Video fluoroscopic techniques for the study of Oral Food Processing

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Abstract

Food oral processing and pharyngeal food passage cannot be observed directly from the outside of the body without instrumental methods. Videofluoroscopy (x-ray video recording) reveals the movement of oropharyngeal anatomical structures in two dimensions. By adding a radiopaque contrast medium, the motion and shape of the food bolus can be also visualized, providing critical information about the mechanisms of eating, drinking, and swallowing. For quantitative analysis of the kinematics of oral food processing, radiopaque markers are attached to the teeth, tongue or soft palate. This approach permits kinematic analysis with a variety of textures and consistencies, both solid and liquid. Fundamental mechanisms of food oral processing are clearly observed with videofluoroscopy in lateral and anteroposterior projections.

Introduction

Food oral processing and pharyngeal food passage cannot be seen directly from the outside of the body. To analyze the kinesiology and physiology of mastication and swallowing, it is important to visualize the food passage through the oral cavity and pharynx and the movement of those structures. Videofluoroscopy (VFS) is the optimal instrumental assessment tool to visualize the movement of the structures and food with a contrast medium simultaneously, as it allows understanding the mechanisms of eating solid food and drinking liquid.

VFS is a dynamic radiographic examination (x-ray video recording) with recordings of fluoroscopic images in subjects eating or swallowing radiopaque materials (Fig. 1). VFS was

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developed as an alternative to cineradiography (x-ray movie recording), an older technique that in use since the 1890s; clinical application of cineradiography to visualize swallowing and oral function began during the 1950s [1], but its use was limited to the relatively high radiation exposure. VFS provides comparable images with a much lower dose of radiation; it has been used routinely to study dysphagia (swallowing difficulty) since the 1970s [2]. VFS or the videofluorographic swallowing study is regarded as the gold standard in the assessment of dysphagia in clinical settings. During the VFS, the patient ingests radiopaque foods and liquids, and oral, pharyngeal, and esophageal stages of swallowing are evaluated. It has then broadly applied to clinical and basic research fields.

Food oral processing and swallowing are in a sequential process of eating food. VFS enables to visualize the entire sequence. The examination area can reach from the lips to the upper esophageal sphincter (Fig. 2). The main feature of videofluoroscopic analysis is to assess the kinesiology of food bolus and oropharyngeal structures using temporal and spatial measurements. Moreover, synchronizing VFS with the other physiological assessments such as electromyography [3], manometry [4], respiratory measurements[5, 6](airflow or plethysmography), enables analysis of the integrated physiology of eating, drinking, swallowing, and breathing.

VFS has many advantages in visualization of food processing and swallowing, but there are some limitations. Since images acquired with VFS are limited to two dimensions information, laterality of function or food passage cannot be evaluated adequately in the lateral projection alone. Therefore, especially in clinical settings, imaging in both lateral and anteroposterior projections is essential. Radiation exposure is also one of the limitations of VFS. However, the radiation dose for swallowing examination is quite low, such as 1.05 mSV in five minutes exposure, and is rarely a limiting factor in adults [7, 8].

VFS Equipment settings and techniques

VFS equipment

The VFS equipment includes standard fluoroscopy apparatus, a seating chair to allow the subject to sit fully upright or recline as needed. Recent VFS systems incorporate high resolution digital imaging with acquisition rates from 15 to 30 frames per second. Review of images after recording is often required, thus storage of the video images with capacity for playback is essential. Sound recording with a microphone and an amplifier is useful to document activities. A video timer to measure the actual time or frame number on each image is essential for temporal analysis (Fig. 2).

Food preparation

Since VFS can visualize only radiopaque materials, use of a radiopaque contrast medium is essential to visualize the bolus. Barium sulfate is the most common contrast medium, and is commercially available as a powder or a suspension of barium in water (so-called liquid barium). Foods are readily mixed with radiopaque material. Liquids are rendered radiopaque by mixing with barium powder. Thickening agent is added if thicker liquids are needed. As standardized viscosity and concentration are essential for reliable physiologic

