

Sensory Input Pathways and Mechanisms in Swallowing: A Review

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Received: 8 December 2009 / Accepted: 14 August 2010 / Published online: 3 September 2010
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Abstract Over the past 20 years, research on the physiology of swallowing has confirmed that the oropharyngeal swallowing process can be modulated, both volitionally and in response to different sensory stimuli. In this review we identify what is known regarding the sensory pathways and mechanisms that are now thought to influence swallowing motor control and evoke its response. By synthesizing the current state of research evidence and knowledge, we identify continuing gaps in our knowledge of these mechanisms and pose questions for future research.

Keywords Deglutition · Deglutition disorders · Sensation · Sensory pathways · Physiology

In her recent review on neuroplasticity in swallowing, Martin [1] argues for the potential importance of sensory stimulation as a mechanism for influencing swallowing behavior. Sensory input is vital to the oral, pharyngeal, and esophageal phases of swallowing, yet evaluation of the integrity of the afferent pathways carrying sensory information to the swallowing control centers in the brain is not part of the standard clinical or instrumental swallowing assessment [2]. Sensory input informs neural control centers about the process of mastication so that boluses are prepared to a desirable consistency and lingual propulsive forces are tailored to transport the bolus efficiently into the pharynx [3, 4]. Sensory input triggers the subconscious pharyngeal swallow and modulates the sequential motor activity of muscles that transport the bolus through the pharynx [5, 6]. Sensory input modifies esophageal swallow intensity and triggers secondary peristalsis [7]. Sensory input synaptically influences multiple pathways, both cortical and brainstem, to trigger swallowing, alter motor output, and simultaneously activate ascending pathways, which reflexively modulate the motor output throughout the swallowing sequence [8].

The pharyngeal phase of swallowing is a well-recognized, complex reflex response [6]. Most experts, however, believe that the pharyngeal swallow involves modulation from sensory input and descending cortical pathways [9–17]. Fundamental studies in animal models indicate that the pharyngeal swallow sequence has a baseline or default mode, a brainstem-driven basic reflex that can then be modified in the normal conscious subject [18]. For example, aspects of the muscular contractile sequence can be modified, including the durations of individual muscle activation and the

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magnitude of EMG activity, reflecting muscle contraction amplitudes [19]. Sensory input is a key mechanism in facilitating such swallow modulation. The goal of this review article is to summarize the existing state of knowledge and research evidence regarding sensory input pathways, mechanisms, and modulation in swallowing (Table 1).

Anatomy Supporting Sensory Input to Swallowing

Sensory Fibers

The pharyngeal phase of swallowing is triggered by specific sensory inputs and is then completed by an entire

