The Development of Swallowing Respiratory Coordination

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Abstract

Research exists that evaluates the mechanics of swallowing respiratory coordination in healthy children and adults as well and individuals with swallowing impairment. The research program summarized in this article represents a systematic examination of swallowing respiratory coordination across the lifespan as a means of behaviorally investigating mechanisms of cortical modulation. Using time-locked recordings of submental surface electromyography, nasal airflow, and thyroid acoustics, three conditions of swallowing were evaluated in 20 adults in a single session and 10 infants in 10 sessions across the first year of life. The three swallowing conditions were selected to represent a continuum of volitional through nonvolitional swallowing control on the basis of a decreasing level of cortical activation. Our primary finding is that, across the lifespan, brainstem control strongly dictates the duration of swallowing apnea and is heavily involved in organizing the integration of swallowing and respiration, even in very early infancy. However, there is evidence that cortical modulation increases across the first 12 months of life to approximate more adult-like patterns of behavior. This modulation influences primarily conditions of volitional swallowing; sleep and naïve swallows appear to not be easily adapted by cortical regulation. Thus, it is attention, not arousal that engages cortical mechanisms.

Introduction

This article could perhaps very aptly be titled “How following a research path takes you to fascinating places you didn’t intend to be.” Because I am a clinical scientist, the research path meandering through my laboratory is directed toward expanding our understanding of neural and biomechanical effects of rehabilitation for swallowing impairment. Our eventual destination is to enhance treatment outcomes for individuals with dysphagia, primarily subsequent to stroke and secondarily subsequent to other acquired conditions. Providing a foundation for this research path is a sidewalk of data that explores the potential cortical modulation of brainstem mechanisms.

Most journeys in my clinical research tend to begin with questions posed sometimes by a single patient. David was referred to our laboratory with a 3-month history of dysphagia subsequent to brain stem stroke. Of particular note in his clinical presentation was an inability to coordinate swallowing and respiration, placing him at significant risk of airway compromise. Curiously, however, during those periods of cortical quiescence typically known as sleep, swallowing respiratory coordination improved considerably. Cortical modulation appeared to have a substantive impact on this behavior that I considered at the time to be fairly hard-wired at medullary levels, and, very interestingly, the cortical adaptation appeared to be, in this case, obstructive. Brainstem contributions to swallowing respiratory coordination have been well researched (Feroah et al., 2002; Larson, Yajima, and Ko, 1994; Saito, Ezure, and Tanaka, 2002). What are less clear are the modulatory capabilities of cortical regions to adapt swallowing, respiration, and the coordination between the two processes. With the efforts of an extremely capable doctoral student, Bronwen Kelly, we embarked on a journey that led us to the world of pediatric swallowing.

Many excellent researchers have studied swallowing respiratory coordination for the purpose of defining biomechanical processes and clinical implications of pathophysiology in the patient population, and the interested reader should refer to those primary sources on clinical application (Martin-Harris, 2008; Lim, Leow, Huckabee, Frampton, & Anderson, 2008; McFarland & Tremblay, 2006; Leslie, Drinnan, Ford, & Wilson, 2005; Leslie, Drinnan, Ford, & Wilson, 2002; Hadjikoutis, Pickersgill, Dawson, and Wiles, 2000; Hiss, Strauss, Treole, Stuart, & Boutilier, 2004). In the interest of time and space, I am limiting this discussion to research from our laboratory, with reference to others, that has targeted elucidation of neural control of swallowing respiratory coordination.

Starting at the End: Adult Patients

An early literature review of research into swallowing respiratory coordination in adults revealed an interesting study by Nishino and HIraga (1991), which provided one of two models for our subsequent work. This group postulated that the “coordination of swallowing and breathing would depend on behavioral control and might be lost in the unconscious state” (Nishino & Hiraga, p. 988). In this study of anaesthetized patients, swallowing apnea occurred during both expiration and inspiration, with no clear preference for either respiratory phase category, as would be typical in the awake, healthy population (Hiss et al., 2001; Klahn & Perlman, 1999). These data suggest that conscious cortical input may have a significant influence over the coordination of breathing and swallowing, albeit the opposite effect seen in our patient David, described above.

