REVIEW OF LITERATURE

Swallowing is defined as “the semiautomatic motor action of the muscles of respiratory and gastrointestinal tract that propels the food from oral cavity to the stomach” (Miller, 1986). Swallowing act is highly complex and it depends on the integration of sensorimotor system. It includes several anatomic areas which have voluntary and involuntary components, and is inclusive of inhibition of respiration during swallowing. Neuromuscular coordination involves the central nervous system, afferent sensory input, efferent motor response, the brain stem and the enteric nervous system. Hormonal factors, although poorly understood, do play a role in swallowing.

Classically, the act of swallowing is described in four phases: the oral preparatory phase, the oral transport phase, the pharyngeal phase and the esophageal phase.

The oral preparatory phase is a voluntary act and begins with intake of food into the mouth and formation of bolus. Food bolus, that requires mastication is prepared in the oral cavity before the beginning of swallow response. The tongue moves the bolus laterally to the molar ridges. Crushing, or the repetitive movement of the jaws reduce the bolus size. Once initiated, chewing continues reflexively, but can be altered by cortical inputs. This activity is not required for liquids. However, momentary containment by the tongue may be necessary so that the liquid does not prematurely enter the airway. The temporalis, masseter, buccinator and the pterygoid muscles are the paired muscles that are active during solid food preparation. This chewing activity stimulates the saliva glands, allowing moisture to form and lubricate the bolus for
facilitating swallowing. Adequate saliva is also important for good oral health (dentition), taste facilitation, and a normal acid base balance in the mouth, particularly at night. The parotid, submandibular, and sublingual glands serve as the main conduits for saliva production. Their stimulation is accomplished through motor autonomic fibers carried by cranial nerves (CN) VII (Facial) and CN IX (Glossopharyngeal). The oral cavity is particularly rich in touch and pressure receptors on the tongue, gums, teeth and palate. These mechanical receptors transmit sensory information through CN V (Trigeminal) to the swallowing centers in the brain that coordinate swallowing action. Information from other receptors that are sensitive to change in temperature is also carried by the sensory branch of CN V. Sensory information pertaining to taste (chemoreceptors) is mediated partially by CN VII on the anterior two thirds of the tongue. Sensory information pertaining to taste, temperature, and mastication is sent to the brainstem and is integrated in the nucleus tractus solitarius of the medulla. Regarding the viewpoint that a person can change his/her swallowing pattern volitionally (particularly during the oral preparatory stage), it is assumed that higher cortical centers that modulate swallowing does exist. These higher centers undoubtedly are capable of exerting influence on the highly programmed swallowing circuitry of the brainstem (Logemann, 1998; Balasubramaniam & Bhat, 2012).

The oral transport phase is voluntary and begins after the bolus is prepared for swallowing. At the moment of swallowing response, the bolus is propelled into the oropharynx and then into the hypopharynx. The key structure in this effort is the tongue whose movement is accomplished by the motor fibers of the hypoglossal nerve (CN XII). As the tongue moves posteriorly (by the contraction of the digastric,
geniohyoid and mylohyoid muscles), its base makes contact with the posterior pharyngeal wall, that is moving anteriorly by the contraction and elevation of the oropharyngeal constrictor muscles. The posterior retraction of the tongue lifts the hyoid bone in a superior and anterior plane to the level of the mandibular ridge. Hyoid elevation is maintained throughout the large portion of the swallow. The bolus is directed downwards with the combined action of peristaltic waves and closure of nasopharynx by the velum (Logemann, 1998; Balasubramanium & Bhat, 2012).

The pharyngeal phase involves the major anatomic landmarks of the epiglottis, vallecular and pyriform sinus spaces, thyroid and cricoid cartilages, cervical spine and pharyngeal wall. The major muscles involved in propelling the bolus include the palatopharyngeal (CN X and CN XII) and stylopharyngeus (CN IX) muscles, which act to elevate and shorten the pharynx and superior (CN X and CN XI), medial (CN X), and inferior (CN X and CN XI) constrictor muscles. The inferior constrictor muscle comprises the oblique musculature of the thyropharyngeus muscle and circular fibres of the cricopharyngeus muscle. During this phase, epiglottis, true vocal folds, false vocal folds and aryepiglottic folds close to prevent aspiration. As the bolus enters the pharynx, it is divided by the vallecular spaces at the level of the tongue base helping deflect it away from the airway as an additional component of airway protection. Simultaneously, the pharyngeal constrictor muscles act to narrow and shorten the pharynx, keeping sufficient positive pressure on the bolus as it flows into the zones of the negative pressure. As the bolus continues towards the esophagus, it remains divided, flowing into the two paired pyriform sinuses lateral to the larynx in the region of the hypopharynx. The two halves of the bolus are rejoined as they enter
the esophagus though the pharyngo esophageal sphincter (Logemann, 1998; Balasubramaniam & Bhat, 2012).

**Esophageal phase:** The pharyngo-esophageal sphincter opens by three mechanisms: a) central nervous system mediated relaxation in response to the pharyngeal contraction (CN IX and CN X); b) mechanical traction applied by the elevation of the hyoid bone, pulling open the pharyngo esophageal sphincter after relaxation; and c) the downward, driving force of the bolus into the cervical esophagus. As the bolus enters the cervical esophagus, many of the structures that were active during the oropharyngeal stages return to their rest position. As the bolus enters the esophagus, the mechanism of peristalsis delivers the bolus from the proximal esophagus to the distal esophagus and into the stomach. The first contractile wave of the peristalsis is usually stronger and its strength depends on the efficiency of the pharynx to clear all its contents. The more efficient the clearance, stronger will be the wave. The peristalsis may be inhibited by the multiple swallows of the same bolus. A secondary wave of the activity to clear the residue in the esophagus is propagated by the bolus itself as it distends the esophagus on its path to the stomach. This is called the secondary peristaltic wave. The beginning of this peristaltic wave sends a message to the lower esophageal sphincter causing it to relax in such a way that the bolus can flow into the stomach (Logemann, 1998; Balasubramaniam & Bhat, 2012).

The duration and characteristics of each of the phases of swallowing varies with the type and volume of the food being swallowed and the voluntary control exerted over it (Kahrilas, Lin, Chen, & Logemann, 1996). Thus the swallowing event varies with the characteristics of food being swallowed and the voluntary control. The frequency
of swallowing also varies across different activities (Lear, Flanagan, & Moores, 1965). Frequency of swallowing is greatest during eating and least during sleep, with other activities taking an intermediate place. Mean swallowing frequency is approximately 580 swallows per day, and one can refrain from swallowing for periods of 20 minutes or more.

Figure 1: Phases of swallowing
Neural Control of Swallowing Mechanism

Neural control of swallowing can be divided into cortical and the brainstem components. Neural control comprises of a complex interaction of afferent sensory neurons, motoneurons and the interneurons that control the voluntary and involuntary phases of swallowing. Cortical regulation includes centers in both the hemispheres of the brain with representations from pharynx and esophagus. These cortical areas have inter-hemispheric connections and projections to the motor nuclei in the brain stem. Also, bilateral hemispheric stimulation produces a greater response than unilateral impulses, and these responses are intensity and frequency dependent. Both the motor and premotor cortical areas have the potential to modulate the contraction of the pharyngeal and esophageal muscles. Input from these cortical areas seems greater to the pharynx compared to the esophagus. Similarly, afferent impulses from the pharynx through superior laryngeal nerve and the glossopharyngeal nerve have the greater impact on cortical area than those from the upper esophagus through the recurrent laryngeal nerve.

The brainstem component responsible for the swallowing event comprises of swallowing center which is an area within the reticular formation of the brainstem that includes the nucleus ambiguus and the nucleus of tractus solitorius which interact with the nuclei of the CN V, CN IX, CN X, & CN XII. This collection of brain stem nuclei coordinates the central pattern generator. Electrophysiologic studies (Westberg, Scott, Olsson, & Lund, 2001; Tsuboi, Kolta, Chen, & Lund, 2003) have indicated that neurons of the brain stem contain the pattern-generating circuitry for governing the oral, pharyngeal, and esophageal phases of swallowing. These premotor neurons also
control the timing of these phases of swallowing. Thus the timing of the motor responses within each phase of swallowing, as well as the timing between phases of swallowing are controlled by the pattern generating circuitry. Lang (2009) summarized the neural correlates for each phases of swallowing which are detailed below.

**Oral phase of swallowing:** Swallowing, though is a voluntary phenomenon, much of this process is composed of stereotyped motor activity. These activities are controlled by brain stem central pattern generators, which control not only the pharyngeal and esophageal phases of swallowing, but also part of the oral phase of swallowing. Anencephalic infants were reported to exhibit rhythmic oral movements and swallow (Pritchard, 1965; Peleg & Goldman, 1978). Therefore it can be assumed that the oral phase of swallowing is regulated by subcortical structures in the brain.

Animal studies have indicated that neural stimulation to the cortical structures results in rhythmic movement of oral muscles which resemble that of oral preparatory phase of swallowing in human beings (Lund, 1991; Nakamura & Katakama, 1995). These movements break up the food and transport the bolus from the tongue to the pharynx. It has been established that the electrical stimulation of the swallowing area in the cortex activates neurons (Lund, 1991; Nakamura & Katakama, 1995; Westberg, et al., 2001; Tsuboi, et al., 2003; Athanassiadis, Olsson, Kolta, & Westberg, 2005) in the reticular formation and vestibular nucleus, and exhibit rhythmical excitation similar to that observed in the oral muscles when activated (Lund, 1991; Nakamura & Katakama, 1995; Tsuboi, et al., 2003). Therefore, the stereotyped movements of oral
phase of swallowing are activated by neurons of the trigeminal nucleus and reticular formation.

**Pharyngeal phase of swallowing:**

*Sensory nuclei:* The pharyngeal phase of swallowing is associated with activation of premotor neurons in the intermediate, ventromedial, and interstitial subnuclei of the nucleus tractus solitarius. Swallowing activated by electrical stimulation of the superior laryngeal nerve (Sang & Goyal, 2001) or recurrent laryngeal nerve (Amirali, Tsai, Weisz, Schrader, & Sanders, 2001) are associated with interstitial and intermediate nucleus tractus solitarius. It was also found that the interstitial and intermediate nucleus tractus solitarius project to two synapses in the pharyngeal muscles. In addition, the electrical (Wang & Bieger, 1991) or chemical (Hashim & Bieger, 1989; Kessler & Jean, 1991) stimulation of interstitial and intermediate nucleus tractus solitarius activates pharyngeal phase of swallowing, and neurotransmitter antagonists injected into this region (Hashim & Bieger, 1989; Kessler & Jean, 1991; Wang & Bieger, 1991) inhibits the pharyngeal phase of swallowing. Hence it can be assumed that the primary nuclei of the pharyngeal phase of swallowing are the interstitial and intermediate nucleus tractus solitarius.

*Motor nuclei:* The activation of motor neurons in the caudal dorsal motor nucleus and dorsal nucleus ambiguus was associated with the pharyngeal phase of swallowing (Lang, Dean, Medda, Aslam, & Shaker, 2004). The neuronal activity was smaller in the dorsal motor nucleus during the pharyngeal phase of swallowing compared to those activated during the esophageal phase of swallowing. These neurons are inhibitory rather than excitatory (McCleak & Hopkins, 1981) and interneurons are often inhibitory. Tract-tracing studies (Lawn, 1966; Holstege,
Graveland, Bijker-Biemond, & Scuddeboom, 1983; Collman, Tremblay, & Diamant, 1993) have pointed out that the motor neurons of the pharyngeal muscles are located in the dorsal nucleus Ambiguus.

**Esophageal phase of swallowing:**

**Sensory nuclei:** The esophageal phase of swallowing has been associated with the activation of premotor neurons (Lang, et al., 2004) in the central, ventral, dorsolateral, and ventrolateral subnuclei of the nucleus of tractus solitarius. Tract-tracing studies have indicated that only the nucleus tractus solitarius central projects to the esophagus with two synapses in comparison to the other nucleus tractus solitarius nuclei. Moreover, the electrical (Bieger, 1984) or chemical (Beiger, 1984; Hashim & Bieger, 1989; Wang & Bieger, 1991; Lu, Zhang, Neuman, & Bieger, 1997) stimulation of the nucleus tractus solitarius central activates the esophageal but not the pharyngeal phase of swallowing. In addition, neurotransmitter antagonists microinjection (Beiger, 1984; Hashim & Bieger, 1989; Wang & Bieger, 1991) or the creation of a lesion in this area (Lu, et al., 1997) inhibits the esophageal but not the pharyngeal phase of swallowing. Therefore, the primary premotor nucleus of the esophageal phase of swallowing is probably the nucleus tractus solitarius central.

