Review Paper: Role of Basal Ganglia in Swallowing Process

Hamideh Ghaemi[1], Davood Sobhani-Rad[2*], Ali Arabi[2], Sadegh Saifpanahi[3], Zahra Ghayoumi Anaraki[2]

1. Department of Speech Therapy, School of Rehabilitation, Tehran University of Medical Sciences, Tehran, Iran.
2. Department of Speech Therapy, School of Paramedical Sciences, Mashhad University of Medical Sciences, Mashhad, Iran.
3. Department of Speech Therapy, School of Rehabilitation Sciences, Hamadan University of Medical Sciences, Hamadan, Iran.

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ABSTRACT

Objectives: The basal ganglia (BG) controls different patterns of behavior by receiving inputs from sensory-motor and pre-motor cortex and projecting it to pre-frontal, pre-motor and supplementary motor areas. As the exact role of BG in swallowing process has not been fully determined, we aimed at reviewing the published data on neurological control in the swallowing technique to have a better understanding of BG's role in this performance.

Methods: English-language articles, which were published before December 2015 and eligible for the present research, were extracted from databases according to the inclusion criteria, i.e. articles related to "neurological aspects of swallowing" and/or "lesions of sub-cortical or BG relevant to swallowing disorders".

Results: This systematic review indicates that BG is a complicated neurological structure with indistinct functions and that swallowing is a sophisticated process with several unknown aspects.

Discussion: Swallowing is a multifaceted performance that needs contribution of the tongue, larynx, pharynx, and esophagus as well as the neurological structures such as neocortex and subcortical regions - BG and brainstem.

1. Introduction

Swallowing is defined as a complex sensorimotor behavior that requires the co-ordinated function of muscles located around the mouth, tongue, larynx, pharynx, and esophagus in order to transport food from the oral cavity to the stomach [1]. The volitional and automatic movements during swallowing, which are controlled by more than 30 nerves and muscles [2-4], could be divided into three inter-related physiological stages: [1] the oral stage that is voluntary and highly variable in duration; [2] the pharyngeal stage during which translocation of bolus occurs from the oropharynx (throat) into the esophagus without aspiration; and [3] esophageal stage in which the bolus moves through the lower

* Corresponding Author:
Davood Sobhani-Rad, PhD
Address: Department of Speech Therapy, School of Paramedical Sciences, Mashhad University of Medical Sciences, Mashhad, Iran.
Tel: +98 (513) 8846711
E-mail: sobhanid@mums.ac.ir

esophageal sphincter into the stomach under the control of autonomic nervous system [5-10]. Accurate control of the swallowing function relies on the exact innervations of several areas in the brain, including the neo-cortex, sub-cortical regions, brainstem, and peripheral nervous system [11]. The brainstem swallowing center is known as the first level of swallowing control while the subcortical structures, such as basal ganglia (BG), hypothalamus, amygdala, and tegmental area of the midbrain, are in the next levels, and finally, there are supra-bulbar cortical swallowing centers [12].

BG is a group of interconnected nuclei including striatum (further subdivided into putamen and caudate nuclei), Sub-Thalamic Nucleus (STN), globus pallidus external and internal segments (GPe and GPi, respectively), and substantia nigra pars compacta and pars reticulate (SNc and SNr, respectively). BG plays a vital role in a variety of motor, cognitive, and limbic functions by integrating the information derived from multiple cortical regions and conveying it back to frontal cortical regions and brainstem nuclei after processing it [13,14].

Although varied investigations have clarified the various functions of the BG, its exact role in the swallowing process has not yet been fully comprehended. For instance, a number of reports have indicated that damages and lesions of BG might lead to some degree of swallowing disorders; but, little has been discussed about the probable mechanisms and pathways in this aspect. Hence, we decided to conduct a systematic review based on a number of clinical studies for a better understanding of BG's function in swallowing.

