Biologically-inspired swallowing robot for investigation of texture modified foods

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Abstract: Textural and rheological characteristics of foods are known to profoundly affect the swallowing process. Food technologists continue to exploit this notion in the management of symptomatic swallowing disorders (dysphagia) where novel foods are designed to elicit more reliable transport characteristics. Currently, little is understood about the relationship between food bolus formulation and its flow-induced interactions with the swallowing tract. Experimentation of a medical nature in this field is extremely challenging, and may put patients at risk. In the rheological domain the deformation fields are dissimilar to that of the biological system. In response to these limitations, quantitative assessment of bolus transport by a novel rheometric testing device is proposed. This paper describes the inspiration for a biologically-inspired robotic swallowing device to be applied to address these issues. This will allow for an improved understanding of swallowing mechanics and food design in the engineering, medical, and food technology fields.

Keywords: swallow; swallowing robot; peristalsis; biological inspiration; texture modified food; TMF; bolus; food technology.

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1   Introduction

The process of swallowing is mandatory for the regular ingestion of a variety of solid and liquid foods. Much has been understood about this process by observation and empirical measurement in the medical domain. However, current research typically remains reflective rather than predictive of swallow efficacy for different bolus formulations. Food scientists are interested in developing novel foods for the management of dysphagic symptoms by modifying the textural, and subsequently the rheological and tribological, attributes of certain foods. These have been challenging to characterise in the current state of the art.

The prediction of bolus transport is of particular interest in the medical field to understand both the healthy and impaired swallowing processes. This is especially true of research into the design and prescription of texture modified foods (TMFs) for the management of dysphagia; the impaired swallowing process. Complications arise in response to reduced muscular strength, sensation or neural coordination which cause a wide variety of symptoms and associated needs for consumer acceptance of food. Food technologists aim to exploit breakdown pathways and aspects of bolus cohesion to develop novel foods for mitigation of dysphagic symptoms. In order to understand their targets, the adequacy of bolus formulations needs to be understood. This involves dynamic investigation of boluses from the point of swallow until they reach their destination, the stomach.

The study of food bolus rheology in the physical sense has typically been of an intrinsically mechanical

nature with rigid boundaries and testing protocols that are fundamentally dissimilar to human swallowing. It has been suggested that current rheological measurements and models alone may not facilitate rigorous prediction of the biological behaviour due to differences in the deformation and sensory conditions of current measurement apparatuses (Bourne, 1992). It is proposed that the flow fields asserted throughout bolus investigation should more closely reflect the mode of transport and interaction with the swallowing tract as observed in the biological system. In addition to this, it has been conceived that the type and transduction of measurements made to understand and model the swallowing process should reflect those that the human body could conceivably measure and interpret (Bourne, 1992).

Throughout *in vivo* medical investigation, via manometry and videofluorography, isolation of different property characteristics has also been particularly difficult due to the known inter- and intra-subject variations from swallow to swallow (Clouse et al., 1998). This renders complications in data comparison and is known to suffer significantly from confounding factors. These complications have allowed for trends and features of the swallowing process to be identified. However, it has been challenging to clarify to what extent individual parameters have on its efficacy in either health or disease. Typically the measurements are quantitative; however their interpretation is more qualitative and holistic. The swallowing process has also been investigated mathematically in the engineering domain using both analytical and numerical methods (Yang et al., 2007; Brasseur, 1987; Misra and Pandey, 2001; Toklu, 2011; Walker and Shelley, 2010; Misra and Maiti, 2012). Insight has been gained towards how model fluids will flow through idealised passages. These models are typically based on a large range of assumptions and may not faithfully reflect the transport characteristics of boluses with more complex structures. These limitations have resulted in a limited overlap between quantitative measurement and prediction of food properties in the engineering domain and qualitatively defined swallowing efficacy in the medical field.

It has been identified that food technologists require new tools and methods to develop novel TMFs with predictable rheological and tribological characteristics to meet the demands of both healthy and dysphagic populations. To address this demand a biologically-inspired swallowing robot is proposed to investigate bolus rheology throughout a dynamic swallowing process. The esophagus has been identified as the target structure to mimic. The focus of the current initiative is to overcome the limitations of current investigation methods by moving into the physical domain. This is to be conducted by communication of the actuation and sensation aspects of the biological process into the engineering field. This paper explores the new possibilities and applications for a robotically mimicking swallowing robot in the medical and food technology fields. In particular, how it may be used in the standardisation of TMFs for the management of dysphagia.

2 TMFs in practice

Rheological properties of food significantly influence the progress of swallowing in healthy and impaired individuals. The current methods towards understanding this relationship in the medical field have typically been based on the correlation of rheological characteristics with temporal-spatial analysis of *in vivo* swallowing studies. These conclusions have been drawn from extensive research and analysis of data captured by videofluorographic and manometric investigation techniques; for example, Ghosh et al. (2006), Kendall et al. (2000), Buettner et al. (2001), Abrahao et al. (2011) and Hobson and Azis (2011). These methods provide complementary information on the progress and behaviour of the transported fluid (Kuo et al., 2012). However, they only provide limited insight into the perception of the bolus from a physiological point of view and cannot separate the multiple confounding aspects in the biological system such as body temperature and muscle deformity.