**Motor nuclei:** The motor neurons of the esophageal phase of swallowing are located in both rostral and dorsal subnuclei of the dorsal motor nucleus, but primarily in the dorsal motor nucleus rostral (Lang, et al., 2004). The neurons in both subnuclei are larger than those of pharyngeal phase of swallowing, reflecting their activity as motor neurons (McClean & Hopkins, 1981). It is likely that the dorsal motor nucleus rostral neurons are excitatory whereas the dorsal sub nuclei are inhibitory during the
esophageal phase of swallowing. The ventral portion of the nucleus ambiguus has also been reported to be activated during swallowing (Lang, et al., 2004). The chemical stimulation of the nucleus ambiguus initiates synchronous or propulsive esophageal contractions (Kruszewska, Lipski, & Kanjhan, 1994). Therefore, the motor nucleus of the esophageal phase of swallowing are located in the nucleus ambiguus and the dorsal motor nucleus.

To conclude, the neural control of each of the phases of swallowing have independent existence and their movements are governed by central pattern generators of the brain stem. The oral phase of swallowing is voluntary and the pharyngeal and esophageal phases of swallowing occurs secondary to stimulation by the bolus. Three sets of brain stem nuclei govern the oropharyngeal, and esophageal phases of swallowing. Central pattern generators for the oral phase can be found in the trigeminal nucleus and reticular formation. The nucleus tractus solitarius consists of sensory neurons and pattern generating circuitry for the pharyngeal and esophageal phases of swallowing. The dorsal motor nucleus and nucleus ambiguus contain the motor neurons and the pattern generating circuitry for the pharyngeal and esophageal phases of swallowing. The ventro-medial nucleus of the nucleus tractus solitarius governs the coupling of the pharyngeal to the esophageal phase of swallowing.

**Assessment of Swallowing:**

Assessment of swallowing is an organized, goal directed process involving a variety of interrelated and integrated components of the swallowing process. It is important to denote the goals of the swallowing assessment to completely assess the nature of swallowing problems. It includes determining the underlying pathophysiology related
to the medical diagnosis, to determining the patient’s abilities and disabilities in the swallowing mechanism and examining the degree to which these impairments can be modified (Langemore & Logemann, 1991).

Some signs of dysphagia are overt, such as cough during eating, whereas others may not be overt such as silent aspiration. Early identification and treatment of dysphagia might prevent the serious medical complications such as pneumonia and under nutrition. Assessment of swallowing involves screening measures as well as comprehensive evaluation which can either be qualitative or quantitative.

**Qualitative measures of swallowing:** Currently there are several forms of subjective assessment tools available for swallowing evaluation. Dysphagia related to oral preparatory and oral phase can be identified easily with visual examination of the oral mechanism with and without food. However assessment of pharyngeal phase poses special challenge owing to poor visibility and involuntary action, research focus in the west has aimed at exploring the pharyngeal stage of dysphagia.

Attempts have been made to identify the risk for aspiration using various clinical factors affected in individuals with dysphagia. Linden and Siebens (1983) investigated fifteen individuals with pharyngeal stage dysphagia using sensorimotor examination. Higher incidence of impaired pharyngeal gag and wet gurgly voice quality was observed in many individuals exhibiting laryngeal penetration on motion fluoroscopy. It was concluded that cough was not a reliable predictor for laryngeal penetration, instead it was recommended to use motion fluoroscopy for the identification of penetration. Dysphonia and weak cough were reported to be the
significant predictors of aspiration using videofluoroscopy and clinical swallow examination by Horner and Massey (1988).

DePippo et al. (1992) used 3-oz water swallow test to conclude that cough during swallow and post swallow gurgly voice were the clinical predictors of aspiration. Horner, Brazer and Massey (1993) examined thirty eight individuals with bilateral stroke and found that abnormal voluntary cough and absent gag reflex significantly correlated with aspiration on videofluoroscopy. But Stanners, Chapman and Bamford (1993) reported association only between weak voluntary cough and aspiration. Gag reflex was recognized to be absent in 30% of healthy young adults and 44% of healthy old adults by Davies, Kidd, Stone and Mac Mohan (1995). This suggests that gag reflex cannot be considered as a sole predictor of aspiration and also, absent pharyngeal sensation was uncommon in normal individuals.

Daniels and Collegues (1997, 1998) investigated the clinical factors associated with the identification of dysphagia severity. Oropharyngeal evaluation and videofluoroscopic investigations were completed on fifty nine individuals with dysphagia. Oropharyngeal evaluation included the identification of clinical features such as dysphonia, abnormal volitional cough, dysarthria, cough after swallow, abnormal gag reflex, and gurgly voice after swallow. The results of videofluoroscopy was scored on a five point rating scale (0=normal, 1=mild, 2=moderate, 3=moderately severe,4=severe) for the assessment of dysphagia severity. Results of logistic regression analysis indicated that abnormal volitional cough and cough while swallowing could predict aspiration with 78% accuracy and these clinical features could differentially diagnose those individuals with moderate to severe dysphagia
from individuals with mild dysphagia and normal swallowing. Smithard et al. (1998) reported that altered consciousness level and weak voluntary cough could predict aspiration. This combination gave 75% sensitivity, 72% specificity, positive predictive value of 41% and negative predictive value of 91% for aspiration in videofluoroscopy.

The ability to cough was also used as a clinical factor to determine the risk for aspiration. In this regard, Addington, Stephens, Gilliland and Rodriguez (1999) examined acute stroke individuals using cough test. This test used nebulized tartaric acid for the assessment of laryngeal cough reflex. Results indicated that a normal cough after an acute stroke was associated with lower risk for developing aspiration. A weak or absent cough indicates a significant risk for aspiration. McCullough, Wertz and Rosenbek (2001) also investigated the clinical predictors of aspiration in sixty individuals with dysphagia due to acute stroke. These individuals underwent clinical swallowing and videofluoroscopic examinations. Clinical swallowing examination included information on case history, assessments on oral motor, speech praxis, trial swallows and voice. Results revealed that cough while swallowing is a reliable predictor of aspiration i.e., those individuals who coughed during swallowing had aspiration on videofluoroscopy. Authors have cautioned the use of clinical swallowing examination.

Water swallowing test and swallowing provocation test was the focus of investigation in few studies to determine the risk for aspiration in individuals with dysphagia. Teramoto and Fukuchi (2000) examined twenty-six individuals with stroke and aspiration pneumonia and twenty six age-matched stroke individuals without
aspiration pneumonia using Water swallowing test and swallowing provocation test. Water swallowing test was performed by asking the individuals to drink 10 and 30 ml of water from a plastic cup within 10 secs. Individuals who drank water without aspiration and without any interruption were considered normal. Swallowing provocation test was performed by injecting water into the suprapharynx. Individuals were considered normal if the swallowing reflex was elicited within 3 secs. Sensitivity and specificity for the first-step water swallowing test in the detection of aspiration were found to be 71.4% and 70.8%, respectively. However, second-step water swallowing test using 30 ml of water gave the sensitivity and specificity of 72% and 70.3%, respectively. Similarly, 100% sensitivity and 83.8% specificity were obtained for first step swallowing provocation test for the detection of aspiration. However, sensitivity decreased to 76.4% and specificity increased to 100% for the second-step swallowing provocation test. Finally authors have concluded that swallowing provocation test is better than water swallowing test in differentiating individuals with and without predisposition for aspiration.

Few researchers have investigated the role of pharyngeal and laryngeal sensation in the identification of aspiration. One such study by Kidd, Lawson, Nesbitt and MacMahon (1993) used videofluoroscopy and bed side water swallowing test to evaluate aspiration in sixty individuals with acute stroke. Results of Videofluoroscopy revealed aspiration for twenty five individuals. Of these twenty five individuals, twenty of them did not have overt dysphagia as assessed through bedside water swallowing test. In all the individuals with stroke who aspirated on videofluoroscopy, pharyngeal sensation was absent indicating clinical significance of assessing pharyngeal sensation in the clinical swallow examination. Aviv et al. (1997, 1998)
stimulated the laryngeal mucosa endoscopically through the air pulses and attempted to determine sensory discrimination thresholds in eighteen stroke individuals and eighteen age matched controls. These individuals were followed for a period of one year and the results indicated that most individuals with clinical dysphagia had sensory deficits, and those with severe sensory deficits exhibited aspiration on follow up visits. However, sensory deficits were also found in acute stroke individuals without clinical dysphagia and it was recommended that silent sensory impairments may possibly predispose the individuals to develop aspiration. Bastian and Riggs, (1999) anesthetized the oral cavity, hypopharynx and larynx using lidocaine injection in thirteen healthy adults. Results revealed that normal swallowing did take place even in the presence of complete local anesthesia.

Swallowing problems were also determined by temporal measures of swallowing. Hinds and Wiles (1998) investigated the risk for swallowing using timed test of swallowing. This particular test gives information about swallow time, volume of bolus per swallows and swallowing capacity. Findings revealed that delayed swallowing, coughing, and/or dysphonia indicated swallowing problems in acute stroke individuals. Those individuals in whom a swallowing rehabilitation was suggested, 97% had an abnormal quantitative water swallowing. They concluded that the timed test of swallowing can be a useful screening tool for swallowing assessment with 69% specificity and may be used for referring patients to a speech pathologist after acute stroke.

The validity of these clinical factors has been correlated with Videofluoroscopy for the reliable detection of aspiration. However, sensitivity and specificity of these clinical
factors revealed varied findings in the range between 42% and 92%. Positive predictive value for clinical swallowing examination ranged from 50% to 75% whereas the negative predictive values ranged from 70% to 90% (Splaingard, Hutchins, Sulton, & Chaudhuri, 1988; Daniels, et al., 1997; Smithard, et al., 1998; Smith, Lee, O’Neill, & Connolly, 2000). Interjudge and intrajudge reliability for clinical examination also varied significantly across the studies (Ellul & Barer, 1996; Smithard, et al., 1998; Mann, Hankey, & Cameron, 2000; McCullough, et al., 2000).

Though the sensitivity and specificity of these clinical swallowing examinations vary widely, they are still used in the assessment of individuals with dysphagia. Of late, there has been an increasing interest in refining these clinical factors and formulating the diagnostic procedures, with the goal of eliminating the need for a videofluroscopic study or other instrumental procedures. Some of these tools target the oral preparatory and oral phase whereas others target the pharyngeal phase of swallowing.

**Formal swallowing assessment tools:** There are many formal assessment tools available for the assessment of swallowing. Some of them use trial swallows and some do not.

**Formal assessment tools without trial swallows:** Following are the assessment protocols which assess various structural and functional components of swallowing. Vittali (1986) developed a test of oral structures and functions for the age range of 7 years to adults, in which the oral structures and functions are assessed through speech and non speech tasks. On a similar line, Jelm (1990) developed an Oral motor/Feeding rating scale for the assessment of swallowing functions. It gives
directions regarding swallowing by assessing the oral motor movements during various feeding and drinking activities.

Following these tests, Dworkin and Culatta developed a comprehensive oromotor assessment and treatment protocol [Dworkin-Culatta Oral Mechanism Exam and Treatment System (Dworkin & Culatta, 1996)] for the assessment of orofacial structures and its functions. It includes a treatment plan for those diagnosed with oromotor deficits. However, Tanner and Culbertson (1999) felt the need to develop a Quick assessment protocol for individuals with dysphagia and standardized the quick assessment for dysphagia for the adolescents and adult population. It provides information about oral, pharyngeal, and laryngeal stage of swallowing without trial feeds. Later, oral speech mechanism screening examination (OSMSE-3) was developed for children and adults in the age range of 5-78 years (Louis & Ruscello, 2000). It assesses the lips, tongue, teeth, palate, jaw, pharynx, velum, breathing, and diadochokinetic rates. It is a quick, and reliable tool for the examination of oral mechanism across range of speech and language disorders. It also provides a normative data for the interpretation of patient data.