2. Methods

Numerous English-language articles that were published up to December 2015 and included keywords like swallowing, basal ganglia, swallowing neurology, neuro-imaging, dysphasia, and neurogenic dysphasia in their title or abstract were extracted from databases such as PubMed, Willy, Springer, and Elsevier (Medline, EBMR, Google Scholar, Science Direct, and ProQuest). Among these articles, eligible studies related to "neurological aspects of swallowing" and/or "lesions of sub-cortical or BG relevant to swallowing disorders" were filtered out in accordance with our pre-decided inclusion criteria. Conversely, papers with no focus on BG and swallowing problems were excluded.

3. Results

The current systemic review revealed that despite extensive data published on swallowing neurology, only a few studies have focused on the topic considered here. For instance, the role of BG in the process of swallowing has been examined in papers on hemorrhagic BG [15], stroke [16-18], dementia, and traumatic brain injury [19, 20]. Some studies have also focused on the role of the extra-pyramidal syndrome, such as Parkinson's, Huntington's, and Wilson's diseases in the swallowing process [21-24]. In addition, there are a few reports on the swallowing performance in elderly individuals [25-28].

These limited publications indicate that swallowing is a sophisticated process with several unknown aspects. Nevertheless, it is necessary to mention that developments in neuroimaging techniques have improved our knowledge about BG functionality throughout the swallowing process, which has been detected through cryptogram of the BG function in brain images during swallowing. As summarized in Table 1, neuroimaging studies have confirmed the fact that swallowing involves the activation of multiple areas in the human brain, including putamen, globus pallidus, substantia nigra, and BG.

Based on the reviewed papers, BG is linked to sensorimotor, supplementary motor, pre-motor, associative and limbic cortices through functionally related loops [32-35], and such somatotopic organization supports both motor and cognitive functions [36]. BG receives input from sensorimotor areas of the cerebral cortex,

Table 1. Published reports on the BG function using neuroimaging technology.

Results	Imaging Technique	References
Recognized swallow-associated augmented blood in the putamen	PET	Hartnick et al. [29]
Rise in swallow-induced local activity in putamen, globus pallidus, and substantia nigra	f-MRI	Suzuki et al. [30]
The right putamen was introduced as a focal point for activation	f-MRI	Martin et al. [31]
Discovered BG activation through water oral combination	f-MRI PET	Hamdy et al. [20]

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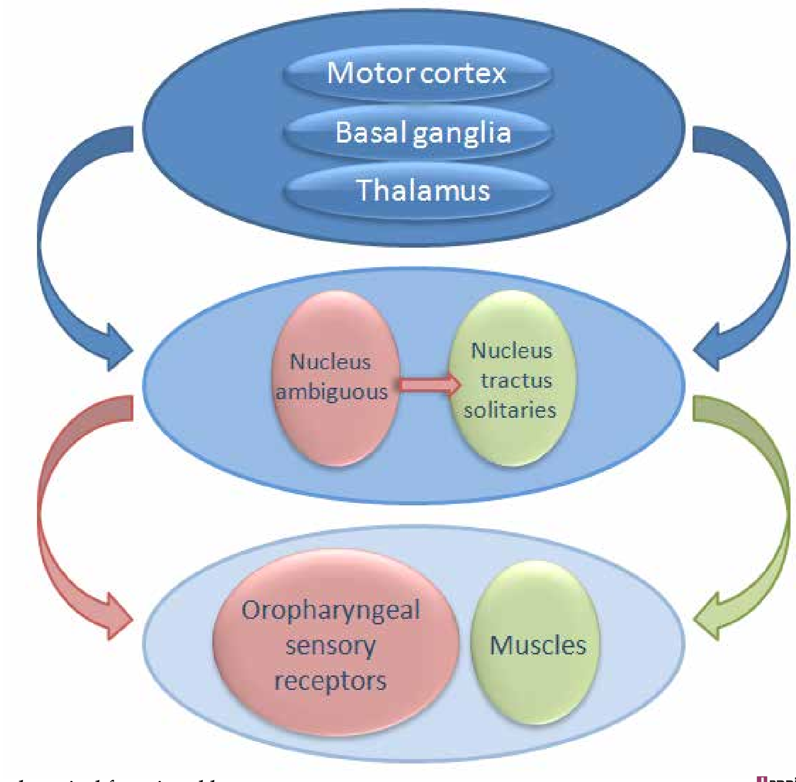

Figure 1. Cortical and subcortical functional loops.