Table 1 Potential sensory stimuli that modulate or can evoke swallowing

Stimulus	Sensory nerve	Source
Gastrointestinal	Olfactory-black pepper oil	Ebihara et al. [35]
Cephalic phase		Maeda et al. [36]
Oral phase		
	Maxillary division (V2)	Pouderoux and Kahrilas [39] and Sweazey and Bradley [60]
	Mandibular division (V3)	Sweazey and Bradley [22, 23] and Thexton [24]
Oral splint		Ali et al. [100]
Pharyngeal phase		
Animal studies		
Electrically stimulate with optimum frequencies (30–50 Hz)	Internal branch of the superior laryngeal nerve (iSLN)	Doty [5]
Electrically stimulate with optimum frequencies (30–50 Hz)	Pharyngeal branch of the glossopharyngeal nerve (IXth)	Sinclair [82] and Kitagawa et al. [20]
Water, tactile, pressure	iSLN	Storey [84, 85]
Ionic fluids (i.e., KCl)		Shingai [25, 26]
Solutions with taste		
Sour (citric acid, acetic acid)		Kajii et al. [124]
Thermal stimuli to anterior pillars		Chi-Fishman et al. [115]
Human studies		
Light pressure		Kaatzke-McDonald et al. [116], Pommerenke [21], Rosenbek et al. [118] and Sciortino et al. [121]
Heavy pressure		Pommerenke [21]
Water		Shaker et al. [122, 123]
Sour solutions		Logemann et al. [125], Pelletier and Lawless [127], Hamdy et al. [126] and Sciortino et al. [121]
Carbonation		Bulow et al. [150]
Thermal stimuli		Kaatzke-McDonald et al. [116], Rosenbek et al. [117–119], Sciortino et al. [121] and Ali et al. [100]
Suggested nociceptive stimuli		Pelletier and Lawless [127] and Pelletier and Dhanaraj [128]
Airpuffs		Aviv et al. [107, 108]
Volume of bolus		Dantas et al. [101], Kahrilas and Logemann [99] and Lazarus et al. [98]
Viscosity		Christensen and Casper [103], Dantas and Dodds [104] and Lazarus et al. [98]
Increased salivation	IXth	Mansson and Sandberg [32]
	iSLN	Mansson and Sandberg [33]
Electrical stimulation to induce laryngeal closure	iSLN	Barkmeier et al. [87]
Site of bolus in pharynx to elicit the swallow		Martin-Harris et al. [75], Daniels and Foundas [73], Daniels et al. [74] and Pouderoux et al. [77]
Inhibit or suppress pharyngeal swallowing		
Local anesthesia to the paraglottic compartment of the pharynx	iSLN	Jafari et al. [86]
Local anesthesia to the laryngeal mucosa	iSLN	Sulica et al. [88]

sequence of bilateral muscle activity [6]. Doty [5] was the first to define the pharyngeal swallow as the most complex reflex elicited by the central nervous system (CNS) and demonstrate that sensory input is integral to “triggering” the response. Afferent input related to swallowing travels via sensory fibers in the trigeminal nerve (Vth), the glossopharyngeal nerve (IXth), the internal branch of the superior laryngeal nerve (iSLN), and other branches of the vagus nerve [20]. Doty’s original studies (and multiple subsequent studies) in the experimental animal have accentuated the importance of the iSLN [5]. Studies in the human using probes with light and heavy pressure have implicated receptors in certain oropharyngeal regions as contributing more than others to evoking the pharyngeal swallow [21]. Deep pressure tactile receptors stimulate sensory fibers that directly synapse in the brainstem [22–24]. Animal studies have shown that receptive fields around the faucial pillars and throughout the pharynx can be stimulated with specific sensory stimuli that include water and a variety of ionic fluids [25, 26]. The esophagus also depends on continued sensory input [27]. Direct infusion of a bolus into the esophagus induces peristaltic contractions that proceed from striated to smooth muscle in an uninterrupted progression [28–31]. Such sensory input uses both brainstem and local neural loops through ganglia in the esophagus [31].

Pathways that Enable Sensory Input to Influence Swallowing

Afferent input that may affect the threshold to induce swallowing can include stimuli that increase salivation [32, 33]. Introduction of food or liquid to the visual and auditory senses, as well as to the mouth, initiates the cephalic phase of control of the gastrointestinal tract, establishing the neurophysiological context in which swallowing emerges [34, 35]. Concepts of providing visual cues related to drinking [36] or strong olfactory stimuli to induce increased salivation to facilitate swallowing are valuable new approaches.

During the oral phase of swallowing, afferent input is carried predominantly by trigeminal sensory fibers from the maxillary and mandibular divisions (V2, V3), which send input into the trigeminal sensory nuclei [23, 37]. Sensory information about touch and pressure transmits over fibers that synapse in the principal sensory nucleus of the trigeminal system. The tongue and palate have touch and pressure receptors that provide distributed sensory input over multiple fibers so that complex input (e.g., information about bolus texture, shape, and size) can be read within the CNS [38]. Studies in the lamb show that tactile receptive fields on the tongue often have reciprocal receptive fields on the hard palate so that sensory input to

both structures can be generated by a bolus between the two tissues [23, 37]. The CNS uses sensory information from the oral cavity to inform and guide both tongue shape and the associated pressures that are generated to squeeze the bolus successfully toward the pharynx [39]. Placing a splint in the mouth of normal subjects to alter tongue movements and position significantly reduces the peak midpharyngeal pressure and hypopharyngeal intrabolus pressure [40]. The splint in the mouth also delays the onset of hyoid motion and relaxation of the upper esophageal sphincter (UES).