measurements, pre-thickened standardized barium liquids with five levels of viscosity (thin, nectar, thin honey, honey, and pudding) are manufactured in North America (Fig. 3). For solid food, hard food like cookie is usually coated with barium powder or paste, and soft foods like purees or chicken salad are mixed with barium powder in advance of the examination. By using the contrast media, the timing and extent of bolus flow, including timing of oropharyngeal bolus transport and swallow can be measured [9, 10]. If the study subjects are patients with dysphagia, the mechanism of swallowing dysfunction can be assessed. Phenomena such as bolus misdirection (e.g., nasopharyngeal regurgitation, laryngeal penetration, or aspiration) and residue after swallowing can be observed. Laryngeal penetration is defined as contrast entering the larynx but not passing through the vocal folds (glottis). Aspiration is defined as contrast passing through the vocal folds to enter the trachea. Anatomical abnormalities seen on VFS including webs, to the tooth surface with dental cement, and are observed, as are opening and closing of the esophageal sphincters (upper and lower).

Marker preparation

Motions of the soft and hard tissues related to eating and swallowing can be observed with VFS. The movements of calcified tissues such as the jaw or hyoid bone can be traced on VFS recordings. However, for quantitative kinematic analysis, radiopaque markers should be attached to tooth surfaces [11]. Soft tissues, including the tongue or soft palate, are visible in VFS and their contours readily observed. However, kinematic measures are simplified by attaching small radiopaque markers on the mucosal surface. This technique enables to trace the movements of the tongue or soft palate [5, 11–13]. In our previous studies, small lead discs (5-mm diameter) were used as the radiopaque markers, and were attached to the tooth surface with dental cement, and to the tongue surface with medical adhesive [14] (Fig. 4). For soft palate marker, a small metal pellet marker glued to the tip of a flexible rubber tube was passed transnasally with a guidewire, and was positioned on the upper surface of the soft palate [5] (fig. 5). For posterior pharyngeal wall marker, the small metal suction cups (4-mm diameter) attached to a flexible plastic tube was passed transnasally, and the markers were attached to the pharyngeal wall by applying suction to the end of the tube with a 5-mL syringe[15, 16]. The detailed explanation of these preparations has been described in previous literature [5, 14].

Food processing seen in VFS

The movements of food in the oral cavity and oropharynx differ substantially between eating solid food and drinking liquid, while bolus passage through the hypopharynx and esophagus is less variable across food consistencies. Thus, the physiology of eating solid food and drinking liquid has been widely studied with VFS based on two paradigmatic models: the Four Stage Model for swallowing a liquid bolus, and the Process Model for eating solid food. The normal swallow in humans is described with a four-stage sequential model. In this model, the swallowing process was depicted as having oral preparatory, oral propulsive, pharyngeal, and esophageal stages that are sequential and rapid [2, 17]. For eating of solid food, the food processing in the oral cavity, oro-pharyngeal food transport and bolus accumulation in the oropharynx can occur simultaneously before swallowing. Thus eating is

not well-described with the four-stage model. Therefore, optimal model for eating solid was proposed as the Process Model [18, 19]. The Process Model explains the feeding sequence with stage I transport, processing, stage II transport, and swallowing. While the stages are sequential in the Four-stage model, stages can overlap in the Process model.

Liquid Processing on VFS

The schematic images of a liquid swallow in lateral projection of VFS are shown in Fig. 6. The liquid bolus is first held in the anterior part of the floor of the mouth or on the tongue surface against the hard palate. The oral cavity is sealed posteriorly by the soft palate and tongue contact to prevent the liquid bolus leaking into the oropharynx before the swallow. Once oral propulsion starts, the tongue tip rises, touching the alveolar ridge of the hard palate just behind the upper teeth, while the posterior tongue drops to open the back of the oral cavity. The area of tongue-palate contact gradually expands from front to back, squeezing the bolus backward. Pharyngeal swallow immediately follows oral propulsion. The soft palate elevates, closing the nasopharynx at about the same time that the bolus head comes into the pharynx. The base of the tongue retracts, pushing the bolus downward and backward against the pharyngeal walls. The pharyngeal constrictor muscles contract sequentially from the top to the bottom, squeezing the bolus downward. The upper esophageal sphincter (UES) opens, often before the bolus reaches the UES. The UES remains closed between swallows due to tonic muscle contraction.