Evaluating swallowing during periods of cortical quiescence seemed a viable approach for investigating cortical modulation, but we postulated that anesthesia may have inhibited not only cortical but perhaps also brainstem modulation in the Nishino and Hiraga study (1991). We, thus, designed a pilot study of 8 healthy participants to evaluate swallowing respiratory coordination in a condition of natural sleep (Kelly, Huckabee, & Friend, 2006). Similar to the findings of Nishino and Hiraga (1991), the coordination of breathing and swallowing was more variable during reflexive swallowing while sleeping than during volitional swallowing of a liquid bolus. Although presenting with substantial limitations, these early pilot data encouraged the development of research methods for a more definitive study of swallowing respiratory coordination.

Using time-locked recordings of submental surface electromyography, nasal airflow, and thyroid acoustics, nonnutritive swallowing respiratory coordination and swallowing apnea were evaluated in 20 adults during three conditions (Kelly, Huckabee, Jones, & Carroll, 2007). These conditions—voluntarily initiated swallows during wakefulness, nonvolitional awake swallows, and reflexively initiated swallows during sleep—were chosen to represent a continuum of volitional through nonvolitional swallowing control on the basis of a decreasing level of cortical activation. All swallows were completed without a bolus, with the exception of the volitional swallowing condition in infants, because infants were unable to swallow "on command." Electroencephalography (EEG) provided confirmation of sleep status, and a mercury switch was used to monitor for postural changes during sleep that may have influenced results (Kelly, Huckabee, Jones, & Frampton, 2007a). The key finding of this research was that swallowing apnea varied significantly between the volitional (voluntarily initiated swallows during wakefulness) and non-volitional conditions (nonvolitional awake swallows and reflexively initiated swallows during sleep), but did not discriminate between wake and sleep conditions. In other words, attention was more important than arousal. These findings suggest that cortical modulation of swallowing respiratory coordination is limited to conditions in which swallowing is voluntarily initiated and, thereby, implicates the contribution of the supplementary motor or insular cortices. Swallowing apnea duration (SAD), on the other hand, appeared to be relatively impervious to suprabulbar influence, with no change across conditions.

Moving Toward the Beginning: Pediatric Patients

Although the pathway of investigating sleep versus wake and voluntary versus involuntary swallowing conditions have provided valuable paradigms for study, we sought other models for investigating cortical modulation of swallowing respiratory behavior, thus beginning our adventures in the unfamiliar territory of pediatric swallowing. Postnatal development of the CNS is characterized by rapidly developing synaptogenesis (Huttenlocher & Dabholkar, 1997) and progressive myelination of the cortex (Gibson, 1991) and corticobulbar tracts (Sarnat, 1989). Thus, there is a substantial increase in descending suprabulbar input, particularly during wakefulness over the first year of life. Longitudinal investigation of swallowing respiratory coordination in developing infants provides an excellent model for evaluating descending corticobulbar control as it naturally develops.

An experiment was designed and executed in which 10 infants (8 females) were studied longitudinally across the first year of life. All infants enrolled in the study were born at or above 38 weeks gestational age and had no reported medical complications surrounding birth. Typical development was documented at each assessment session throughout the first year of life. A total of 10 assessments were conducted: within the first 48 hours of life, at 1, 2, 3, and 4 weeks, 2, 3, 6, 9, and 12 months of age. Each assessment involved the infant with his/her parent and investigated swallowing respiratory coordination under three conditions meant to approximate the 'continuum-of-volition' paradigm evaluated in the adult study: during nutritive, non-nutritive wake, and sleep swallows. An exact comparison to the adult conditions could not be replicated in infants because even the most skilled researcher or engaging parent would not be able to convince an infant to swallow "on command." Thus, inclusion of a feeding task in the infant study was substituted to ensure some component of volition. Although this disallows a direct comparison of the infant and adult data, it allows for longitudinal evaluation of developmental feeding behavior. All infants were breast-fed, if possible; however, bottle-feeding could not be avoided in three infants as a result of maternal health concerns such as milk production problems or maternal anemia. Post hoc analysis of the data revealed no influence of method of feeding on respiratory phase categories. Although the sample size is small for both breast-fed and bottle-fed infant groups, the means and standard deviations of the percentage frequency occurrence of swallows were similar for both groups. Similar to the adult study, time-locked recordings of submental surface electromyography, nasal airflow, and thyroid acoustics delineated the phase and duration of swallowing apnea. EEG and a mercury switch documented sleep state and position, respectively.