Taste, the other form of afferent input arising in the mouth, travels via the chorda tympani branch of the facial nerve (VII) and synapses predominantly in the nucleus tractus solitarius (NTS) [41, 42]. Studies by Hamdy et al. [15] indicate that regardless of the type of sensory taste stimulation (sweet, sour, salty, or bitter), the same four to five regions of the cortex are excited, including the insula and primary sensory cortex (regions that are known to be active during swallowing). Chemical stimulation of the amygdala and nucleus accumbens with dopamine and apomorphine facilitates pharyngeal swallowing induced by electrical stimulation of the SLN in an anesthetized cat [43].

The pharyngeal epithelium is richly innervated with sensory fibers, but deep receptors are less common than in the oral cavity [44]. The greatest density of pharyngeal sensory receptors is found at the junction of the naso- and oropharynx [45–47]. The laryngeal and epiglottic epithelia contain both superficial and deep nerve terminals, predominantly in the form of free nerve endings [48]. The highest density of laryngeal sensory receptors is located in the supraglottic mucosa near the arytenoid cartilages [49]. The laryngeal surface of the epiglottis has many more sensory fibers than the lingual surface [48]. The cell bodies for these sensory fibers reside in the sensory ganglia of the trigeminal, glossopharyngeal, and vagal nerves [50]. The glossopharyngeal nerve (IXth) and the pharyngeal branch of the vagus nerve (Xth) primarily innervate the pharynx, and their afferent fibers are interwoven in a dense plexus [44].

Central Connections

Sensory fibers of the glossopharyngeal and vagus nerves synapse directly in the NTS and do not appear to synapse in the trigeminal sensory nuclei [20]. Transynaptic neural tracers like the pseudorabies virus (PRV), when injected to affect vagal afferents in the rat, show that the sensory fibers terminate in the interstitial and intermediate NTS subnuclei [51]. Another anterograde and retrograde tracer, cholera toxin horseradish peroxidase (CT-HRP), shows that palatal, pharyngeal, and laryngeal afferents overlap in their synaptic contacts in the interstitial and intermediate NTS subnuclei, while esophageal afferents terminate exclusively

in the central subnucleus [52]. These sensory neurons contain both excitatory and inhibitory neurotransmitters, including glutamate and γ -aminobutyric acid (GABA).

To date, much of the research regarding afferent influences in swallowing has been derived from animal models or studies of healthy human subjects. Jean et al. [53, 54] has shown the importance of the NTS as the “dorsal swallowing group” (DSG) in the brainstem swallowing control centers or “central pattern generator.” Sensory input must proceed and synapse in the DSG region. Such sensory input may partially include trigeminal sensory input, but it always involves input from the pharyngeal branch of the glossopharyngeal nerve (GPNph) and the iSLN. Work by Sumi [55–57] and Amri et al. [58, 59] has provided electrophysiological evidence that sensory fibers from the iSLN bifurcate to synapse in and around the NTS, and, simultaneously, to proceed rostrally. This ascending sensory input lays the anatomical foundation that facilitates cortical interaction in the process of pharyngeal swallow initiation. The ascending pathways transmit sensory information to higher regions in the brainstem, subcortical, and cortical levels.