Several influencing factors change the bolus flow. Viscosity is known to alter swallow initiation and bolus flow in liquid swallows [20]. Increased bolus viscosity slows bolus flow, thus the oral transit time is extended [21, 22]. The time of initiation of the pharyngeal swallow is correspondingly delayed and a bolus position at swallow initiation is higher up in the pharynx [21, 23]. Taste and chemesthesis can facilitate swallow initiation. Sour taste promotes initiation of swallowing more effectively than the other tastes [24, 25]. Chemesthesis is the feeling of irritation responsible for the perception of the hotness of capsaicin (for example, in hot peppers), coolness of menthol, and tingling with carbonated beverages via the transient receptor potential vanilloid 1 and ankyrin 1 (TRPV1 and TRPA1, respectively) [26, 27]. These receptors are widely distributed in the human oropharynx. Chemesthetic stimuli facilitate swallow initiation and may improve swallow response [28–30].

Solid food processing on VFS

When eating solid food, the food is first transported to the occlusal surfaces of the postcanine dentition (stage I transport). Then, in chewing, the food is reduced in size and lubricated with saliva (food processing). During chewing the food, the triturated food is transported to the oropharynx (stage II transport) and collects there (bolus aggregation) until swallow onset.

After food ingestion, the food is transported to the postcanine region of the teeth backward movement of the tongue surface (Stage I transport). This process of carrying the food posteriorly on the surface of the tongue is called a "pullback" mechanism of intraoral food

transport. The tongue also rotates to push the food bolus onto the occlusal surfaces. Stage I transport can be observed with VFS in lateral [19, 31, 32] and AP projections [14, 33]. During stage I transport, the mandible opened and the tongue and hyoid bone moved posteriorly and inferiorly. The initial food size and consistency affects the duration and frequency of stage I transport. Okada et al., [32] reported that stage I transport is closely bound to the recognition process when humans take natural food eating rice sticks freely.

After food is transported to the postcanine region, food processing begins. During food processing, both mechanical and enzymatic digestion are initiated. Food particles are reduced in size by mastication and softened by saliva for bolus formation. Masticatory jaw motion continues until swallowing, but food processing depends on not only the motions of the jaw and teeth, but also the coordinated motions of the tongue, cheek, and soft palate [5, 11, 33–36].

Tongue kinematics during mastication has been studied with VFS recordings using radiopaque tongue markers. Tongue motion is temporally and spatially linked with cyclic jaw movement in food processing [11]. The tongue continuously moves both anteroposteriorly and mediolaterally, during chewing; it also rotates on its three spatial axes during chewing [11, 14](Fig. 7). Those tongue movements reposition the food on the occlusal surfaces before each closing stroke of the teeth [33].

Cyclical motion of the soft palate during mastication is seen on VFS in about 50% of individuals. This movement is temporally linked to jaw movement [5, 37] (Fig. 7). During processing, the soft palate moves upward as the jaw opens and downward as the jaw closes. Since the soft palate and tongue moves continuously, the fauces are not closed during food processing. This permits air to flow between the oral and nasal cavities during mastication, providing access for odorants in food within the oral cavity to reach smell receptors on the nasal mucosa. Indeed, the perception of flavor requires the sensations of both smell and taste.

Stage II transport is readily observed with VFS in the lateral projection. When a portion of the masticated food in the oral cavity is ready for swallowing, triturated food is propelled back through the fauces to the oropharynx by the tongue squeezing it against the palate (stage II transport, Fig. 8) [19, 38]. Stage II transport usually occurs in the later chewing cycles of mastication [19, 39]. During stage II transport, the tongue surface raises, gradually expanding the area of tongue-palate contact from anterior to posterior, squeezing the bolus back along the palate and into the pharynx. The tongue motion during stage II transport is different from that during chewing [14]. In AP projection VFS, the tongue moves mediolaterally and rotates during chewing, but moves upward and remains medial during stage II transport. The frequency of stage II transport is greater with hard than soft food.

The number of chewing cycles and chewing duration to prepare a food for swallowing increases with hardness of food. The duration that the masticated food is aggregated on the pharyngeal surface of the tongue is also longer with greater hardness of the food [19].