The first published manuscript from this study documents the maturation of swallowing respiratory coordination during feeding across the first year of life (Kelly et al., 2007b). The dominant pattern of swallowing respiratory coordination within the first 48 hours of life was swallowing within the mid-expiratory phase of respiration. However, only 45.4% of nutritive swallows occurred during mid-expiration and the prevalence of this pattern declined rapidly in the first week to only 29.1% ($p = 0.012$). Swallowing at the inspiratory-expiratory cusp was less common at birth, but increased with age ($p < 0.001$), particularly between 9 (37.0%) and 12 months (50.4%). In the last 6 months of testing, between 6 and 12 months of age, infants approximated adult-like characteristics with up to 75.0% of swallows followed by expiration (swallows occurring in mid-expiration plus those occurring at the inspiratory expiratory cusp). These data document that post-swallow expiration is a robust feature of swallowing respiratory coordination, albeit not as consistent at birth as is seen in adults. Two major shifts in development of swallowing respiratory development can be identified: the first after 1 week of postnatal feeding experience and the second between 6 and 12 months.

The first experimental hypothesis from this study proposed that the impact of feeding on swallowing respiratory coordination would be obvious in the neonatal period as reflected in significant differences between nutritive and non-nutritive swallowing conditions. Because some authors report no obvious impact of ingestion on adult swallowing respiratory coordination (Nishino et al., 1985), it was further hypothesized that the differences between conditions would diminish with age. As expected, swallowing respiratory coordination differed markedly between the two swallowing conditions with several major findings. First, there were higher proportions of swallows occurring in mid-inspiration and at the inspiratory-expiratory and expiratory-inspiratory cusps during nutritive than during non-nutritive swallowing conditions, patterns of coordination that exhibit a lower degree of airway protection than the mid-expiratory phase that is common in adulthood. Conversely, mid-expiratory swallow proportions were higher in the non-nutritive than nutritive swallowing condition at 2 weeks and 2 months, but the reverse was true at 48 hours. Finally, fewer swallows occurred during respiratory pauses during nutritive than non-nutritive swallowing throughout the first 6 months of life but not beyond. In summary, the number of respiratory-phase categories subject to a condition effect was low initially, but peaked between 2 weeks and 2 months and then declined until only inspiratory-expiratory swallows differed between conditions from 6 months onward. These data suggest a 'critical period' in infantile neural response to oropharyngeal stimulation during feeding and that the impact of this on infants with neurological and/or respiratory disorders should be further investigated.

Consequently, SAD was investigated across the three conditions targeted in this study. SAD during feeding was significantly shorter than SAD of both conditions of non-nutritive swallowing (during wakefulness and sleep) irrespective of age. The absence of an age effect implies that the neural mechanisms controlling SAD are fundamentally brainstem-mediated and largely hard-wired at birth in healthy term neonates.

The final experimental hypothesis from the study proposed that non-nutritive swallowing during sleep would differ from that during wakefulness in newborns and that this difference would become increasingly pronounced across the first year of life as corticobulbar connections are established (Kelly, et al., 2008). This hypothesis was rejected. Swallowing respiratory coordination during sleep and wakefulness did not differ at any point in the first year of life. This suggests that, at least in the first 12 months, the cortex has limited or no influence on swallowing respiratory coordination. A presumed corollary is that the brainstem exerts essentially full control over the coordination of respiration and non-nutritive swallowing during the first year of life.

Summary

This research program represents our journey down the path of swallowing respiratory coordination as a means of behaviorally investigating cortical modulation of a single aspect of swallowing biomechanics. Our primary finding is that, across the lifespan, brainstem control strongly dictates the duration of swallowing apnea and is heavily involved in organizing the integration of swallowing and respiration, even in very early infancy. However, there is evidence that cortical modulation increases across the first 12 months of life to approximate more adult-like patterns of behavior. This modulation influences primarily conditions of volitional swallowing and, despite the early research by Nishino and Hiraga (1991) that started us on this path and our own pilot research, sleep and naïve swallows appear to not be easily adapted by cortical regulation. Thus, it is attention, not arousal, that engages cortical mechanisms.

From a clinical perspective in the adult population, the influence of cortical modulation on volitional swallowing provides support for rehabilitative intervention and the strengthening of cortical regulation of swallowing behavior. In the pediatric population, our data suggests a possible critical period for the development of protective coordination during ingestive swallows between 2 weeks and 2 months. Clinical correlation of this finding would be of value in future research.

Acknowledgment

The author of this summary extends great kudos to Bronwen Kelly for her commitment to this work.

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