Sweazey and Bradley’s studies [22, 23, 60] in sheep have provided much of the experimental information about sensory input from the oropharynx. The majority of neurons in the lamb trigeminal nucleus respond to mechanical stimulation, while a few respond to thermal input and very few to chemical stimuli. Convergence of receptive fields does not occur often. By contrast, neurons in the NTS are more responsive to chemical and mechanical stimuli, and many have multimodal responses [22, 61, 62]. The finding that the NTS neurons are more multimodal supports the concept that reflex initiation of pharyngeal swallowing would involve neurons that respond to multiple types of stimuli.

Detailed studies of taste reception show that the trigeminal and glossopharyngeal nerve (GPN) fibers that carry this information synapse in the rostral NTS [63, 64]. Whether some of these afferent fibers also synapse at the more middle and caudal regions of the NTS (i.e., in the “dorsal swallowing region”) remains unproven [63, 65]. The synaptic connections between taste sensory input pathways and the primary swallowing pathways needs further analysis.

Sensory input from both the pharynx and the esophagus is vital to the esophageal phase of swallowing. Esophageal sensory input proceeds both locally using enteric reflexes and rostrally to the brainstem [7]. Detailed experimental studies of vagal afferents innervating the esophagus indicate that short-activity neurons respond during swallowing but not to activity of the longitudinal muscles, while long-activity neurons respond to distension as mechanoreceptor neurons [27, 66–68]. Recordings from primary afferent fibers of the vagus nerve, the thoracic sympathetic nerves,

and the splanchnic nerves of the opossum showed different patterns of sensitivity to esophageal distension [68]. Some vagal afferent fibers were low-threshold mechanoreceptors, responding to pressures as low as 0.29 mmHg and increasing their discharge to pressures of 50–70 mmHg. Distension-sensitive afferents in the thoracic sympathetic and splanchnic nerves were either wide-dynamic-range or high-threshold mechano-pain receptors.

Potential Mechanisms to Alter Swallowing

Observed Variations Demonstrate the Potential for Sensory Modulation

Evidence of the potential for sensory modulation of swallowing can be drawn from variations observed in swallow physiology across different bolus consistencies and subjects [69]. Palmer et al. [70, 71] showed that the ingestion of solid foods involves transport of the bolus to the occlusal surface of the molar teeth, chewing by the molar teeth to reduce the bolus to smaller-size pieces, and subsequent further transport of the bolus into the vallecular space, where it collects prior to pharyngeal swallow initiation. This pattern of ingestion contrasts with that usually observed in single (discrete) sips of liquid, in which the bolus is held in a chamber between the dorsal surface of the tongue and the hard palate, and then squeezed in a rostrocaudal direction toward the pharynx by virtue of upward and anteriorly directed tongue movements [39, 72]. Discrete boluses of liquid do not usually accumulate in the hypopharynx prior to swallow onset, except in the case of sequential liquid swallowing and during straw drinking [73, 74].

Martin-Harris and colleagues [75] and Daniels et al. [73, 74] have found that healthy subjects vary in their patterns of triggering the pharyngeal swallow. Although discrete boluses of liquid do not usually accumulate in the hypopharynx prior to swallow onset, differences in the pattern of swallow triggering are seen during sequential liquid swallowing and straw drinking. Under these circumstances, some healthy individuals trigger the pharyngeal swallow when the bolus reaches a position on the tongue base parallel to the mandibular ramus; others do not trigger swallowing until the bolus reaches more caudal positions. This pattern varies depending on whether the swallow is the first or a subsequent swallow in a series. Instructing subjects to hold the bolus in their mouth and wait for a command to swallow induces a higher trigger position [76]. Poudroux et al. [77] have shown that the latency to evoke a pharyngeal swallow is shorter with liquid infusion to deeper positions in the pharynx.