Dysarthria/Dysphagia clinical battery (Linden, Kuhlemeier, & Patterson, 1993) was developed to assess the factors related to subglottic penetration. These factors include recumbent posture, abnormal laryngeal elevation, wet spontaneous cough, abnormal phonation, abnormal palatal gag, and drooling. However, on discriminant analysis, these factors predicted only two thirds of individuals with subglottic penetration.
Depippo, Holas and Reding (1994) validated the Burke Dysphagia Screening Test [BDST] on one hundred and thirty nine individuals with stroke. They considered features such as stroke site and difficulty with meals. The outcome measures considered for this study were recurrent upper airway obstruction, pneumonia, and death. It was found that the risk for developing any of these complications was 7.65 times greater in those who failed BDST. It was concluded that BDST is a good tool in the identification of individuals at a risk for developing swallowing problems in the post stroke rehabilitation.

*Formal assessment tools with trial swallows:* Apart from the assessment of sensory and motor components involved in swallowing, few assessment protocols use trial feeds to obtain further information about the swallowing.

Mulpeter and Rosenfield (1993) developed a Program for the assessment and instruction of swallowing (PAIS). It examines the oral mechanism with the structural and functional tasks and also includes trial swallows. Following this, Hardy (1995) has developed a comprehensive protocol for the bedside assessment of adults with dysphagia [Bedside evaluation of dysphagia (BED)]. There are three major components in BED. First component aims to prescreen non-physiological factors associated with the swallowing disorder. Second component involves oral motor and oral sensory assessment of each articulators. Third component involves trial swallows to assess the oropharyngeal dysphagia. A screening form for faster administration at the bed side is also available. This tool can be used for assessing neurogenic dysphagia and does not target dysphagia caused due to other problems such as glossectomy.
Manns Assessment of Swallowing Ability (MASA), a psychometrically validated test was developed by Mann (2002) for the assessment of swallowing abilities in adults and geriatrics. This includes assessment of various components of swallowing with and without trial swallows. It is a quick and reliable tool to determine the need for further instrumental evaluation. It also gives information about the individuals risk for aspiration, supported with rigorous psychometric evaluation. This tool can also be utilized for monitoring the progress in swallowing rehabilitation. However, it can be used only for assessing individuals with neurogenic dysphagia.

Ross-Swain, Kipping and Yee (2003) have also developed and standardized the Swallowing ability and function evaluation (SAFE) test for providing a diagnosis of dysphagia at the bedside. It emphasizes on obtaining a case history from the individuals and the care givers before evaluating the oral and pharyngeal phases of swallow. Evaluation of individuals cognitive and behavioral status related to swallowing is the first stage followed by the physical examination of the oropharyngeal mechanism. Third stage is the functional analysis of swallowing using feeds. Here the ability to manage the oral preparation phase, oral phase and pharyngeal phase of swallowing are evaluated. SAFE also targets individuals with neurogenic dysphagia.

Hines functional dysphagia scale (HFDS) was developed specifically to refine the results of Videofluoroscopy in individuals with dysphagia in the age range of 20-86 years (Klorr, Bacon, Cook, & Milianti, 2005). Here the clinician rates the swallowing ability on five clinically relevant items such as food, liquid, aspiration, efficiency, and
compensation for the individuals with dysphagia. The sum of these ratings provide the total score.

Suman (2009) developed the clinical protocol for swallowing disorders in adults. It comprised of assessment of posture, respiration at rest, cognitive status, sensory abilities, cranial nerves, oral reflexes, physical examination of oral mechanism and assessment of swallowing across all the phases of swallowing. However, it was neither standardized nor field tested.

Thus, there are few published clinical dysphagia assessment tools that provide detailed assessment of swallowing with and without trial feeds. Among these, only few are supported with rigorous psychometric evaluation. Moreover, these tools are standardized either for neurogenic dysphagia or mechanical dysphagia.

**Quantitative measures of swallowing:** A number of imaging and non imaging tools are available with the speech pathologists to study the physiology of swallowing. These include ultrasound, videoendoscopy, videofluoroscopy and scintigraphy. They provide some information about the oropharyngeal anatomy and physiology in different ways. However, they are invasive and expensive. To overcome these limitations, inexpensive non imaging procedures without radiation exposure are also available. These procedures provide information about the swallowing behavior without the pictures/video of the food being swallowed. They provide information about amplitude over time displays of the swallow parameters (e.g., Surface EMG (sEMG), Cervical auscultation, and Nasal airflow monitoring during swallowing).
**Surface EMG:** Electromyography (EMG) gives us information about the temporal and amplitude characteristics of muscle contraction during swallowing (Doty & Bosma, 1956; Palmer, 1988; Palmer, et al., 1989; Perlman, et al., 1989; Perlman, 1993). Since swallowing action involves various muscle coordinations and contractions, EMG would be suitable in the evaluation of dysphagia (Schultz, et al., 1994). Information about the amplitude of electric activity (Ertekin & Palmer, 2000), and the timing of selected muscle contraction during swallowing (Palmer, 1988; Logeman, 1994) can be obtained from EMG. Moreover, the procedure is easy to learn by the professionals (Gupta, Reddy, & Canilang, 1996; Crary & Baldwin, 1997).

Electromyographic investigations during swallowing have been performed on animals as well as humans and on structures ranging from lips to esophagus. They have been performed with various types of electrodes such as surface, surface-suction, needle, hooked wire, monopolar, and bipolar electrodes. The use of different types of electrodes varies depending on the purpose of investigation. Needle electrodes are generally preferred for the research purposes to investigate specific muscle functions. Though needle electrode has been reported to be a safe procedure (Mu & Yang, 1990), there can be still some discomfort for the individuals as the time taken to manipulate the needle electrode onto the muscle of interest takes more time. Anesthesia given during the procedure may alter the sensory and motor processes normally available during swallowing (Ertekin & Palmer, 2000) which may affect the results. Hence, it is advisable to have few needle electrodes at a time for the electromyographic investigations (Ertekin, Yuceyar, & Aydogdu, 1998; Ertekin & Palmer, 2000). However, normal swallow cannot be performed when a needle is placed on a muscle, because of the movements associated with swallowing process.
Also, it is not possible to look at the morphology of the individual motor units during swallowing owing to the semiautomatic nature of swallowing process (Kimura, 1989). In contrast, sEMG is used when the investigators are less concerned about the cross talk of muscle activity. sEMG can be recorded from a group of muscles within a wide field range. For example, submental sEMG records the muscle activity from a group of muscles such as geniohyoid, mylohyoid and the anterior belly of digastric muscles. It does not provide any discomfort to the patient, thereby allowing several muscles to be examined at the same time. This is of particular concern when several muscles involved in swallowing are in close proximity to each other with a probability of cross talk. These cross-talks can be minimized by analysing the independent components of raw sEMG waveforms which is proven to reduce the variability in the raw sEMG recordings (McKeown, 2000; McKeown & Radtke, 2001). Another problem is that the repeated measurements of the same movement would vary results (Boline, et al., 1993; Goodwin, et al., 1999). Owing to these limitations, sEMG can be used as a biofeedback tool in the swallowing rehabilitation and not as a diagnostic tool (Barofsky, 1995; Cram & Kasman, 1998; Huckabee & Cannito, 1999).

Electromyographic studies of normal swallowing: The first traceable literature on EMG was by Doty and Bosma (1956) who investigated swallow reflex in dogs, cats and monkeys. When the pharynx was stimulated with a cotton swab or by rapidly injected water, the superior laryngeal nerve got stimulated, thereby eliciting swallow reflex. However, the investigators reported no significant difference in the amplitude and the duration of muscle contraction in swallows elicited by various methods. A group of muscles (superior constrictor muscles, palatopharyngeus, palatoglossus,
posterior intrinsic muscles of tongue, styloglossus, stylohyoid, geniohyoid and mylohyoid) fired in tandem with the initiation of swallow reflex.

The muscles such as geniohyoid, mylohyoid, genioglossus and anterior belly of digastrics were activated in the oral stage of the swallow as examined by Hrycyshyn and Basmajian (1972) in humans. They found no universal firing pattern among these four muscles. However the consistency and the volume of bolus appeared to affect the duration and amplitude of the muscle activity. Perlman, et al., (1989) used hooked wire electromyography to investigate the superior pharyngeal constrictor muscle during swallowing and other voluntary acts such as producing speech sounds, falsetto voice, valsalva maneuver and gagging. Swallowing and other voluntary actions were compared for the level of muscle contraction. Results indicated that the electrical activity in the superior pharyngeal constrictor was greatest for swallowing followed by gagging, valsalva, effortful articulation, falsetto, and other speech production tasks respectively. Results also revealed that the electrical activity produced by the muscles of swallowing could not be compared across individuals due to the inter subject variability.

Gupta, et al. (1996) investigated dry and wet swallowing in 35 normal individuals using sEMG at the throat. Mean power values of the EMG signals were calculated for both dry and wet swallowing and the results revealed significant difference between the means of power values during dry and wet swallowing. Hence, it was concluded that the mean power values could be used as a reliable non invasive tool in the assessment of swallowing.
The effects of bolus volume and viscosity on oropharyngeal swallowing was studied by Ertekin et al., (1997). Here, Submental EMG activity was recorded for dry swallow, 3ml, 10ml, and 20 ml water swallowing in fourteen normal individuals. Cricopharyngeal EMG was recorded for 3 ml and 10 ml of water swallowing in ten normal individuals. Semisolid and liquid swallowing was also compared in eight normal individuals. It was found that the total duration of submental and cricopharyngeal muscle EMG increases significantly with increase in bolus volume. This duration was shorter for semisolid swallowing in comparison to liquid swallowing. Finally it was concluded that the temporal measures of swallowing are altered by the sensory inputs such as bolus consistency and volume.

The influence of different lung volumes on pharyngeal swallow physiology was studied using simultaneous recordings of videofluoroscopy, intramuscular EMG and plethysmography (Gross, Atwood, Grayhack, & Shaiman, 2003). Twenty eight healthy individuals swallowed three standard bolus consistencies at three different lung volumes (total lung capacity, functional residual capacity and residual volume). The results indicated that the duration of pharyngeal swallow produced at the residual volume were significantly longer than at the other two lung volumes. It was also found that there were no significant differences for the bolus transit time across the lung volumes. Hence authors have concluded that the respiratory system might regulate swallowing function and that the positive subglottic air pressure may be an important entity for swallowing integrity.

Normative database for swallowing was reported for children by Vaiman, Segal and Eviator (2004). They performed sEMGs on 100 normal children in the age range of 4-
12 years. They measured the timing and amplitude of muscle activity for the masseter, orbicularis oris, infrahyoid, submental muscles and platisma muscles. Children were asked to perform dry swallow, voluntary single water swallow, voluntary single swallow of excessive amount of water (up to 15ml), and continuous drinking of 50ml of water. The group of 40 adults in the age range of 18-30 years served as control. Normative data for the amplitude and duration of muscle activity during single water swallowing and continuous drinking were established for healthy children. They reported that the duration of muscle activity decreases with age across all the tasks with no statistically significant differences between male and female children. Also, there was no statistically significant difference in amplitude measurements across adults and children. Vaiman, Eviator and Segal (2004) also established normative for sEMG recordings in 420 normal adults with the same procedure. Adults were asked to perform dry swallow, voluntary single water swallow, voluntary single swallows of excessive amount of water (up to 20ml), continuous drinking of 100 ml of water. They observed that submental muscle activity during swallowing decreases with the age. There were no significant differences in other muscle activities across the different age groups. Leow, Huckabee, Sharma and Tooley (2007) reported that taste also can influence the swallowing musculature contraction, especially submental muscle amplitude and duration, which was not controlled in these investigations.

Crary, Carnaby, Mann and Groher (2006) investigated the biomechanical correlates of swallowing using submental EMG and videofluoroscopy in seventeen healthy adults. Hyoid elevation, pharyngeal constriction and the opening of the cricopharyngeal muscle was analyzed in Videofluoroscopy. For each of this event, onset, peak and offset time in submental EMG was identified. Results indicated that the onset of
submental EMG signal preceded all the biomarkers assessed in Videofluoroscopy suggesting that the sEMG signal is a significant indicator for biomechanical events during swallowing.

