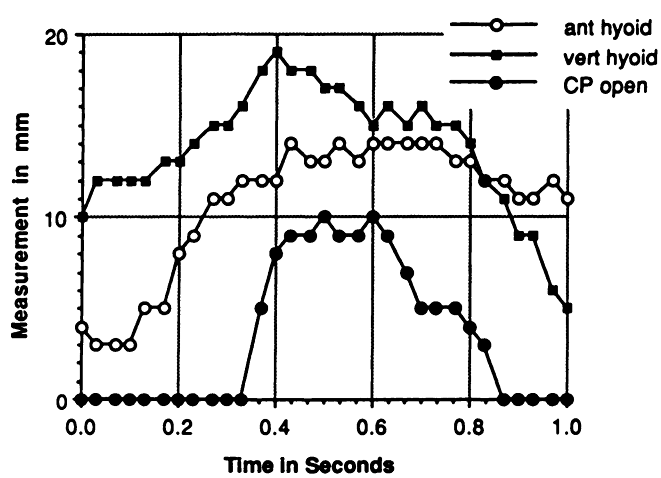

Fig. 3.—Anterior and vertical hyoid motion and cricopharyngeal (CP) opening for a 5-ml barium liquid swallow.

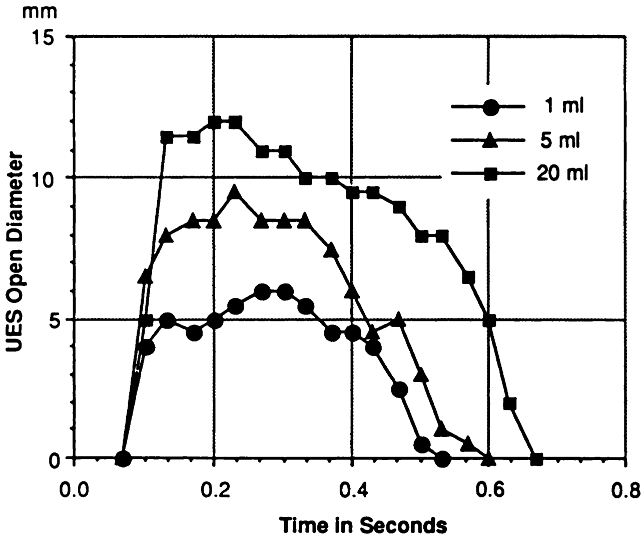

Fig. 4.—Upper esophageal sphincter (UES) (cricopharyngeal) open diameter as affected by barium bolus volume in one subject.

plotted in relation to cricopharyngeal opening in one 5-ml swallow with the 0 point of the *x*-axis representing the onset of hyoid movement. Figure 4 illustrates the effect of various bolus volumes on the diameter of the upper esophageal sphincter opening in one subject, again using the onset of hyoid movement as time 0. Upper esophageal sphincter diameter and duration of opening clearly increase in this subject as bolus volume increases.

Figures 3 and 4 are examples of relationships that can be examined by means of a biomechanical analysis of the oral pharyngeal swallow. The interactive computer program described here can be applied to the assessment of all aspects of the normal oral pharyngeal swallow, including velopharyngeal closure, posterior to anterior tongue movement, pharyngeal wall movement, laryngeal closure, and cricopharyngeal opening. The systematic effects of various bolus characteristics, maneuvers, and other variables on various components of the normal oral pharyngeal swallow can be quantified. Such evaluations are tedious by hand analyses. Therefore computer methods, such as the one described in this report, represent an important step in obtaining quantitative information that will be used for defining normal values, determining normal physiology, and evaluating abnormal swallows in clinical studies.

Biomechanical analyses such as these also should provide important information on the nature of swallowing dysfunction in patients with various types of structural and neurologic damage, and on the selection and effects of appropriate treatment.

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