Additional evidence of the potential for sensory modulation in swallowing comes from experiments employing

(electrical) nerve stimulation and/or sensory inhibition techniques [49, 78–83]. Sinclair [82, 83] showed that swallowing was evoked most effectively by electrical stimulation applied to the pharyngeal branch of the GPN in rabbits. In the rat, swallowing is evoked more easily with mechanical stimulation of the GPN (the posterior pillars, posterior pharyngeal wall, and the soft palate) than with electrical stimulation [20]. Sectioning the pharyngeal branch of GPN eliminates swallow elicitation, while sectioning the lingual branch has no effect [20].

Storey [84, 85] showed selective response patterns in cat superior laryngeal nerve fibers to laryngeal cartilage displacement, tactile stimuli (<0.3 g), pressure (>0.3 g), water, and saline. Afferent fibers responsive to water overlapped with those responsive to tactile stimuli. Water was specific in inducing maximum discharges from sensory fibers compared to solutions with ions or sugars. Cold stimulation (2°C) increased tactile fiber activity [84, 85]. Anesthetizing the internal branch of the superior laryngeal nerve (iSLN) by transcutaneous injection of bupivacaine into the paraglottic compartment of healthy humans alters the evoking of swallowing [86]. Under these circumstances, swallowing requires greater effort and is accompanied by an illusory globus sensation in the throat and penetration of fluid into the larynx. Electromyographic recordings from the thyroarytenoid muscle during water swallows show that iSLN stimulation induces laryngeal closure in humans [87]. Intact afferent signals from the iSLN appear necessary to facilitate laryngeal closure in normal deglutition.

Interrupting normal afferent input interferes with healthy swallowing. Endoscopic studies of swallowing, using liquid and puree of different consistencies, have shown that applying anesthesia to the larynx of normal subjects significantly increases spillage, pharyngeal residual material, laryngeal penetration, and tracheal aspiration [88]. Intravenous injection of the inhibitor nitric oxide synthetase (NOS) prolongs latency to fictive swallow induction and the interval between swallows in urethane-anesthetized rats [89].

Effective Mechanisms and Stimuli for Sensory Modulation

Swallow elicitation appears to involve the activation of multiple sensory fibers across many receptive fields [5]. Sensory physiologists have proposed that normal swallowing stimuli activate “sheets of sensory fibers” so that afferent input proceeds over multiple parallel pathways [90]. When triggering a pharyngeal swallow, some afferent stimuli may contribute to lowering the threshold for swallow initiation in the NTS, the major sensory center in the brainstem swallowing pathway [91, 92]. Direct swallow facilitation can occur when the proper stimuli affect responsive receptive fields with sensory fibers that synapse in the brainstem,

exciting the dorsal region around the NTS [54]. Swallow facilitation and modulation can also occur indirectly via ascending cortical pathways that in turn modify the brainstem pathway’s threshold to stimuli in the primary receptive zones that evoke pharyngeal swallowing [55, 93]. The importance of sensory input for evoking swallowing is graded, with the most potent stimuli being those detected in the region innervated by the iSLN, immediately above the vocal cords in the hypopharynx [82, 83]. The sensory stimuli that trigger and modulate swallowing include tactile stimuli (light and heavy pressure, air puffs, different bolus volumes and viscosities), chemical stimuli (water, other solutions, cations, and anions) thermal stimuli, and combined stimulus modalities [84, 85, 94, 95]. Other stimuli may interfere with sensory integrity for swallowing; for example, cigarette smokers have higher thresholds for evoking laryngeal reflexes like vocal cord adduction (i.e., pharyngoglottal closure reflex), UES reflexes (i.e., pharyngo-UES contractile reflex), and pharyngeal swallowing [96, 97].

Tactile Stimuli

Touch and pressure have been used to stimulate pharyngeal swallowing in human subjects and experimental animals. Larger bolus volumes elicit greater tongue propulsive forces and shorter latencies to evoke the swallow [98–102]. Another bolus characteristic detected via touch and pressure mechanoreception is viscosity [103]. Higher bolus viscosities elicit increases in oropharyngeal transit times [98], intrabolus pressures [104], duration of pharyngeal peristalsis [98], duration of tongue base contact to the posterior pharyngeal wall [98], duration and excursion of hyoid movement [105], and duration of UES relaxation and opening [101, 104].