The influence of aging on oropharyngeal swallowing was studied by Aydogdu, et al., (2007). He had used submental EMG and laryngeal relocation time for the same purpose. For this, 110 individuals in the age range of 17-81 years were asked to perform dry and wet swallowing. Duration of the submental EMG was measured across the age groups. Results indicated that the total duration of submental muscle activity, and laryngeal relocation time were significantly prolonged in the older individuals in comparison to the younger age groups. Triggering of swallow reflex was also found to be delayed in older age groups.

Study by Selcuk, Uysal, Aydogdu, Akyuz and Ertekin (2007) has reported that temperature does influence pharyngeal swallow. For this, Submental EMG and Laryngeal relocation time were recorded for three different temperatures [normal (23–25 °C), cold (8–10 °C), and hot (58–60 °C)]. It was found that the time required for triggering the pharyngeal swallow using cold and hot water was shorter than the water at normal temperature. The duration of the pharyngeal phase of swallowing as assessed through submental EMG was also found to be shorter during cold and hot water than the normal temperature water and it was concluded that the temperature stimulation could be effective in triggering pharyngeal swallow.

Tsukada, Taniguchi, Ootaki, Yamada and Inoue (2009) described the electromyographic activity of genioglossus and suprahypoid muscles during
swallowing in three different head positions. EMG was recorded when the individuals swallowed liquid, syrup and paste bolus in three different head positions. Mean values of peak amplitude, and the duration of the muscle activity were measured across food consistencies and head positions. The results demonstrated that the duration of tongue and suprahyoid muscle activity were increasing with the increasing thickness of food bolus during swallowing. However, amplitude did not show any significant difference across the food consistencies. Also, it was found that the head positions did not alter the EMG muscle activity across the food consistencies.

*Electromyographic studies in patients with dysphagia:* As the incidence of swallowing disorders is more in several neuromuscular disorders (Willig, et al., 1994), EMG is often used in the diagnosis of swallowing disorders. Most of the studies on human swallowing targeted a single muscle or muscle pairs (Ship, Deatsch, & Robertson, 1970; Hrycyshyn & Basmajian, 1972; Perkins, Blanton, & Biggs, 1976; Van Overbeek, et al., 1985; Perlman, et al., 1989; Ertekin, et al., 1997; Ertekin & Aydogdu, 2002; Tachimura, Ojima, Nohara, & Wada, 2005). However, reports from a single muscle or the combination of two muscles do not provide enough information related to the interaction of various components involved in the swallowing process. Therefore, studies targeting a series of muscles during swallowing in normal individuals (Gay, Rendell, & Spiro, 1994; Perlman, Palmer, McCulloch, & Vandaele, 1999; Ertekin & Palmer, 2000) would be useful for comparison in the clinical population.
Most of the EMG data in clinical population has been collected from individuals with neurogenic dysphagia which affects swallowing muscle function and an individual's ability to safely manage the oral feeds.

**Myasthenia Gravis:** Myasthenia gravis is an acquired autoimmune disorder affecting the nerve-muscle junction, causing weakness of the muscles which worsens with activity and improves with rest. These individuals with myasthenia gravis often experience dysphagia (Carpenter, McDonald, & Howards, 1979). Ertekin et al. (1998) compared fifteen individuals with Myasthenia gravis and ten individuals without Myasthenia gravis and the results indicated that all the individuals with Myasthenia gravis had dysphagia, which subsided following anticholinesterase and corticosteroid treatments. Submental EMG duration was significantly longer in individuals with Myasthenia gravis (with and without dysphagia) than in normal individuals. It was also observed that sEMG amplitude was least in Myasthenia gravis individuals with dysphagia. No abnormalities were observed in cricopharyngeus muscle activity of individuals with Myasthenia gravis. Decreased sEMG amplitude in these individuals suggest difficulties with oral transport phase of swallowing. However, further studies are warranted to investigate the effects of medications and behavioral swallowing treatments on swallowing.

**Myositis:** It is an autoimmune disease characterized by swelling of muscles and loss of function. Several studies have reported dysphagia in individuals with a diagnosis of dermatomyositis and polymyositis (Bohan, Peter, Bowman, & Pearson, 1977; Sonies, 1997). Individuals with myositis have been reported to have an elevated upper esophageal sphincter pressure suggesting spasms in the cricopharyngeus muscle
(Williams, Grehan, Hersch, Andre, & Cook, 2003). However, some studies have also documented flaccidity in the cricopharyngeal muscle (Ertekin, Secil, Yuceyar, & aydogdu, 2004). Though the triggering of swallow reflex was within the normal limits, differences in pharyngeal transit time have been observed in these individuals (Ertekin, et al., 2004). Thus, EMG can be useful in monitoring benefits of cricopharyngeal myotomy in these individuals. Hence it can be hypothesized that simultaneous EMG recordings and manometry from the submental field and from the cricopharyngeal segment would be more beneficial in the decision making process. For example, if EMG revealed decreased submental muscle activity, insufficient anterior-superior movement of the hyolaryngeal complex is expected to occur which would result in limited opening of the Upper esophageal sphincter. In this case, it is likely that the patient would be benefited from cricopharyngeal myotomy. However, a patient with decreased submental muscle activity but normal upper esophageal sphincter opening is not a candidate for myotomy.

Motor Neuron Disease: Amyotrophic lateral sclerosis is the motor neuron disease characterized by fasciculations, progressive weakness, muscle atrophy, spasticity, breathing difficulties, hoarseness and dysphagia. Individuals with early Amyotrophic lateral sclerosis present with imprecise articulation, hypernasality and dysphagia. Most of these individuals retain their sensory skills but they may show signs of motor weakness. Dysphagia is characterized by difficulty in managing the oral stage of deglutition with silent aspiration being high after the disease progression. EMG would be the preferred method to determine the muscle weakness in these individuals. Sometimes EMG can also identify the muscular involvement which is not symptomatic (Shipe & Zivkovic, 2004). Ertekin, et al., (2000) studied forty three
individuals with Amyotrophic lateral sclerosis by means of clinical swallowing examination and EMG. Laryngeal elevation was recorded by a piezoelectric sensor and EMG of submental muscles and needle EMG of cricopharyngeal muscle was recorded in individuals with Amyotropic lateral sclerosis. Results indicated that the submental muscle activity of the laryngeal elevators was significantly prolonged, whereas the laryngeal relocation time remained within normal limits. It was also found that the opening of the cricopharyngeal muscle was delayed or the closure occurred prematurely with the poor coordination of submental muscles and cricopharyngeal muscle. These results were attributed to delay in activation of pharyngeal swallow and the hypertonic cricopharyngeal muscle, which is known to occur due to the progressive nature of the disorder.

Post Polio Syndrome: Poliomyelities is a viral disease affecting the nerves, which leads to the paralysis of muscles. Approximately 25% of post poliomyelitis individuals experience the progressive muscle weakness (Driscoll, et al., 1995). Hence, post Poliomyelitis can be regarded as a clinical condition referring to the neuromuscular symptoms occurring at least 15 years after stability in individuals with the previous diagnosis of acute paralytic poliomyelitis. It progresses slowly, and there may be periods as long as 3 years in which the disease does not progress (Dalakas, 1995). The symptoms include weakness and atrophy in the limbs or respiratory muscles, and excessive muscle fatigue. Hence, Electromyography can be a useful diagnostic tool for confirming progressive denervation in individuals with post polio syndrome and also to differentiate it from neuropathology (Sandberg, Hansson, & Stalberg, 1999). Studies have reported fasciculations and fibrillations on conventional EMG, increased jitter and blocking on single fiber electromyography, and smaller
macro-EMG amplitudes in newly weakened post-polio muscles (Robinson, Hillel, & Waugh, 1998). It was also found that Denervation affects both clinically affected and unaffected muscles at a more rapid rate than that of the normal aging process (McComas, Quartly, & Griggs, 1997). Similar findings were obtained in the laryngeal function in patients with post Polio syndrome (Driscoll, 1995). Clinical experience does support the presence of dysphagia as there were evidences of pharyngeal and laryngeal muscle weakness. Intervention studies on post Poliomyelitis patients also reported that they may be able to swallow safely when the Mendelsohn maneuver is employed (Kahrilas, Logemann, Krugler, & Flanagan, 1991).

Muscle Paralysis: Muscle paralysis related to oropharyngeal anatomy causes significant impairments in swallowing, e.g., Lateral medullary syndrome. Lateral medullary syndrome is a disease causing an injury to the lateral part of the medulla, often resulting in dysphagia (Proseigel, Holing, Heintze, Wagner-Sonntag, & Wiseman, 2005). Although the lesion in lateral medullary syndrome is unilateral, its effect on oropharyngeal swallowing is usually bilateral (Aydogdu, et al., 2001). Aydogdu, et al. concluded that the disconnection between the cells within the nucleus ambiguus could be responsible were responsible for dysphagia.

Scleroderma: Scleroderma is a connective tissue disease affecting the skin, muscles and internal organs. Given the link between connective tissue disease and muscles, dysphagia can be expected in these individuals. Fulp and Castell (1990) have reported the association between dysphagia and scleroderma in some individuals. Tibbling, Ask and Pope (1986) studied the individuals with esophageal motor disorders to determine the synchrony of EMG obtained within the esophagus with the
manometric changes from the same esophageal site. Vigorous EMG activity was observed in individuals with scleroderma. The EMG activity in the absence of simultaneous pressure changes indicates that the muscular activity in esophagus is continuous even after the swallow behavior is terminated. Bortolotti (1989) also performed simultaneous esophageal EMG and manometry recordings in two groups of individuals with scleroderma and normal controls. First group consisted of individuals who were newly diagnosed as having dysphagia a normal-sized esophagus whereas the second group consisted of individuals with dilated hypotonic esophagus. Five individuals with normal swallows served as controls. The results revealed that dysphagia in the first group of patients with scleroderma was characterized by incompetent myoelectric hyperactivity with a possible manometric appearance similar to that of diffuse spasm, whereas the second group was characterized by a noticeable decrease in myoelectric activity which corresponded to the typical manometric finding of scleroderma involving the esophagus.

*Myotonic dystrophy:* Myotonic dystrophy is an inherited multi systemic disease characterized by muscle wasting, heart conduction defects, cataracts, endocrinal changes and myotonia. In the view of wasting of swallowing muscles, dysphagia is an expected sequel in these individuals. Ertekin, Yuceyar, Aydogdu, & Karasoy (2001) used electromyography to characterize the oropharyngeal swallowing in individuals with myotonic dystrophy. Eighteen individuals with myotonic dystrophy were recruited and examined by clinical swallow examination and electrophysiological methods such as EMG and 30 healthy volunteers served as normal controls. Needle EMG of the cricopharyngeal muscle and submental muscles were recorded during swallowing. Results indicated that the duration of the
swallowing reflex was significantly prolonged in 70% of individuals with myotonic dystrophy especially in dysphagic patients. Triggering of the pharyngeal swallowing was also prolonged in individuals having both dysphagia and central nervous system involvement. Cricopharyngeal muscle activity during swallowing were also found to be abnormal in 40% of the individuals with myotonic dystrophy. Finally, it was concluded that both myopathic weakness and myotonia in oropharyngeal muscles play an important part in the occurrence of swallowing dysfunction in myotonic dystrophy.

Cervical dystonia: Various studies have suspected dysphagia in cervical dystonias such as spasmodic dysphonia and spasmodic torticollis (Ludlow, Naunton, Sedary, Schulz, & Hillett, 1988; Riski, Horner, & Nashold, 1990; Comella, Tanner, Defoor-Hill, & Smith, 1992; Horner, Riski, Weber, & Nashold, 1993; Holzer & Ludlow, 1996). However, no systematic investigations were performed to assess the swallowing in these individuals.