The modification of bolus formulation, particularly those that influence rheological attributes, is known to influence swallow efficacy. This has been, and is expected to be further, exploited in the medical field to mitigate dysphagic symptoms. The methods of prescription and evaluation of their success have been challenging to estimate as they are observational in nature. It is anticipated that current techniques in the clinical setting result in an 'acceptable' swallow; not necessarily a 'desirable' or 'optimal' swallow. Further work needs to conducted in this field to determine the suitability of different bolus formulations for patients of varying condition.

2.1 Overlap of engineering and biological fields

The alteration of food structure by mechanical means, whether achieved orally or external to the human body, can have profound effects on the rheological and tribological transport properties. The fields of texture evaluation and rheological measurement are highly linked, where textural attributes are typically correlated with time-varying rheological measurements (Bourne, 2002). It is common that rheological behaviour of liquid and semi-solid fluids flow is communicated in quantitative metrics. This provides a convenient method to make comparisons between the flow behaviours of different fluids. However, in the clinical setting more qualitative descriptions are used, typically relating only to the fluid viscosity. Current terminology to describe formulations includes: thin (water), medium (nectar), or thick (puree) among other words in different institutions. Certainly aspects of fluids such as those that exhibit a shear history or change of behaviour over small variations in formulation deserve more significant attention.

There is still significant scope to increase the understanding of overlap between the quantitative and qualitative observations of the swallowing process (Figure 1). Bolus properties relating to the rheology, tribology and texture all influence the efficacy with which the process is undertaken. They are exclusive fields in their

own right; however, describe highly linked phenomena. It is proposed that more rigorous investigation of these links should be undertaken.

Figure 1   Relationship between current food investigation fields (see online version for colours)
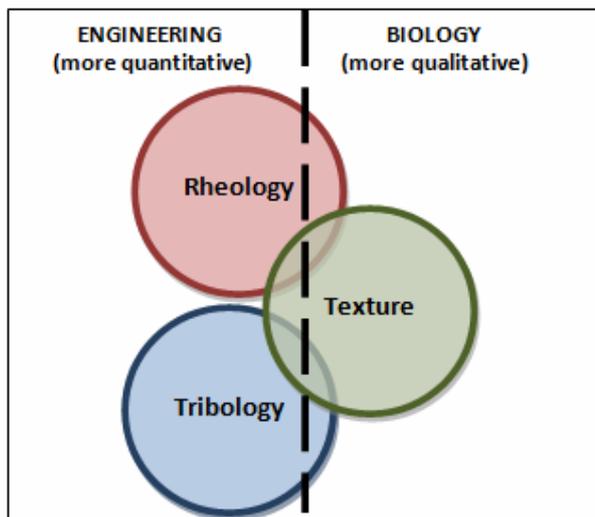
2.2   Prescription of TMFs

The medical field is certainly interested in understanding trends of swallowing efficacy in response to novel food formulations, and in particular those in pursuit of TMF for the management of dysphagia. To be standardised in provision, it is strongly desired that there is a set of quantitative metrics to test the behaviour against. The current trial-and-revise approach is of a qualitative nature which has made it challenging to compare between different strategies. Certainly there is an element of rheological investigation of the formulations; however, current rheological methods cannot sufficiently describe all of the effects observed in the ingestive tract.

2.3   Identification of issues with TMF

The prescription of TMF requires a firm understanding of the medical diagnosis and hypotheses to be developed about how formulation methods may improve swallow efficacy. However, there is a lack of evaluation protocols to determine the requirements of dysphagic patients as well as little standardisation for the provision of modified diets for mitigation of their symptoms (Keller et al., 2012). The current TMF techniques may also exhibit inter-batch and or time varying rheological characteristics. The magnitude of these effects in relation to the treatment protocol need to be further clarified. Standardisation of both formulation and prescription methods is imperative in achieving positive outcomes in the clinical setting. New methods are required to achieve the depth of bolus description to facilitate rigorous replication of formulations and experiments in different laboratories and clinical environments.

3   Bolus modelling

The vast array of rheological and structural differences in raw and processed foods has led to the development of many food breakdown, lubrication, and cohesion models. These demonstrate preliminary insight into how food boluses are formed as well as initiate swallowing under suitable conditions. The rheological and structural characteristics of suitable food boluses at the point of swallow are of utmost interest in the food technology and medical fields. These represent a target to elicit at the conclusion of the oral preparation to ensure safe and effective transport.

Investigating the relationships between inputs and outputs of the bolus formulation phase (Table 1) prior to swallowing will allow food technologists to create 'desirable' boluses. It is understood that there are many contributing factors to rheological and tribological outputs in the biological domain. This represents an opportunity to artificially elicit certain attributes by careful structuring and formulation of foodstuffs. These can then be exploited to target specific swallowing behaviours in healthy or dysphagic individuals.