One of the more recent approaches to evaluate pharyngeal sensory integrity and elicit swallowing has been the use of air puffs [106–108]. Air pulse stimuli have been applied to the mucosa innervated by the iSLN during flexible fiberoptic endoscopic examination of swallowing [109]. When sensation is intact, these air pulses elicit visible tissue reaction at sensory thresholds of less than 4.0 mmHg air pressure, while patients with sensory deficits exhibit higher thresholds [110]. Individuals with normal air pressure sensation do not demonstrate food spillage, laryngeal penetration, or aspiration [111]. Stimulating the arytenoids and interarytenoid areas with air pulses elicits UES contraction (the laryngo-UES contractile reflex) in humans [111]. Studies with air puffs during flexible endoscopy also suggest that the pharyngeal sensation changes with age [107, 108, 112]. The use of air puff stimulation as a mechanism to elicit swallowing is currently under investigation [113, 114]. These studies suggest that healthy individuals

experience a strong urge to swallow in response to air puffs directed at the posterior faucial arches.

Thermal Stimuli

Experimental studies have shown that stimulating the anterior pillars with a cold probe while simultaneously stimulating the iSLN increases the number of pharyngeal swallows elicited in the anesthetized adult cat [115]. Ambient (25.3°C) or cold (8.9°C) probing of the anterior faucial pillar with a thermode did not induce swallowing in this preparation. Several studies in the human have evaluated temperature stimulation applied to the faucial pillars (e.g., bilateral light stroking with an ice-cold laryngeal mirror) [116–121]. Cold stimulation of the anterior tonsillar pillars in healthy subjects did not affect regional transit and clearance times or UES coordination [102]. Metal probes were found to warm to body temperature during the time between removal from a cup of ice chips and arrival at the faucial pillar; light faucial pillar stimulation with these probes did not change swallow latency or frequency [116]. The latency to swallowing-associated submental muscle activity during evoked swallowing has been shown to be shorter following combined mechanical, cold, and gustatory stimulation, but the effect did not persist beyond the first swallow during continuous infusion of water following stimulation [121]. However, stimulating the faucial pillars with a combination of mechanical, cold, and sour stimuli significantly decreased the latency to induce one swallow [121]. Both cold stimulation to the human anterior tonsillar pillars or application of topical anesthesia in normal subjects did not alter the regional transit time and clearance time of a bolus suggesting that stimulation of the anterior tonsillar pillars is not critical to evoking the pharyngeal swallow [102].

Chemical Stimuli

Saliva is an important sensory stimulus in the normal swallow: methods to enhance its secretion improve pharyngeal swallow elicitation. Manson and Sandberg [32, 33] counted the number of pharyngeal swallows performed in a 10-s period when subjects sucked on different lozenges. Their data showed that while the task was difficult without lozenges, neutral lozenges facilitated saliva secretion, and the best performance was seen with sour lozenges.

There are water-specific receptors in the pharyngeal region (particularly in the supraglottic space) that are vital to evoking a pharyngeal phase swallow [84, 85, 94]. Injection of water (0.3 and 0.6 ml) into the pharynx in healthy human subjects induces pharyngeal swallowing and closure of the larynx (i.e., pharyngoglottal closure reflex) [122, 123]. Adding potassium chloride to water in

different concentrations differentially excites receptors that elicit pharyngeal swallowing [25, 26].

Taste pathways may also be used to lower the threshold to evoke swallowing [124]. Taste sensory input synapses almost exclusively in the NTS, but predominantly in regions rostral to the subnuclei that contain interneurons vital to eliciting swallowing [63]. Many of the sensory fibers that terminate in the NTS respond to potassium chloride and hydrogen chloride [25, 26, 41]. Acetic acid and citric acid evoke swallowing more effectively than other solutions in anesthetized rats. Acetic acid evokes swallowing in regions innervated by the GPN pharyngeal branch and the iSLN. Water is effective in the iSLN region but only slightly in the GPNph region.