Ertekin, Aydogdu, Secil, Kiylioglu, Tarlaci and Oezdemirkiran (2002) investigated the oropharyngeal swallowing in craniocervical dystonia. Clinical swallow examination revealed dysphagia in 36% of individuals with craniocervical dystonia. This proportion increased to 72% when assessed through EMG during pharyngeal swallowing. The results indicated that the duration of submental EMG and laryngeal relocation time were prolonged significantly during pharyngeal swallowing with a delay in the triggering of swallow reflex. It was also found that the cricopharyngeal muscle EMG indicated hyperflexia in some patients.
**Salivary gland diseases:** Salivary gland diseases often result in disorders of salivary secretion. It may be an excessive or decreased secretion observed in these individuals. EMG can be used to assess the spontaneous swallowing of saliva secreted by these individuals with salivary gland diseases. This might give information regarding the relationship between swallow rate and salivary flow. Also, factors regulating the rate of spontaneous swallowing in normal individuals and individuals with salivary gland diseases are not completely known. Though it is assumed that rate of salivary flow influences the rate of spontaneous swallowing, the normal database for spontaneous swallow rate is not available in the literature.

Hence, Vaiman, Nahlieli, Seigal and Eviater (2005) used surface electromyography to characterize and monitor spontaneous saliva swallowing rate in individuals with salivary gland diseases. Number of spontaneous saliva swallows were calculated during first two hours of sEMG recordings and compared with the sialometric data from the healthy volunteers. Results revealed one spontaneous saliva swallowing every 2 minutes and 15 secs for normal controls; 1 spontaneous saliva swallowing every 13 minutes for Sjogren syndrome; 1 spontaneous saliva swallowing every 3 minutes and 24 secs for parotid gland surgery; 1 spontaneous saliva swallowing every 5 minutes and 04 secs for submandibular gland surgery. Individuals with Sjogren syndrome and individuals after submandibular surgery had hyposalivation compared to the other groups of individuals. Parotid gland surgery did not significantly affect salivary flow rate. Hence, it can be concluded that Sialometry combined with sEMG monitoring would provide a valuable combination to assess salivary gland disorders.
To conclude, these studies on EMG activity during swallowing revealed a lack of agreement among experts regarding differentiation between the values that represent normal and abnormal function. Thus, establishing a normative database for deglutition using surface EMG for adults is essential. Although western norms are available in adults (Vaiman, et al., 2004) and children (Vaiman, et al., 2004), it is important to establish normative suitable for Indian population.

Nasal air flow monitoring: Respiration and swallowing are the physiologic events exhibiting a finely tuned coordination in the survival of human beings. It is well recognized that breathing and swallowing do not occur simultaneously and that these two functions are mutually exclusive. However, recent studies have discarded these observations and reported that these two functions complement each other. Clinical and experimental evidence also supports the existence of structural and functional interdependence between respiration and swallowing. Moreover evidence from swallowing rehabilitation suggest that alterations in breathing mechanism while swallowing modifies the abnormal swallowing physiology e.g., Supraglottic swallow (Martin, Logemann, Shaker, & Dodds, 1994). Further, modifications in the bolus consistency and volume do influence the swallowing behavior as evidenced during videofluoroscopy or endoscopy (Kahrilas, Dodds, Dent, Logemann, & Shaker, 1988; Jacob, Kahrilas, Logemann, Shah, & Ha, 1989; Cook, et al., 1989; Dodds, Stewart, & Logemann, 1990; Robbins, Hamilton, Lof, & Kempster, 1992; Kendall, McKenzie, Leonard, Goncalves, & Walker, 2000). But the impact of these swallowing maneuvers on the central pattern generators of breathing and swallowing coordination is not well understood.
The interrelationships between the respiratory and swallowing processes are clearly demonstrated through their shared anatomic structures and muscles. Respiration shares many muscles that are active even during swallowing (Atkinson, Kramer, Wyman, & Ingelfinger, 1957; Shedd, Scatliff, & Kirchner, 1960; Kawasaki, Ogura, & Takenouchi, 1964; Takenouchi, Koyama, Kawasaki, & Ogura, 1968; Suzuki & Kirchner, 1969; Shipp, Deatsch, & Robertson, 1970; Suzuki, Kirchner, & Murakami, 1970; Sauerland & Mitchell, 1970; Murakami & Kirchner, 1972; Lowe & Sessle, 1973; Fukuda, Sasaki, & Kirchner, 1973; Fink & Demarest, 1978; Ekberg & Sigurjonsson, 1982; Sasaki & Buckwalter, 1984; Kennedy & Kent, 1985; Berne & Levy, 1988; van Lunteren & Dick, 1992; Logemann, et al., 1992; Adachi, Lowe, Tsuchiya, Ryan, & Fleetham, 1993; Fregosi & Fuller, 1997; Zemlin, 1997; Fuller, Mateika, & Fregosi, 1998; West, 2000; Numasawa, Shiba, Nakazawa, & Umezaki, 2004). These findings suggest that breathing and swallowing are the two physiological entities complementing each other, thus ensuring proper gas exchange taking place during breathing and preventing aspiration during swallowing (Martin, et al., 1994; Martin-Harris, Brodsky, Price, Michel, & Walters, 2003).

With the technological advancements, breathing and swallowing can be recorded simultaneously. Hence, the respiratory swallowing coordination is defined as an occurrence of swallowing apnea in one of the following stages of respiratory phase i.e., during inspiration, during expiration, at the transition between inspiration and expiration or between expiration and inspiration (Bamford et al. 1992). Literature on these aspects points to the fact that swallowing always interrupts the exhalation phase of respiration in infants and adults (Wilson, et al., 1981; Weber, Woolridge, & Baum, 1986; Martin, et al., 1994). These experiments have used different instruments to
measure the respiratory swallow phase relationship. Some studies have used nasal cannula to study this relationship and few others have used stethograph, respiratory plethysmography and hot wire respiratory flow meter to study this relation.

Following are the studies which have investigated the respiratory swallow coordination in infants and children.

<table>
<thead>
<tr>
<th>Investigators</th>
<th>Participants</th>
<th>Instrument</th>
<th>Bolus consistency and volume</th>
<th>Respiratory swallow phase relation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wilson, at al., (1981)</td>
<td>Nine infants</td>
<td>Pharyngeal manometry, submental EMG, nasal cannula</td>
<td>Spontaneous swallows</td>
<td>Swallows interrupted all the phases of respiratory cycle during sleep</td>
</tr>
<tr>
<td>Paydarfar, et al., (1995)</td>
<td>Infants</td>
<td>Submental EMG, Pharyngeal manometry, Videofluoroscopy</td>
<td>Bolus swallows, Spontaneous swallows, visually cued swallows of previously placed bolus</td>
<td>Few spontaneous swallows were initiated near the expiratory-inspiratory transition whereas most occurred from late inspiration to mid-expiration.</td>
</tr>
</tbody>
</table>

Table 1: Respiratory swallow phase relationships in infants and children
Following studies have used hot wire respiratory flow meter, stethograph and respiratory plethysmography to investigate the respiratory swallow phase relationship in adults and geriatrics.

<table>
<thead>
<tr>
<th>Investigators</th>
<th>Participants</th>
<th>Instrument</th>
<th>Bolus consistency and volume</th>
<th>Respiratory swallow phase relation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Nishino, Yonezawa &amp; Honda (1985)</td>
<td>Normal adults in the age range of 25-35 years</td>
<td>Hotwire respiratory flow meter</td>
<td>Water and saliva swallow</td>
<td>82% exhalation before the swallow for saliva, 84% exhalation before the swallow for water.</td>
</tr>
<tr>
<td>Shaker et al., (1992)</td>
<td>Young adults in the age range of 18-34 years &amp; elderly individuals in the age range of 63-83 years</td>
<td>Stethograph</td>
<td>Dry swallow at rest; dry swallow with tachypnea; 5ml water at rest; 5ml water during tachypnea</td>
<td>Exhalation before the swallow in young adults; inhalation before the swallow in elderly.</td>
</tr>
<tr>
<td>Smith, Wolcove. Colacone, &amp; Kreisman (1989)</td>
<td>Normal men in the age range of 22-45 years</td>
<td>Respiratory plethysmography</td>
<td>2 glasses of water in 1-2 min; 2 doughnuts in 5-10 min.</td>
<td>Exhalation is the most predominant pattern interrupts the swallow followed by 16% of inhalation exhalation pattern and 0.7% of inhalation-inhalation pattern ;</td>
</tr>
<tr>
<td>Martin, et al., (1994)</td>
<td>Normal adults in the age range of 17-30 years</td>
<td>Respiratory plethysmography</td>
<td>100 ml water</td>
<td>46.1% exhalation-exhalation pattern; 38.5% exhalation-inhalation; 15.4% inhalation-exhalation.</td>
</tr>
<tr>
<td>McFarland &amp; Lund (1995)</td>
<td>Normal adults in the age range of 19-25 years</td>
<td>Respiratory plethysmography</td>
<td>Carrot; 5, 10, 20 ml of water; 5 ml of thin, thick, syrup, semisolid kool-aid; 1 bite of cookie</td>
<td>77% exhalation-exhalation regardless of consistency.</td>
</tr>
<tr>
<td>Preiksaitis &amp; Mills (1996)</td>
<td>Normal adults in the age range of 18-25 years</td>
<td>Respiratory plethysmography</td>
<td>200 ml water</td>
<td>Exhalation before the swallow is the preferred pattern.</td>
</tr>
</tbody>
</table>

Table 2: Respiratory swallow phase relationships in adults and geriatric individuals using traditional instruments
Following are the studies which have utilized nasal cannula to investigate the respiratory swallow relationship.

<table>
<thead>
<tr>
<th>Investigators</th>
<th>Participants</th>
<th>Instrument</th>
<th>Bolus consistency and volume</th>
<th>Respiratory swallow phase relation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Selly, Flack, Ellis, &amp; Brooks (1989)</td>
<td>Elderly individuals in the age range of 60-90 years</td>
<td>Nasal cannula</td>
<td>5ml of fruit juice</td>
<td>95% exhalation after the swallow; 5% inhalation after the swallow;</td>
</tr>
<tr>
<td>Preiksaitis, et al., (1992)</td>
<td>Normal adults in the age range of 20 – 48 years</td>
<td>Nasal cannula</td>
<td>Dry swallow, 5 ml, 10 ml, 15 ml, 20 ml of water</td>
<td>Exhalation is the predominant pattern interrupts the swallow</td>
</tr>
<tr>
<td>Klahn &amp; Perlman (1999)</td>
<td>Normal adults in the age range of 18-25 years</td>
<td>Nasal cannula</td>
<td>Water and apple sauce</td>
<td>100% exhalation before the swallow for water and apple sauce</td>
</tr>
<tr>
<td>Hadjikoutis, Pickersgill, Dawson, &amp; Wiles, (2000)</td>
<td>21-73 year old normal individuals</td>
<td>Intra nasal pressure instrument</td>
<td>Tepid water of 5ml, 10ml and 20 ml</td>
<td>91% exhalation after the swallow; 9% inhalation after the swallow</td>
</tr>
<tr>
<td>Perlman, Etterna, &amp; Barkmeier, (2000)</td>
<td>20-29 year old normal adults</td>
<td>Nasal cannula</td>
<td>5 ml and 10 ml of Liquid barium and 5ml of barium paste</td>
<td>79% exhalation before the swallow; 96% exhalation after the swallow</td>
</tr>
<tr>
<td>Hiss, et al., (2001)</td>
<td>Normal adults in three age groups 20-39 years; 40-59 years; 60-83 years) participated in the study</td>
<td>Nasal cannula</td>
<td>10ml, 15ml, 20ml, and 25 ml of liquid</td>
<td>62% exhalation-exhalation; 75% exhalation before swallow; 86% exhalation after swallow; No difference between age groups</td>
</tr>
<tr>
<td>Hirst, Ford, Gibson, &amp; Wilson (2002)</td>
<td>Eldery individuals in the age range of 62-84 years</td>
<td>Nasal thermister</td>
<td>5 ml and 20 ml of water; cup and straw drinking of</td>
<td>91% exhalation after the swallow; 9% inhalation after</td>
</tr>
</tbody>
</table>
Leslie, Drinnan, Ford, & Wilson, (2002)  
20-78 years old normal individuals  
Nasal cannula  
5ml of water and yogurts  
98% exhalation after the swallow for water; 80% exhalation after the swallow for yogurt.