New Computed Tomography techniques for swallowing analysis

Although VFS is still regarded as the gold standard for visualizing swallowing mechanisms, the image of VFS is limited to two dimensions. In recent rapid advances in imaging techniques, dynamic area detector computed tomography (ADCT) has been emerging in swallowing evaluation. The recent ADCT detectors of 320 rows with 0.5-mm thickness can scan the area of 160-mm width during 0.275 msec per image. The scanned area can cover the whole oro-pharyngeal region from the nasopharynx to the cervical esophagus. This high speed scanning enables to visualize not only the static 3D oropharyngeal morphology but also oropharyngeal swallowing dynamics with acquisition rate of 10 images/sec (Fig. 9). Radiation exposure is relatively higher compared to VFS, but thanks to recent low dose image reconstruction technique, the dose has decreased substantially. ADCT and VFS provide complementary information, thus ADCT is intended to supplement rather than to replace VFS.

Swallowing analysis with 320-ADCT (swallowing CT) has brought the understandings of 3 dimensional change of oropharynx during swallowing from any angles, which has been never seen with VFS (Fig. 10). Swallowing CT analyzes quantitatively the changes in volume of the pharynx, area of the upper esophageal sphincter, or timing of vocal folds closure, all of which have not able to been observed by VFS. Swallowing CT also has reveal the laterality of pharyngeal contraction in 3D in patients with dysphagia. Swallowing CT is an important development in swallowing research with potential application in patient care.

Conclusion

The movements of food in the oral cavity and oropharynx differ substantially between eating solid food and drinking liquid. VFS analyses with lateral and anteroposterior projections have revealed the fundamental mechanisms of food oral processing and swallowing for eating and drinking. By adding a radiopaque contrast medium to liquid or solid food, the motion and shape of the food bolus can be visualized. By applying radiopaque markers to the teeth, tongue or soft palate, quantitative kinematic analysis of the oropharyngeal structures is enabled. Swallowing CT will help understand more 4 dimensional change of food oral processing in the future.

Acknowledgments

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Highlights

Videofluoroscopy reveals the movement of oropharyngeal structures in two dimensions

Videofluoroscopy permits quantitative kinematic analysis of oral food processing

Imaging in both lateral and AP projections allows understanding the 3D information

a

b

Figure 1.
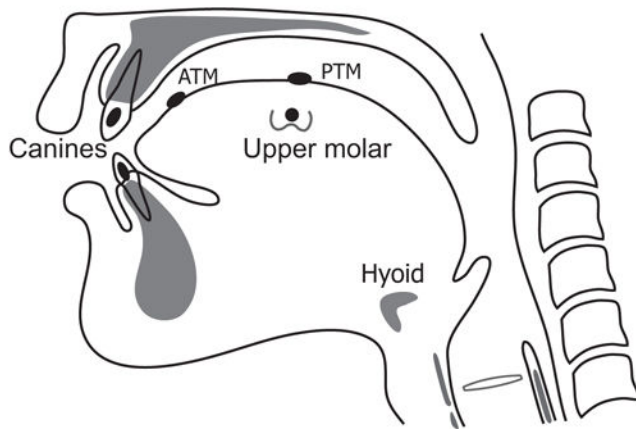A subject sitting in the videofluoroscopic apparatus in lateral and anteroposterior projections.

a

b

Figure 2.
Videofluoroscopic images in lateral and anteroposterior projections.

Figure 3.
Pre-thickened standardized barium liquid (Varibar, Bracco diagnostic inc., NJ, USA)

(a) Marker locations

(b) Cartesian coordinates
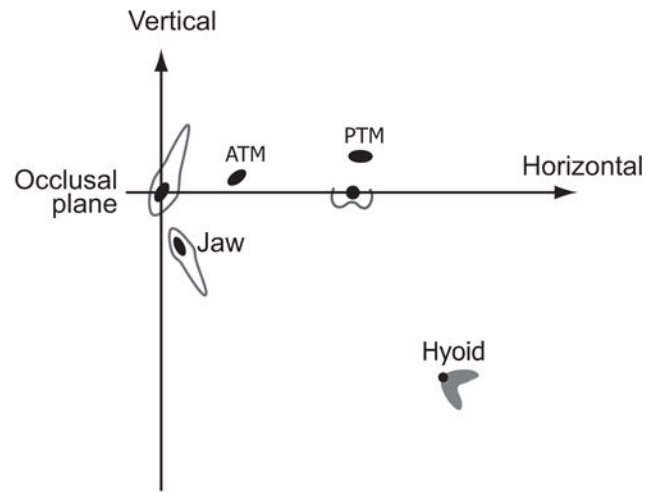
Figure 4.
Tongue markers from Matsuo paper