Logemann et al. [125] measured differences between swallowing a regular barium suspension and a sour barium suspension prepared in a 50% ratio with lemon juice in patients with neurogenic dysphagia. Both oral and pharyngeal transit times were shortened with the sour bolus. Further research by Hamdy et al. [126] used a fairly low-intensity solution of 10% citric acid and showed little or no change to swallowing. This raises the possibility that the effect observed by Logemann and Lawless [127] relied on a high intensity of citric acid, sufficient to suggest to some investigators that the stimulus is activating trigeminal nociceptive pathways. Improved swallow onset timing with sour stimuli may be facilitated by such nociceptive mechanisms and will require further study [125, 127, 128].

Despite these studies that evaluate sensory input affecting swallowing, research in normal subjects has also suggested that locally anesthetizing the oral and pharyngeal mucosa did not affect the regional transit and clearance times as assessed by videoradiography and manometry [129]. However, local anesthetizing the pharyngeal mucosa did significantly reduce the duration of the midpharyngeal contraction wave but not its amplitude.

Esophageal Responses to Different Stimuli

Different esophageal reflexes can be induced depending on the site and type of sensory stimulation [130]. Reflexes can be elicited based on the inflation rate of air distension to the esophagus. Primary peristalsis is induced by stimulation in the pharynx and the initiation of pharyngeal swallowing, while secondary peristalsis is induced by direct stimulation in the esophagus [28–30]. Inhibition of both primary and secondary peristalsis occurs with rapid water injection into the pharynx evoking repeated pharyngeal swallows [131, 132] and with air injection into the esophagus [133]. Rapid air injection into the pharynx induces UES contraction and lower esophageal sphincter (LES) relaxation and inhibits esophageal peristalsis [134, 135]. When air is injected into the esophagus above the level of a distending balloon, the

UES relaxes [136]. Air injection below the balloon induces increased UES contraction. Both contractile and inhibitory LES reflexes can be induced via sensory input from the pharynx, larynx, stomach, and esophagus [137]. Infusion of lidocaine into the human esophagus decreases the number of times air distension can induce secondary peristalsis [138].

Studies in the anesthetized cat have evaluated whether vagal sensory fibers innervating the esophagus can be sensitized by acid infusion to mimic problems with acid reflux in the human [139]. These vagal sensory fibers respond normally to graded esophageal distension, increasing their discharge with more distension. Infusion of acid with pepsin into the esophagus does not change the response to distension. However, neurons in the brainstem do become modified, suggesting that acid in the esophagus may alter sensory input and its affect centrally [139].

Sensory Input and the Cortex

Increased sensory input can modify motor areas of the cerebral cortex, fostering the concept that increased sensory input might be useful in rehabilitating dysphagic patients with cortical strokes [140, 141]. Some sensory inputs may induce cortical reflexes [142, 143]. Stimulation of the iSLN induces a reflex in the recurrent laryngeal nerve, activity in interneurons in the NTS, and simultaneous rostral activation of multiple cortical sites, including a cortical descending reflex that can affect the motoneurons in the cranial motor nuclei and interneurons in the NTS swallowing pathway [144]. If pharyngeal stimulation with a single electrical pulse is given prior to transcranial magnetic stimulation (TMS) to the motor cortex, the TMS facilitates the pharyngeal evoked potential elicited from the cortex [142]. Pharyngeal stimulation induces increased excitability of the swallowing cortex and short-term improvements in swallowing in dysphagic stroke patients. Stimulation of the pharynx can change the motor cortex and increases the area of representation of the pharynx, but it simultaneously decreases the esophageal representation [143]. For at least 30 min after pharyngeal stimulation, motor cortex excitability and the area of pharyngeal representation increased, suggesting potential ideas of protocols to enhance swallowing motor expression [145].