21-40 year old adults  
Nasal cannula  
5ml of liquid barium  
79%-82% exhalation-exhalation pattern; 18-21% inhalation-exhalation

Martin-Harris, Brodsky, Michel, Ford, Walters, Heffner (2005)  
21-97 year old individuals  
Nasal cannula  
5ml of liquid barium  
Predominant pattern was exhalation braketting the swallow in both the trials

<table>
<thead>
<tr>
<th>Study</th>
<th>Age Range</th>
<th>Method</th>
<th>Stimulus</th>
<th>Exhalation Pattern</th>
</tr>
</thead>
<tbody>
<tr>
<td>Leslie, Drinnan, Ford, &amp; Wilson, (2002)</td>
<td>20-78 years old normal individuals</td>
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<tr>
<td>Martin-Harris, Brodsky, Michel, Ford, Walters, Heffner (2005)</td>
<td>21-97 year old individuals</td>
<td>Nasal cannula</td>
<td>5ml of liquid barium</td>
<td>Predominant pattern was exhalation braketting the swallow in both the trials</td>
</tr>
</tbody>
</table>

**Table 3: Respiratory swallow phase relationships in adults and geriatric individuals using nasal cannula**

From the above studies, is clear that swallowing always interrupts the breathing among humans, which also includes premature infants. Moreover, exhalation braketting the swallow is the predominant pattern which has been observed in adults.

*Swallow apnea duration in infants and children:* The oro-pharynx and larynx is a common forum for both breathing and swallowing. Hence, breathing and swallowing cannot be performed at the same time. The breathing is arrested in infants
for a very short duration during swallowing (Hanlon, et al., 1997). However, this swallow related apnea (cessation of respiratory airflow) is different from the nondeglutitive apneic pauses in the healthy term infants. This apneic pauses in healthy infants could be as short as 2 secs (Hoppenbrouwers, Hodgman, Arakawa, Harper, & Sterman, 1980) or as long as 15 secs (Hoppenbrouwers, et al., 1977). But swallowing apnea is much shorter in duration i.e., 0.672 secs for nutritive swallows (Hanlon, et al., 1997) and 1.03 secs for non-nutritive swallows (Wilson, et al., 1981). Little information exists in the literature on swallow apnea duration in the normally developing infants beyond 1 week of age (Hanlon, et al., 1997). Much of the previous data were gathered from human preterm infants (Koenig, Davies, & Tach, 1990) and other pediatric clinical populations (Wilson, et al., 1981). Normative data beyond this age range is important for the identification of aspiration in children/infants with dysphagia. Hence this particular component is very essential in the successful integration of breathing and swallowing (Pinnington, Smith, Ellis, & Morton, 2000).

Spontaneous swallows were recorded in nine preterm infants. It was recorded when they were asleep and awake (Wilson, et al., 1981) using pharyngeal manometry, submental electromyogram, and nasal airflow monitoring. Two hundred and seventeen swallows were elicited during spontaneous breathing. These swallows interrupted either inspiratory or expiratory airflow approximately for 1 sec of duration. This airway closure duration was independent of respiratory rhythm.

Koenig et al. (1990) studied the coordination of suck, swallow, and breath in healthy infants (8 full-term and 5 preterm). Respiratory movements and the airflow were recorded. It was found that sucking did not interrupt breathing and did not cause the
minute ventilation to drop during non nutritive sucking. It was also seen that minute ventilation during bottle feeding was inversely proportional to the frequency of swallowing i.e., ventilation decreased as the swallowing frequency increased. Swallowing was associated with a period of airway closure called as apnea which lasts for 530 +/- 9.8 ms. Occasional instances of prolonged airway closure were observed in all the infants during feeding. These findings indicated that the decreased ventilation during bottle feedings could be due to the fact that airway closure associated with swallowing inhibits the respiration.

Suck swallow breath sequence was also investigated by Lau et al. (2003) who examined the relationship between suck and swallow, and also between swallow and breathe. Twelve healthy preterm (<30 wk of gestation) and 8 full-term infants were recruited for this purpose. Sucking, swallowing, and respiration were recorded simultaneously in preterm and term infants. Rate of milk transfer (ml/min) was used as an index of feeding performance. Sucking and swallowing frequencies (per minute), average bolus size (ml), and suction amplitude (mmHg) were measured. Results indicated that the rate of milk transfer in the preterm infants increased over a period of time and this rate was found to be correlated with average bolus size and swallowing frequency. However, average bolus size did not correlate with swallowing frequency. Bolus size did correlate with suction amplitude, and the swallowing frequency correlated with sucking frequency. Preterm infants swallowed during all the phases of respiration than that of full-term infants. Hence, authors have concluded that sucking and swallowing frequency, bolus size, and suction amplitude increases as feeding performance improves. Hence it can be assumed that feeding difficulties in
preterm infants could be attributed to the inappropriate respiratory swallow coordination than the suck and swallow coordination.

In a similar line, Kelly, Huckabee, Jones and Frampton (2008) measured the swallow apnea duration during wakefulness, sleep, and feeding. For this, 10 healthy term infants within one year of age were recruited and swallow apnea duration was measured 10 times. 19,402 swallows were analyzed. Results revealed that swallowing apnea duration was significantly shorter during feeding than the swallowing apnea duration of non-nutritive swallowing (during wakefulness and sleep). However, this swallowing apnea duration did not change significantly within the first year of life across the three conditions. The absence of an age effect suggests that brainstem is still regulating the swallowing apnea duration and hence there is no significant age effect.

These findings in infants and children were difficult to generalise as age ranges vary considerably in these studies.

Swallow apnea duration in adults and geriatrics: Plenty of attempts have been made in the past decades to investigate the respiratory swallowing coordination in the adults and geriatric population. One such study was by Nishino et al. (1985) who investigated the effects of spontaneous and water swallows on the respiratory pattern in eight normal adults. The presence of swallows was identified by submental EMG and visual observation of laryngeal elevation. It was found that the mean swallow apnea duration for the saliva swallow was 1.13 secs in comparison to the apnea duration of 1.06 secs for water swallow. This difference was also statistically
significant. Authors finally concluded that the changes in respiratory pattern during swallowing might depend on some mechanism that regulates the coordination of respiration and swallowing.

Selly et al. (1989) have investigated the respiratory swallow coordination in thirty three individuals using 5ml of fruit juice. All the individuals exhibited a well defined respiratory pattern, and the mean apnea duration was found to be 1 sec irrespective of the respiratory phase in which the apnea had occurred. Results also showed an effect of aging on the normal breathing and swallowing coordination with a greater occurrence of inspiration surrounding swallowing. Though the older individuals exhibited greater apnea duration, they did not aspirate during the swallowing attempts. However, associated comorbid conditions such as stroke, head and neck cancer etc may involve the risk of aspiration in these individuals.

Preiksaitis et al. (1992) also investigated the respiratory swallow coordination using nasal cannula for capturing the airflow. They also investigated the effect of changes in the volume of the bolus (0-20 ml) on the swallow apnea duration in 12 normal individuals. Spontaneous swallowing was presented with an apneic duration of 1.90 +/- 0.26secs. Results also indicated that apnea duration increases with increase in bolus volume. This suggests that the respiratory swallow coordination is modulated by the volume of the bolus swallowed. However, in some individuals, apnea duration decreases with increase in bolus volume. Hence it can be stated that two different patterns of responses exists with changes in bolus volume.
The influence of aging and respiratory rate on the swallowing apnea duration was investigated by Shaker et al. (1992). They had recruited young and elderly individuals for the purpose. Dry swallow and 5ml water swallow was performed with and without tachypnea. The results revealed that apnea duration decreases with increase in respiratory rate. However, apnea duration increases with increase in age. It was concluded that aging and respiratory rate does influence respiratory swallow coordination and these two factors correspond to the variability seen in apnea duration. McFarland, Lund and Gagner (1994) reported that the respiratory swallow coordination can also be influenced by the changes in the whole body posture of the individual i.e., swallowing occurred on the early part of the respiration when the individuals attempted to swallow with the hands and knees planted on the ground, and the swallow occurred later in the expiratory cycle in the standing position.

Swallow apnea duration was also studied during 100 ml cup drinking. Martin et al. (1994) examined the young adults in the age range of 17-30 years using respiratory inductive plethysmography. During 100 ml cup drinking, mean apnea duration was found to be 7.71 secs. As the volume of the bolus increases, apnea duration increases. This could be due to the increased demand on the laryngeal mechanism to protect the airway and hence increased duration. Paydarfar et al. (1995) studied the relationships between respiratory timing and swallowing in thirty healthy adults. Swallowing was assessed through submental EMG, pharyngeal manometry and videofluoroscopy. Respiration was recorded by the measurement of nasal airflow through nasal cannula. Bolus swallows, spontaneous saliva swallows, and swallows of bolus previously placed in the mouth were investigated in this study. The results revealed that the swallow apnea duration for saliva swallows were shorter than that for 5 ml bolus
swallows. Swallow apnea duration was unaffected by the respiratory phase of swallow initiation.

Preiksaitis and Mills (1996) measured breathing and swallowing by plethysmography, submental EMG, and a throat microphone in 10 normal adults during drinking and eating tasks. The tasks included were single boluses of varying consistency and volume (5-20 ml), a 200-ml drink with and without the straw, and a sandwich meal. Results revealed that swallowing was associated with a brief period of apnea which lasted around 1 sec. Expiration bracketing the swallow was a predominant pattern in all the tasks. Inspiration bracketing the swallow was observed in less than 5% of single bolus swallows. However, this pattern increased significantly with a 200-ml cup/straw drinking and during a sandwich meal. Hence, it was concluded that the respiratory swallow coordination observed with a single bolus swallow may not be the same during regular eating and drinking behavior.

Normative data on the temporal relationship between respiration and swallowing was obtained in 12 young adults using Respirodeglutometer (Klahn & Perlman, 1999). The temporal relationship considered were swallow apnea, direction of airflow before and after the swallow apnea. Swallows were performed three times using water and apple sauce which yielded a total of 72 swallows. The onset of submental surface EMG and the laryngeal movement were found to differ between males and females i.e., males initiated submental muscle contraction before females and laryngeal elevation after the females. Duration of swallow apnea was 0.75 +/- 0.14 secs for all the swallows. Expiration occurred 93% of the time before the apnea and 100 % of the time after the apnea.
The effect of age, gender, bolus volume and the trials on the respiratory swallow coordination was studied by Hiss, et al. (2001) in normal adults. Sixty adults in the age range of 20–39, 40–59, and 60–83 years participated in the study. Each group consisted of ten males and ten females. Swallowing apnea duration was measured through nasal airflow during saliva swallows and 10, 15, 20, 25ml bolus volumes across three trials. Results indicated the consistency of swallowing apnea duration across the trials. Significant main effects was observed for the age, gender, and bolus volume i.e., elderly individuals were found to be having a longer swallowing apnea duration than the young and middle-aged adults; women had longer swallowing apnea duration than men; and swallowing apnea duration increased with the increase in bolus volume. There was a significant interaction of age and gender for the saliva swallows, i.e., males demonstrated decreased swallowing apnea duration with increase in age whereas the females showed an increase in swallowing apnea duration with increasing age. Exhalation braketting the swallow was a predominant pattern in all the participants. However, age, gender, and the bolus volume could not predict the pattern of exhale–swallow–exhale relationship.

In line with this, Hirst, et al. (2002) measured the respiratory swallow coordination in 29 elderly individuals during rest, single water swallows, and continuous drinking. The results indicated that respiratory rate increases after 5ml swallows with the decrease in the duration of respiratory cycle from a mean of 3.8 secs at rest to 3.5 secs after swallowing. However, the respiratory patterns were regular. Swallow apnea showed a trend indicating that as the volume of the bolus increases from 5ml to 20 ml, apnea duration increases from 1.06 to 1.24 secs. Results of oxygen saturation levels
also showed a median fall of 2% during swallowing. This kind of swallow induced respiratory changes in the elderly population forms the basis for future investigation in the elderly individuals with dysphagia. Hiss, Straus, Treole, Stuart and Boutilier (2004) also studied the swallowing apnea duration with respect to age, gender, bolus volume and consistency. Forty adults in the age range of 20-30 years and 63-79 years were recruited and the swallowing apnea duration was measured during 5ml and 20ml of water and apple juice across 3 trials. The effects of age, gender, bolus volume, and consistency on the onset of swallow apnea was determined. Results indicated that elderly adults exhibited swallowing apnea onset earlier than the young adults, and 20 ml bolus elicited an apnea onset earlier than the 5ml bolus irrespective of the age groups. Young men demonstrated swallowing apnea onset significantly later than the older men for bolus with larger volume. However, this difference was not observed for bolus with smaller volume and also across the young and older women. A significant main effect of bolus consistency was also observed indicating that the onset of swallowing apnea appeared later with the increase in bolus viscosity.