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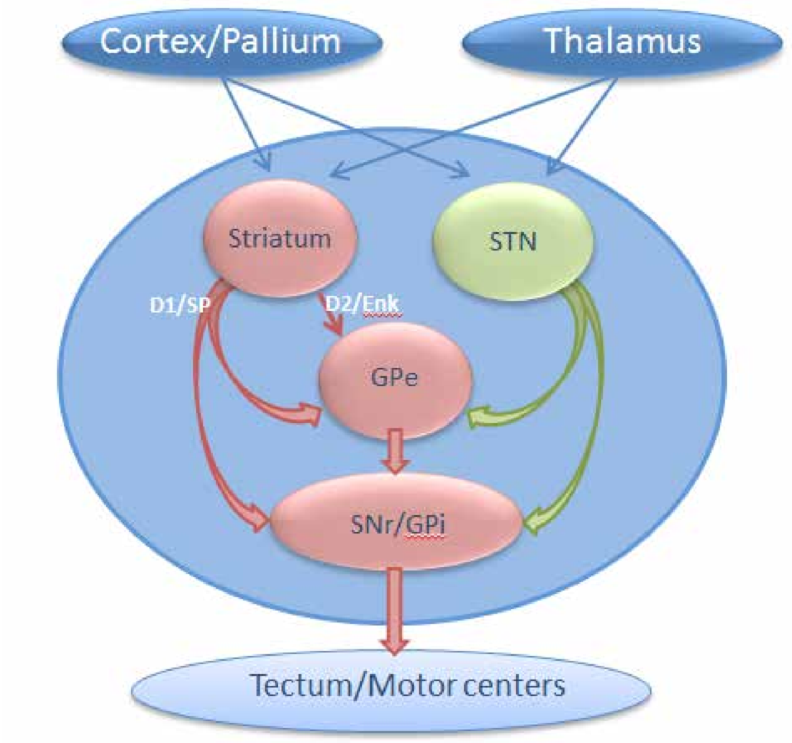

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Figure 2. Striatum including GABAergic neurons (red), as globus pallidus externa (GPe) too, globus pallidus interna (GPi) and substantia nigra pars reticulata (SNr). SNr and GPi signify the output level of the BG, and are projected via various subpopulations of neurons to tectum and brainstem motor centers. The indirect loop is represented by the GPe, the subthalamic nucleus (STN), and the output level (SNr/GPi). The striatal neurons of the direct pathway to SNr/GPi express D1R and substance P (D1/SP) while the indirect pathway neurons in striatum express D2R and enkephalin (D2/Enk).

which are primary and secondary somato-sensory, primary motor cortex, and premotor areas [37, 38]. In addition, BG has extensive connections with the thalamus and other sub-cortical structures [39, 40].

As presented in Figure 1, BG (striatum) receives input from all cortical areas and projects through the thalamus to prefrontal, premotor, and supplementary motor areas that are involved in motor planning. In the BG-thalamo-cortical circuits, the thalamus acts as a sensory-relay station and conveys information about the sensation of eating and swallowing to other cortical and sub-cortical structures [39]. Both voluntary and involuntary movements happening during ingestion are further modified by the feedbacks received from kinesthetic images and other afferents converging onto the BG, which further monitor and refine the movement progression in order to ensure the temporal and spatial accuracy [41]. Finally, BG notifies about the movement-related cortices involved in the preparation for next act while promoting muscle relaxation [42].

4. Discussion

Swallowing is a multi-faceted performance with active neural synchronization at the cerebral and brainstem levels. Studies on functional magnetic resonance imaging (fMRI) have recognized the anatomic sections, which are active during swallowing, including the chief sensory and motor cortex, additional motor area (SMA), cingulate cortex, insula, operculum, prefrontal and inferior frontal cortices, BG, thalamus, and cerebellum [43-48]. As mentioned earlier, automatic movements of swallowing are controlled by BG that establishes accurate timing and spacing in this process [37, 38].