(a) Marker locations
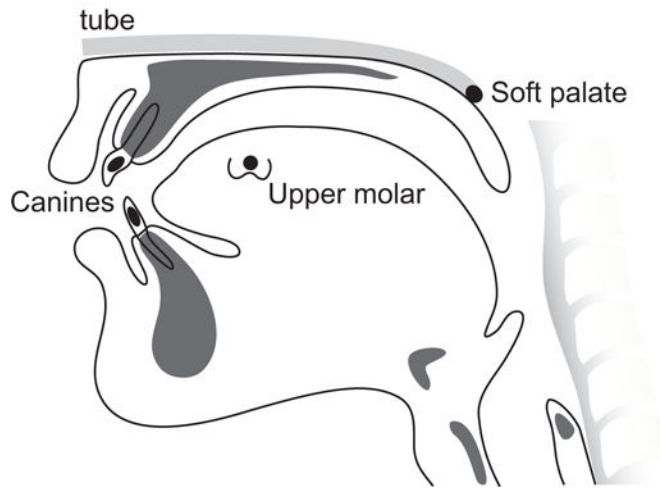
(b) Cartesian coordinates
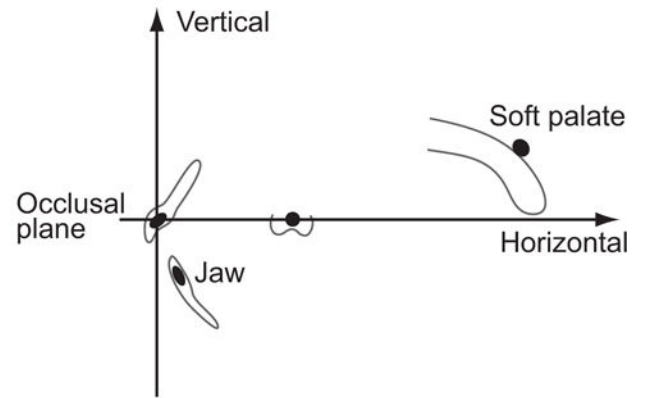
Figure 5.
Soft palate markers from Matsuo10 paper.
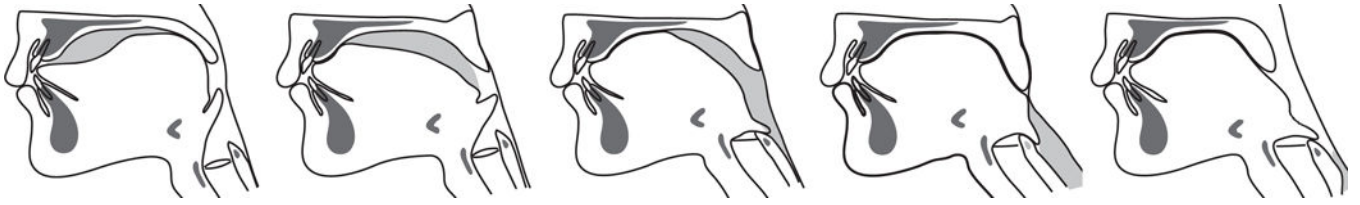
Figure 6.
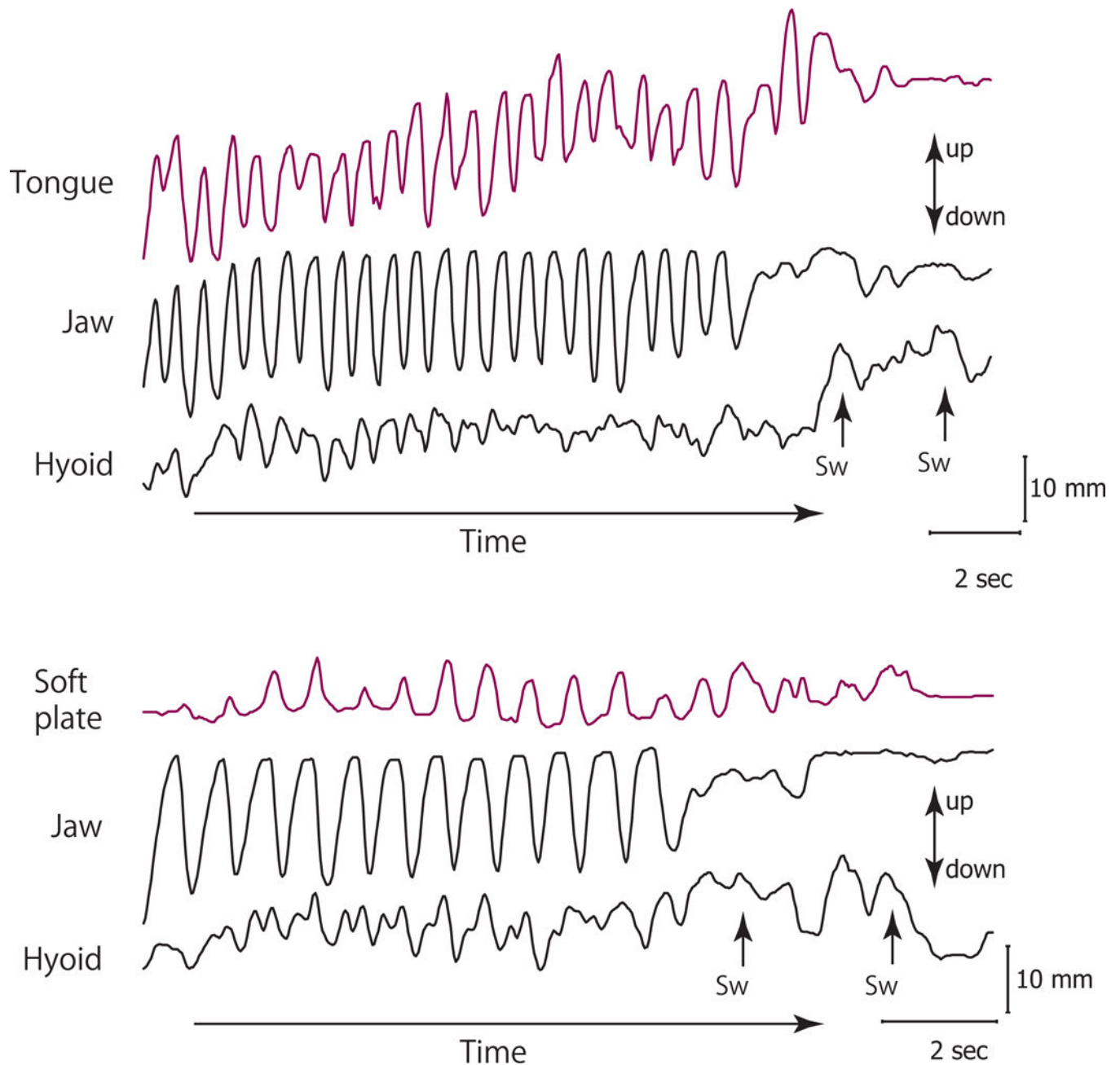Schematic images of a liquid swallow in lateral projection of VFS.