Few investigators were interested in studying the respiratory swallowing coordination during sleep and wakeful state of individuals. Kelly, Huckabee and Cooke (2006) used submental surface electromyographic activity and nasal airflow in 16 young and elderly individuals to study the same. Swallowing interrupted the expiration more frequently during wakefulness than during sleep. The interaction of age and gender was significant only for males with respect to the frequency of occurrence of midexpiratory swallows. The duration of swallow apnea was significantly shorter for midexpiratory swallows than for any other respiratory phase category. However, this pattern was not influenced by age and gender. Reduced variability in respiratory
swallow coordination was observed during wakefulness than during sleep suggesting that cortex plays a significant role in coordinating the respiratory swallow behaviors.

The control of airflow and the diaphragmatic activity was studied during swallowing and swallowing apnea (Hardemark Cedborg, et al., 2009). An airflow discriminator was used for capturing the nasal airflow in conjunction with the EMG of diaphragm and abdomen, spirometry and pharyngeal and oesophageal manometry. Respiratory swallow co-ordination was examined in six healthy individuals at rest, during hypercapnia and at breathing rate of 30 breaths per minute. The passive expiration of the diaphragm was interrupted by active breath holding which might have preserved the respiratory volume for expiration after swallowing. Abdominal EMG was found to be increased before and after the swallowing expiration. This was more during hypercapnea than normocapnia which is believed to assist in the expiratory airflow. In these individuals, swallowing was always preceded by expiration. 93% and 85% of swallows were also followed by expiration in normocapnea and hypercapnia respectively indicating that swallowing during the expiratory phase of breathing may be the predominant pattern. This co-ordinated pattern of breathing and swallowing possibly reduces the risk for aspiration.

From these studies, it is clear that swallow apnea occurs during the expiratory phase of respiration and the duration of which varies across the age, gender, bolus consistency and volume. Also it is to be noted that these studies have taken a smaller sample size with wide range of food consistencies and volume. Hence, the findings are difficult to be generalized.
Respiratory swallow coordination in individuals with dysphagia: There is research focus on the respiratory swallow coordination in individuals with dysphagia. Shaker, et al., (1992) studied the effects of aging, tachypnea, position and chronic obstructive pulmonary disease on the respiratory swallow coordination using respirography and submental surface EMG. Results indicated that there was a coupling of swallowing with the expiratory phase of respiration in the healthy young adults during rest. This pattern increased in relation to other phases of respiration during thin liquid swallows and tachypnea. The respiratory swallow coordination was found to be different in the elderly individuals with the occurrence of other respiratory patterns during the swallowing. Even the individuals with chronic obstructive pulmonary disease were presented with abnormal patterns compared to the respiration at rest. It was also found that position did not influence the coordination of respiration and swallowing. Hence, it was concluded that age and chronic obstructive pulmonary disease can alter the respiratory swallow coordination significantly.

Butler, Stuart, Pressman, Posage and Roche (2007) investigated the swallowing apnea duration and respiratory swallow phase relationship in individuals with cerebrovascular accident. Simultaneous videofluoroscopic and respiratory measures were recorded across 5ml, 10ml, 15ml, and 20ml thin and thick liquid bolus trials. These data were also compared with previously acquired data on healthy elderly individuals. Results indicated that the respiratory phase relationships differed among individuals with dysphagia and Cerebrovascular accident and healthy elderly individuals. Swallowing apnea duration was found to be significantly longer in those individuals who aspirated in comparison to those who did not aspirate for any bolus viscosities and volumes. In addition, swallowing apnea duration of those individuals
who aspirated was two times longer than that of the healthy elderly individuals for all conditions. It was also found that inhalation braketting the swallows was observed more in individuals with aspiration i.e., the inhale-swallow-inhale pattern increases significantly with the increase in the severity of dysphagia. Hence it was concluded that the individuals with aspiration secondary to cerebrovascular accident can present with abnormal respiratory swallow coordination.

Gross, Atwood, Ross, Olszewski and Eichhorn (2009) examined the coordination of breathing and swallowing among 25 individuals with and without chronic obstructive pulmonary disease. Respiratory inductance plethysmography and nasal thermistry was used simultaneously to detect the nasal flow during respiration. Submental surface EMG was used to indicate the presence of swallow within the respiratory cycle. The individuals were asked to swallow solids and semi-solids in a random fashion. Results of logistic regression indicated that individuals with chronic obstructive pulmonary disease swallowed solids during inhalation than the normal controls and had a higher occurrence of inhalation after the swallowing of semi solid bolus. Significant differences in swallow apnea durations were also found indicating that individuals with chronic obstructive pulmonary disease had a longer apnea duration than the normal controls. This altered respiratory swallowing coordination might place the individuals at risk for aspiration with advanced chronic obstructive pulmonary disease.

With these studies in individuals with and without dysphagia, it is clear that swallow apnea occurs in the expiratory phase of respiration, and the temporal measures of respiratory swallow coordination such as swallow apnea duration are variabe in the
normal individuals. However, studies in individuals with dysphagia revealed that swallow apnea duration appears to be a major variable relating to aspiration. Hence, measuring these physiological variables are critical in the assessment of swallowing.

**Cervical Auscultation:** It is a technique wherein the clinician listens to the sounds of swallowing using a stethoscope or any other microphone placed on the external surface of the neck (Bosma, 1976). Usually, stethoscope microphone is placed on the lateral aspects of the thyroid cartilage in front of the sternocleidomastoid muscle and the large vessels. This technique is based on the assumption that the normal biological sounds are different from the abnormal biological sounds. Also, it is a simple, easy to handle non invasive procedure, and can be easily used for the clinical evaluation of swallowing.

Stott (1953) and Russell (1956) described the utility of cervical auscultation in the evaluation of pharyngeal swallow in individuals with bulbar poliomyelitis. Subsequently, pharyngeal auscultation using a stethoscope has gained popularity in the evaluation of individuals with pharyngeal wall paresis/paralysis across all the ages (Bosma, 1976). Cervical sounds have been tape recorded and analyzed by sonography in the studies of infant cry analysis (Truby & Lind 1965; Truby & Lind, 1966a; Bosma, Truby & Lind, 1966) and also in the cry of infants with cleft lip and palate (Truby & Lind, 1966b). Microphone recordings of infant swallow sounds have been described by Soentgen, Pierce and Brenman (1969). The taped sounds of normal adult pharyngeal swallow have been described by Mackowiak, Brenman and Friedman (1967) and Logan, et al. (1967).
Studies have also used more advanced technologies to capture the swallow sounds using digital signal processing techniques. They have developed devices such as microphones and accelerometers to capture the swallowing sounds accurately (Mackowiak, et al., 1967; Logan, et al., 1967; Hamlet, et al., 1990; Takahashi, Groher & Michi, 1994). This digital analysis technique provides a better understanding and interpretation of the acoustic swallowing signals, leading to more accurate assessment. They have further confirmed that the swallow sounds analyzed using digital signal analysis can distinguish between individuals with and without dysphagia (Mackowiak, et al., 1967; Bosma, 1976). Zenner, et al. (1995) incorporated cervical auscultation with stethoscope for the clinical examination of dysphagia and supported the fact that cervical auscultation is a highly sensitive and reliable method for dysphagia identification.

Stroud, Lawrie and Wiles (2002) reported the inter and intrarater reliability of five speech and language pathologists in the detection of aspiration in sixteen swallow sounds. The swallow sounds were recorded concurrently with videofluoroscopy. The results revealed fair agreement between the judgments made by speech language pathologists. Although the results suggest that raters have a tendency to accurately identify aspiration, there seems to be a bias/overestimation in the detection of aspiration. Leslie, Drinnan, Finn, Ford and Wilson (2004) reported poor agreement between judgments. The sensitivity and specificity were found to be 62% and 66% respectively. However, sensitivity and specificity values improved to 80% and 90% respectively when group consensus was considered. The authors concluded that the overall accuracy of this technique in predicting abnormality in swallowing can be improved by improving the ratings given by the judges. Huckabee, Coombes and
Robb (2005) investigated the reproducibility of the acoustic swallowing sounds in normal adults and confirmed that acoustic signal is reproducible and suggested to use analysis of acoustic swallowing sound in the clinical assessment of dysphagia. Borr, Hielscher-Fastabend and Luking (2007) also concluded that the cervical auscultation contains audible cues which serve as a tool in the early detection of individuals at risk for aspiration.

**Physiology of swallow sounds:** The acoustic signal generated by the swallowing sound consists of two distinct temporal components, sounding like that of a double click pattern (Lear, et al., 1965; Logan, et al., 1967; Mackowiak, et al., 1967). Physiologically, the acoustic signal captured during swallowing reflects the action of pharyngeal walls. Lear et al. (1965) suggested that the parting of the mucus membrane adjacent the pharyngeal wall contributes to the generation of swallow sound i.e., when the bolus flows through the regions of pharynx, the mucus membranes separate resulting in the generation of swallow sounds. Hamlet et al (1990) correlated the generation of swallowing sound with the simultaneously recorded videofluoroscopy. The findings revealed that the signal corresponded to flow of the bolus through the lower pharynx into the oesophagus. It was also observed that the structural movement related with the deflection of the epiglottis or hyolaryngeal movement corresponded to swallowing signal. Cichero and Murdoch (1998) reported that the vocal tract configuration changes rapidly during the act of swallowing. These changes correspond to the generation of swallowing sounds.

**Cervical auscultation in infants and children:** Very few studies have attempted to characterize the acoustic properties of swallow sounds in infants and
children. Vice, Heinz, Giuriati, Hood and Bosma (1990) were the first one to place the microphone on the neck of six infants to capture the swallow sounds (within the first two postnatal days) during suckle feeding. These recorded sounds were fed into the tape-recorder and analyzed using digital signal processing techniques. Results indicated that the discrete sounds were present and it preceded and followed the bolus transit sound. These sounds were consistent during rhythmic and non-rhythmic suckle feeding. During the rhythmic suckle feeding, the discrete sounds were approximating the swallow breath sounds. The initial discrete sounds were continuous with the inspiration followed by final discrete sounds preceding the expiration. Initial and final discrete sounds were brief and they did not mimic each other. Though both the sounds were repeatable, initial discrete sounds were highly reproducible than the final discrete sounds. The discrete sounds were having duration of 10-30 msec with a single monophasic or biphasic deflection.

Pharyngeal swallows during infant suckle feeding were reported by Vice, Bamford, Heinz and Bosma (1995). They reported that pharyngeal swallows in suckle feeding were characterized by a sequence of sounds which were either audible by stethoscope or by an accelerometer/microphone placed over the larynx. This sound sequence includes initial and final discrete sounds, and it precedes and succeeds the pharyngeal swallows in rhythmic feeding of neonates. Results of Digital signal analysis revealed similarities in morphology between the discrete sounds preceding and succeeding swallows. Morphology of succeeding swallows were highly variable in temporal relation to swallows, and amplitude which were attributed to the variations in the pattern of inter swallow respiration i.e., apnea. Authors finally suggested that the cervical auscultation can be used in the clinical observation of infants during feeding.
Digital cervical auscultation was performed in normal children to characterize the swallow sounds in children in the age range of 3-11 years (Almeida, Ferlin, Parente & Goldani, 2008). It was performed on 118 children by means of a piezoelectric microphone secured to the lateral borders of external neck. Children were asked to swallow 5 ml of liquid and yogurt. The components of analysis included were initial discrete signal, swallowing sound, final discrete signal, and expiratory return. The results indicated a swallowing sequence pattern (an initial discrete signal, main swallowing signal, final discrete signal, and expiratory return) in 60% of the children. There was no significant difference in swallowing sound duration between the genders for both the food consistencies. There was also no correlation found between age and duration of the swallowing sound across the food consistencies.