Although the rhythmic pattern of mastication is controlled by the central pattern generator in the brainstem, it is supplemented by the motor cortex that provides preprogrammed movement patterns based on expectations and sensory feedbacks in conjunction with BG. The production level of BG includes active GABAergic neurons arising from two nuclei, GPi and SNr. The sub-populations of GABAergic neurons from the structure have outstanding projections to diverse motor cores in the brainstem [49]. As these neurons are tonically energetic at rest, they can sustain the incessant inhibitory drive [50-56].

Therefore, starting a motor program similar to swallowing depends on the elimination of such tonic reticence; hence, the pallidal output neurons must be inhibited from the input layer of BG [51, 53, 57-59]. Beyond the pallidal control of motor centers, the neurons projected by pallidum returns to the groups of cells inside the thalamus and are further projected back to the cortex. The pallido-thalamo-cortical loop controls emotions, swallowing, and motor and cognitive functions [60]. It is worth mentioning that in neurological diseases like Parkinson's, the cortex is out of the loop, and hence, all the actions of BG are done straightforwardly over brainstem targets [61].

It is also essential to review the BG-nuclei that manage the output level as discussed in previous studies. As demonstrated in Figure 2, the projection neurons in the striatum are divided into two groups. Firstly are the dopamine receptors D1 type (D1R) that project straightforwardly to subpopulations of neurons at the production level (SNr/GPi) and get involved in the beginning of motor programs of swallowing, and secondly are the dopamine D2 receptors (D2R) that project to GPe - a neural structure that contributes with STN and restrain movements [61-63].

The subpopulation of D1R projected neurons control the fundamental aspects of motor performance of swallowing and depend on the excitatory inputs from thalamus and cortex/pallium, which further verifies whether they are activated or not. In case activated, the D1R neurons will participate in the instigation of a given motor program for swallowing [64, 65]. The tonic level of dopamine discharge resolves the responsiveness of the striatal neurons, and thus, the negligible dopamine makes it intricate to activate the movements, similar to that observed in Parkinson's disease [66]. Dopamine neurons of BG have another characteristic importance in the motor system, i.e., they react with short-lasting bursts of activity throughout the awareness - a trait that can be important in promoting the knowledge of swallowing behavior [67, 68]. Despite their significance, our understanding of neural circuits, which are responsible for the value-based changes in dopamine discharge, is not complete [69-71].

It is, therefore, important to mention the dissimilar components inside the BG-controlled special motor programs. The swallowing process depends on the input from pallium/cortex, thalamus and the dopamine system and includes various parts of both direct (D1) and indirect pathways (D2). The production cells from GPi and SNr aim at the diverse motor centers [55, 71]. The selection of specific units depends on the excitatory input from thalamus and pallium/cortex along with the degree of tonic dopamine activity, which collectively define the prototype of BG's behavior. In addition varied other motor patterns can be shared, for instance, one can swallow and chew simultaneously while one can only turn left or right and not both at the same time [59].

Therefore, mechanisms must be discovered for governing different behaviors of BG. Nevertheless, it is obvious that the BG plays a key role in making a flat series of movements [65]. Therefore, movement skills are compromised in patients with Parkinson's disease, and there is a propensity to carry out merely one motor pattern at a time [72].

In this review study, we aimed at clarifying the role of the BG in the swallowing process for the first time. Reviewing of the published data on neurological control in swallowing process revealed that BG is one of the most complicated neurological structures, partially due to its location in the brain with indistinct performances. On the other hand, few published studies have focused on neurological aspects of swallowing, indicating that it is a sophisticated process with several unknown aspects. However, with the help of neuroimaging techniques, it has been confirmed that BG is linked to neural structures that support motor and cognitive functions such as the one involved in swallowing. BG receives input from all the cortical areas and projects to prefrontal, pre-motor, and supplementary motor areas through the thalamus. In BG-thalamo-cortical circuits, the thalamus conveys the information about the sensation of eating and swallowing to other structures while BG monitors the movement of progression to ensure the accuracy of swallowing from its different aspects.

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Conflict of Interest

The authors declare that there is no conflict of interest regarding the publication of this article.

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