Figure 7.
Vertical motion of (a) the tongue and (b) soft palate during eating of solid food. (a) When eating solid food, the tongue moves cyclically in vertical dimensions. Tongue movement showed tight temporospatial linkage to jaw and hyoid movements during feeding. (b) Motion of the soft palate is temporally linked to jaw movement but not in every motion cycle. The soft palate moves upward as the jaw opens, and moves downward as the jaw closes.
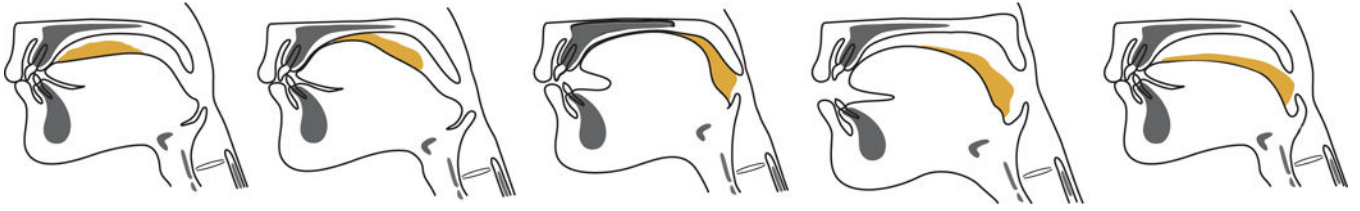
Figure 8.
Schematic images of stage II transport in lateral projection of VFS.