Cervical auscultation in adults and geriatrics: Cervical auscultation in adults has received considerable attention since 1960s. These studies have analyzed the morphology of the swallow sounds and differentiated it from the morphology of coughing, vocalization, normal and forced breathing. Lear, et al., (1965) was the first one to examine the dry swallows in young adults and reported a double peak pattern in the swallowing sound. Logan, et al., (1967) later examined the wet swallows in 16 individuals without dysphagia and contrasted with the spectrographic patterns during volitional coughing, vocalization, forced and normal respiration. Their study revealed that swallowing sounds have a distinct and identifiable spectrographic pattern in comparison to volitional coughing, vocalization and respiration. They also reported that a spectral frequency range of swallow sounds lie in the frequency range of 0-8000 Hz with a swallowing duration ranging from 250-900 msec. Hamlet et al. (1990) reported that double peak pattern is the frequently observed pattern during the liquid
barium swallows in individuals without dysphagia. Takahashi et al. (1994) also supported the viewpoint that two distinct spectral peaks were observed during the wet swallows in adults without dysphagia. These studies point to the fact that swallow sounds have distinct morphology (double peak) in comparison to the spectrographic pattern during coughing, vocalization and breathing.

Research has also focused on the spectral and the temporal properties of the swallow sounds using various instruments. Lear, et al. (1965) was the first one to report the spectral and the temporal measures of swallow sounds. In this study, the spectral peak and the swallowing sound duration were found to be 4600Hz and 500msec respectively. Two distinct spectral peaks at 556 Hz and 1384 Hz were reported by Hamlet, et al. (1990) during swallowing. Takahashi et al. (1994) investigated the wet swallows in adults without dysphagia in the age range of 22-41 years. Two distinct spectral peaks were observed at approximately 450Hz and 620 Hz, respectively. The duration of swallows was consistent across the trials, with the mean duration of 529msec.

Frequency, intensity, and duration characteristics of swallowing sounds were examined by Mackowiak and coauthors, (1967) using oscilloscope and sound spectrograph. In this study, the individuals were asked to perform dry swallows and swallow involving water. Three bursts of swallowing sounds could be identified. Oscillographic analyses revealed a 50 msec duration of swallowing signal, followed by a 100-150-msec quiet interval. The second burst had an average duration of 150-200 msecs but similar in amplitude compared to that of first burst. The third burst was seen with a smaller amplitude and shorter duration following a 300-400 msec period.
This third burst was not consistently obtained across the individuals. The results of dry and thin liquid swallows revealed that the dry swallows were longer in duration with lesser intensity than wet swallows. Wet swallows had a frequency range of 400-600 Hz than 1000Hz frequency of dry swallows.

Spectral and the temporal properties of the swallow sounds were compared during wet and paste swallowing. They found that the wet swallow was longer in duration (500msec) as compared to the paste swallows (250msec). Similarly, spectral prominence of 1500 Hz was observed for wet swallows in comparison to 2200 Hz during the paste swallows (Hamlet, Patterson, Flemming, & Jones, 1992).

Zenner and coworkers (1995) examined 50 individuals without dysphagia using clinical dysphagia evaluations and cervical auscultation to determine the level of agreement between the two assessment procedures. Authors did find some level of agreement between two methods. However two assessment methods were neither conducted simultaneously nor were counterbalanced i.e., the clinical dysphagia evaluation with cervical auscultation always preceded the videofluoroscopic evaluation. Moreover, the food boluses considered were not standardized on either assessment procedures. The authors finally stated that cervical auscultation was an imprecise method for evaluating risks for tracheal aspiration because of the lack of standard research on swallowing acoustics.

Wet and yoghurt swallows were examined in young adults in the age range of 18-26 years and the results revealed that the duration of the swallows increases with increase in bolus volume (Boiron, Rouleau, & Metman, 1997). The duration of both
wet and yoghurt swallows ranged from 500 to 1000 msec. Cichero and Murdoch (2002) sampled the individuals in the age range of 18-67 years during the swallowing of three volumes of thin liquids. Results indicated that the swallowing duration increases with age, with an overall mean duration of 400msec. However, this pattern was observed only for small volume of liquids, and swallowing duration decreased with increase in bolus volume across all the age range. In a similar line, Youmans and Steirwalt (2005) characterized normal swallowing sounds in ninety seven healthy adults using acoustic analysis technique. Here the individuals were asked to consume bolus of various consistencies and the swallowing sounds. Measures analyzed include frequency, intensity and the duration of the acoustic swallowing signal. Results indicated significant correlations among several of the variables i.e., duration of the acoustic swallowing signal increases with advancing age and intensity of the signal decreases with advancing age. There was no significant difference observed across the gender. These findings could serve as a reference point for comparison against disordered swallows.

Moriniere, Beutter and Boiron (2006) also used acoustic analysis technique for analyzing swallowing sound signals in thirty healthy individuals. These individuals were asked to consume a particular consistency and volume of a food bolus. A microphone was placed on the lateral border of the trachea and under the inferior border of the cricoid cartilage. The dependent variables considered were total duration of the sound, the number of sound components, the duration of each sound component and the intervals between the sound components. The mean durations of acoustic parameters were calculated for each of their recordings in both the genders and the
results revealed that there was no significant difference in these parameters across the gender.

The stability of initial discrete sounds in adults and infants were examined using cervical auscultation (Reynolds, Vice, & Gewolb, 2009). The microphone was attached to the neck in 20 healthy adults and infants. Each participant was asked to consume liquid, puree, and solid. The variance index was calculated to assess the stability of initial discrete sounds in adults and preterm infants. The variance index of adult liquid swallowing did not differ from that of preterm infants older than 36 weeks post menstrual age but was lower than the variance index of infants younger than 36 weeks post menstrual age. The stability of initial discrete sounds of preterm infants approached normalcy with age.

Shukla (2012) compared the characteristics of swallow sound recorded from different recording sites on the throat in typically developing children and adults across different bolus consistencies. Amplitude and duration measures were considered for analysis. Results revealed that the measures of swallowing sound vary depending on the recording site on the throat with respect to amplitude and duration of the swallow sound. Recordings from thyroid lamina yielded better amplitude measures whereas the recording from base of the tongue yielded better durational measures. However, recording at each site did not happen simultaneously and hence it was difficult to come to a conclusion that amplitude and durational measures vary with recording site. It was further noted that the amplitude and duration of the swallow sound were sensitive to age and gender.
Cervical auscultation in individuals with dysphagia: A small body of literature profiles the acoustic properties of the swallowing among the individuals with mechanical dysphagia. Hamlet, et al., (1992) investigated adults in the age range of 41-71 years who were post laryngectomy. Swallowing signals were obtained for both wet and paste swallows. The post laryngectomy individuals demonstrated no significant difference in the duration and spectral components of swallowing signal with respect to wet and paste swallows. However, tongue protrusion in the swallows of laryngectomee individuals occurred close in time to the distinctive spectra change due to the bolus flow in the esophagus. Uyama, et al., (1996) examined the barium swallows of pre and post surgical head and neck cancer patients. The average swallow duration of approximately 1600 msec was reported. Similarly, Thammaiah (2010) profiled the acoustic characteristics of swallow sounds in 10 healthy individuals, two partial laryngectomees and two total laryngectomees using thick liquids, thin liquids and solids of 10ml, 15ml and 20 ml bolus quantity. Duration of the acoustic signal, duration of peak intensity, frequency at peak intensity and peak spectral frequency were measured. As the bolus was directly propelled into the esophagus by tongue action rather than being propelled by pharyngeal walls, all the selected parameters showed significant difference between and within the groups. However, sample size considered was too small to generalize the results in partial and total laryngectomees.

Few studies have investigated the acoustic characteristics of swallow sounds in neurogenic dysphagia. One such study is by Marrara, et al. (2008) who retrospectively analyzed the clinical swallow examination records in children with neurogenic dysphagia. The parameters analyzed in the clinical swallow evaluation included food consistency, functional swallowing behavior and results of cervical auscultation. Videofluoroscopy was then performed to verify the dynamic aspects of the oral and
pharyngeal phases of swallowing. Results indicated a greater incidence of poor bolus control while swallowing both liquid and paste consistencies during the oral phase of swallowing. Normal findings in cervical auscultation were frequently observed before swallowing. However, abnormal findings were observed during swallowing in cervical auscultation. In the videofluoroscopic evaluation, inadequate food propulsion was the most frequent finding for both the consistencies during the oral phase of swallowing. However, the aspiration predominated during the pharyngeal phase of swallowing. Also, there was a statistically significant correlation between the cervical auscultation and the laryngeal elevation, & between the cervical auscultation and aspiration. This correlation was found for both the liquid and paste consistencies. Hence, they concluded that both procedures are equally important and complement each other in the diagnosis of dysphagia.

An acoustic analysis of swallowing sounds in healthy individuals and individuals with neurogenic dysphagia were performed by Santamato, et al., (2009). Previously recorded data of normal swallowing sounds of 60 healthy individuals was compared with those of 15 individuals with dysphagia. The results indicated that the mean duration of swallowing signal during a 10 ml liquid swallow was significantly different across healthy individuals and individuals with dysphagia. In line with this, Jose (2012) studied the acoustic characteristics of swallow sounds in normal healthy individuals and individuals with neurological impairments using thick liquids, thin liquids and solids of 15ml and 20 ml bolus quantity. Duration of the acoustic signal, duration of peak intensity, peak intensity, frequency at peak intensity and peak spectral frequency were measured. Results revealed that there was a significant difference between the groups across bolus consistency and volume for the durational
measures. However, no significant differences were observed for frequency and intensity related measures although the scores were higher in normal healthy individuals in comparison to individuals with neurological impairments. The limitations for the study include smaller sample size, broader age group and selective neurological impairments.

Few studies have focused on the analysis of swallow sounds in preterm infants. Reynolds, Vice, Bosma and Gewolb (2002) performed accelerometric and physiological studies during the bottle feeding in preterm infants between 32 and 39 weeks postmenstrual age. Accelerometer was used to perform cervical auscultation. It was attached to the larynx and the initial discrete sounds were recorded twelve times. These initial discrete sounds were used to calculate a variance index in each infant. The results revealed that there was a significant negative correlation between variance index and the post menstrual age suggesting that the morphology of initial discrete sound waveforms became progressively better with age. The developmental differences in the initial discrete sound morphology in infants with and without bronchopulmonary dysplasia were examined using cervical accelerometry (Reynolds, Vice, & Gewolb, 2003). The modified variance index method was derived to achieve the objectives of this study. They included 12 healthy preterm infants and 12 infants with Bronco pulmonary dysplasia. Modified variance index was then measured from the swallowing signals of these 24 infants. It was found that a significant inverse relation existed between the variance index and post menstrual age for the healthy preterm group but not for the infants with Bronco pulmonary dysplasia. Results also revealed that the modified variance index in infants with Bronco pulmonary dysplasia was significantly different from that of infants without Bronco pulmonary dysplasia.
The acoustic properties of swallowing in twenty three premature infants using cervical auscultation was also studied by Nobrega, Boiron, Henrot and Saliba (2004). Swallow signals were captured during tube-bottle and bottle feeding through a small microphone placed in front of the cricoid cartilage. The percentage of time the infants were involved in swallowing, swallowing bursts and the numbers of swallows were calculated for each infant. The results revealed that mean number of swallows and swallowing bursts increased significantly during bottle feeding compared with tube to bottle feeding for all premature infants.

It is clear that there appears to be no reliable pattern available for the swallowing sound. Apart from the double click pattern, spectral and temporal components of swallowing sounds have failed to provide a clear indication of normal and disordered swallow.

It is clear that methodological issues related to normal swallowing poses a challenge to swallowing assessment. These issues cover both the qualitative and the quantitative measures. Although various qualitative assessment tools exist in the literature, necessary information needed for treatment recommendation may not be incorporated in all of them. Majority of the previous researches have not examined the influence of age and gender on the swallowing event. The type and volume of bolus has not been uniform across studies. But, in view of the influence of the bolus type, volume, chronological age and gender on the swallowing pattern, there is a need for systematically exploring these aspects. Hence, the present study was attempted to develop a comprehensive qualitative assessment tool as well to quantify the
swallowing pattern across the age, gender, bolus type and volume using quantitative measures using Kay Digital Swallowing Workstation and Swallowing Signals Laboratory.