Future Directions

This review has summarized the current state of knowledge regarding the anatomy that subserves sensory input to swallow initiation and modulation and evidence supporting the potential for modulation of swallowing in response to sensory stimuli. Synthesis of this information reveals a number of areas for possible future research. These can be

grouped under the themes of (1) effective mechanisms and stimuli for sensory modulation, (2) pressure and tactile stimuli, and (3) chemical stimuli.

Effective Mechanisms and Stimuli for Sensory Modulation

An early animal study by Doty [5] using iSLN stimulation found that optimum frequencies to evoke swallowing were between 30 and 50 Hz in the anesthetized dog, monkey, and cat. Outside these frequencies, swallows were evoked only with higher-intensity current. The optimum frequency of electrical stimulation to a peripheral nerve means that a pattern of excitation must be applied to sensory fibers of different diameters [146] and that this pattern must be detected in the dorsal NTS swallowing group in order to trigger specific interneurons to start the swallow [54, 91, 147]. However, electrical stimulation of a peripheral nerve is a nonphysiological form of stimulation that excites the largest-diameter fibers [146] first, rendering it an artificial approach to stimulation. Future studies of sensory modulation of swallowing in the human with a damaged or impaired CNS may rely on techniques that use electrical sensory patterns similar to those studies ongoing in the auditory system with cochlear implants or with stimulation of peripheral nerve [148, 149].

Pressure and Tactile Stimuli

Larger boluses elicit shorter latencies to pharyngeal swallow onset and increased muscle contractile activity [101, 104]. Such findings suggest that a larger bolus moving across more receptive fields excites more sensory fibers which synapse in the NTS and enhance the NTS drive of the motoneurons. This hypothesis has yet to be confirmed experimentally.

Chemical Stimuli

Few studies have controlled for or explored the olfactory aspects of stimuli that might affect swallowing [35]. Olfactory inputs appear to enhance pharyngeal swallowing through increasing salivation. Bülow et al. [150] have studied carbonation as a stimulus to evoke swallowing, but it remains unclear which characteristics of carbonated stimuli might be important in evoking swallowing. Gas in a swallowed bolus may constitute both a touch-pressure stimulus and a dynamic taste or chemesthetic stimulus.

Summary

Boluses of liquids and solids normally initiate pharyngeal swallowing using multiple modalities, including taste,

water, touch, pressure, and possibly temperature to excite several types of sensory fibers of different diameters that innervate the receptors in the oropharyngeal mucosa. It appears that stimulation of a greater number of receptive fields and their individual sensory neurons induces a stronger reflex with greater muscle recruitment and force. Movement of portions of a bolus to the hypopharyngeal region will induce the pharyngeal swallowing reflex with a shorter latency. Stimulation of the oral region, which includes the pillars of fauci, appears to facilitate swallow reflex initiation, with air puffs and combined thermal-gustatory-tactile stimuli eliciting preferential responses. Enhancement of salivation, including the use of visual and olfactory stimuli, also appears to facilitate the evoking of swallowing. The potential of enhancing stimuli to the mucosa through air puffs appears promising and follows some of the excellent studies using sour boluses and sour stimuli with other stimuli. Many of these findings are drawn from experiments in animals or observations of swallowing in healthy humans. Therefore, these conclusions lay the foundation for future experiments in which specific sensory inputs may be further examined for their potential to elicit and modulate swallowing in humans with dysphagia.

Acknowledgments This review article was born out of conversations at a meeting in Christchurch, New Zealand, in 2005. We recognize Dr. Maggie-Lee Huckabee, who had the vision to organize that meeting and initiate those discussions. The first author acknowledges the support of the Toronto Rehabilitation Institute which receives funding under the Provincial Rehabilitation Research Program from the Ministry of Health and Long-term Care in Ontario. The views expressed do not necessarily reflect those of the ministry.

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