Figure 9.
320 row area detected computed tomography and a swallowing examination chair.
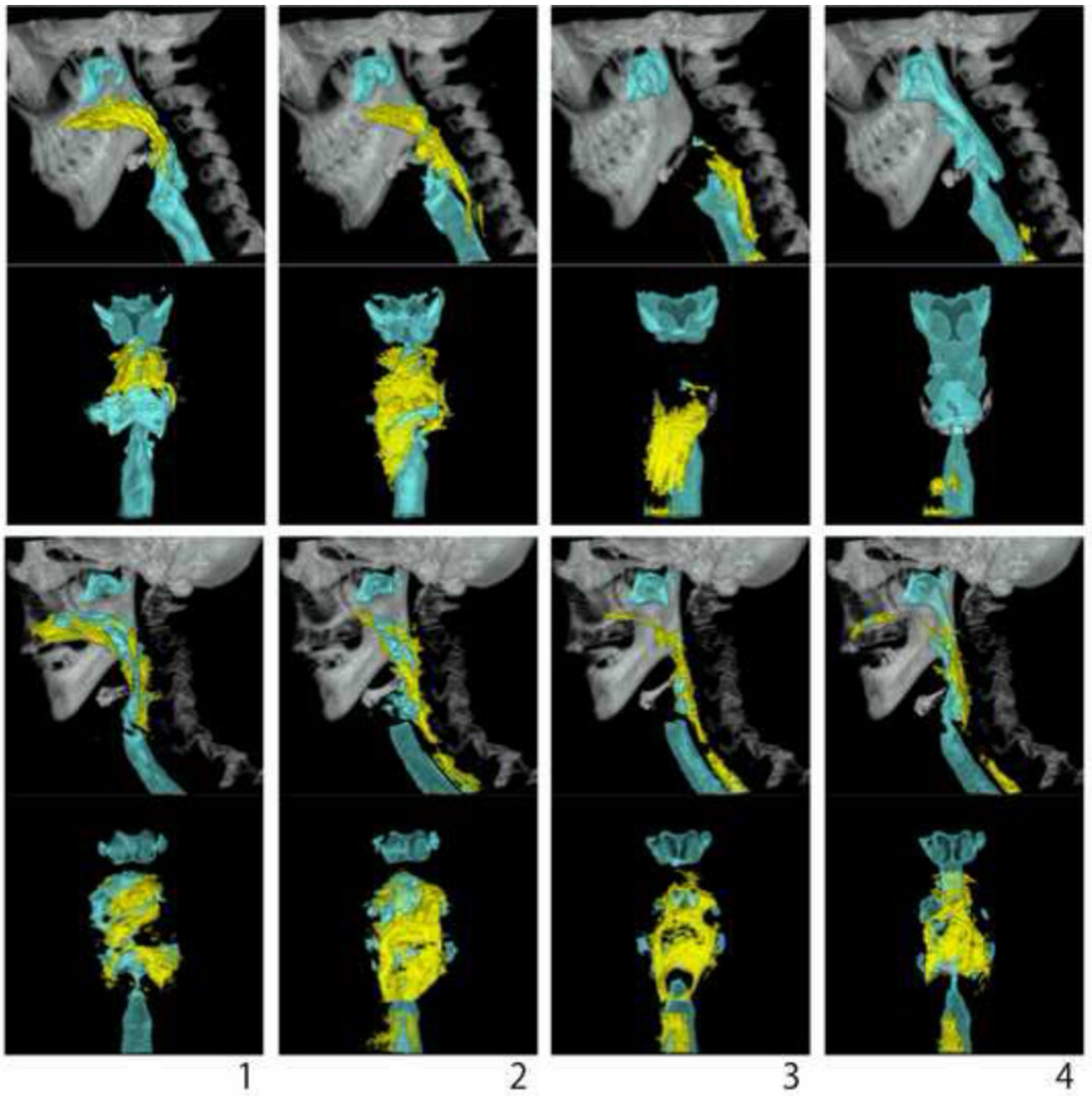
Figure 10.
Swallow-CT images of normal adult swallowing 10ml nectar thick barium from lateral and posterior 3D view.