Table 1   Attribution of bolus properties in response to food design variables

Food bolus formulation	
Inputs	*Outputs*
Food	Flow
Saliva	Swallow Behaviour
Breakdown	Cohesion
Manipulation	Lubrication
Enzymes	Sensation
Temperature	Nutrition
Physiology	Texture
Phases	Structure

3.1   Current models

The Hutching-Lillford (Hutchings and Lillford, 1988) and Prinz-Lucas (Prinz and Lucas, 1997) models are the two most prevalent approaches to conceptualising bolus formulation and characterisation at the point of swallow. They manifest as qualitative and quantitative descriptions of the oral manipulation phase which aims to conclude with a swallow safe bolus.

The Hutchings-Lillford model provides a qualitative inspiration for the differences in food oral processing and the subsequent variety of formulations determined reasonable to undertake the swallowing process. This demonstrates both the importance of the structure of the food offering as well as its manipulation. Significantly, the parameters for this model reflect the behaviour throughout oral residence which has been simplified to: degree of

structure, amount of oral residence time, and lubrication. It is proposed that critical aspects of all three contribute to formulation of boluses with desirable transport characteristics. However, the relationship between parameters of bolus formulation and their contribution to different features of the transport process have not yet been wholly communicated.

The Prinz-Lucas model of bolus cohesion is concerned with the mathematical description of rheological characteristics based on fluid-particle interaction. It is proposed that the particle size distribution and liquid content determine the cohesion through parameters linked to surface tension. It is further elaborated that the bolus formulation of highest cohesion is attributed to initiation of the swallowing process. However, this hypothesis has been contested as it is not an obvious physiological choice (Chen and Lolivret, 2011); the bolus at this point would be most difficult to deform.

These models are complimentary in nature and conceptualise safe bolus formulation from two differing perspectives. There are specific merits and limitations, as pointed out by the hypothesis of swallow-ready bolus formulation by Prinz and Lucas. Further work is required to parameterise these concepts such that they can be exploited in the medical field.

The prescription of TMFs for the management of dysphagia typically involves feeding of formulations requiring little oral manipulation. Thus, the focus is on interpretation of bolus formulation artificially elicited by preparation outside of the human body. Typically these fluids are described in the clinical context as thin (water), medium (nectar), or thick (puree), each of which require little or no mechanical manipulation; they are 'readily swallow-able'. The main alterations of these fluids before swallowing are saliva mixing and lingual preparation at swallow initiation. This represents a fast-track to the conclusion of the models above.

3.2 Identification of opportunity to improve current philosophy

The models for conceptualising swallow suitability do little for the prediction of flow characteristics. Their relevance to observations of oral manipulation and subsequently swallow initiation are very high; however their parameters have not seen rigorous interpretation or application in the clinical context. The relationship between the breakdown pathways and the transport characteristics of the final bolus formulation require further investigation. These concepts, as described by the Hutchings-Lillford model, need to be related to flow and deformation effects in the biological domain. Certainly this will help to determine an envelope of formulations deemed suitable for safe and effective swallowing.

These models and interpretations of bolus formulation require further experimental investigation. Certainly they need an element of prediction for swallow safety of boluses at their conclusion. This may manifest as the specification of an envelope of acceptable formulations for healthy and/or impaired populations. The current understanding of TMF for dysphagia management has been achieved by observation of the transport behaviour of artificially prepared boluses. These formulations have been successful and seen significant use in the clinical context making them good candidates for exploration of what characteristics are suitable for reliable swallowing. It is proposed to link these with pressure interactions during a modelled swallowing process in order to decipher which attributes contribute to their swallowing efficacy in man.

4 Demand for a robotic swallowing device

The exploration of TMF for the management of dysphagia requires a more scientific approach. The current methods of investigation suffer from many confounding factors and qualitative observational outcomes which are difficult to compare. In turn, this leads to difficulty in clarifying the extent of alteration or improvement to swallow efficacy in the medical domain. The trial-and-revise nature of these practices also puts patients at risk throughout the study of what bolus types are acceptable to them. This poses some very ethical issues.

It is envisaged that novel methods are required to further the understanding of food formulation on the deformation and subsequent transport behaviour in the swallowing apparatus. These areas of the medical and food technology fields require more rigorous investigation to determine the suitability of TMF for dysphagia management and the development of associated prescription protocols.

The issues related to inter- and intra-subject variability from swallow to swallow also make quantitative comparison of transport in the medical domain challenging. Thus, the body is not an ideal apparatus upon which to test scientific theories in a controlled manner; especially when investigating fine boundaries or small alterations in formulation. It is proposed that target criterion should be specified by understanding the relationship between formulation variables and their transport behaviour. These then need to be related to the envelope of acceptable formulations for human swallowing. Investigation of rheological characteristics via a biomimetic robotic technique would facilitate generation of repeatable swallowing trajectories to overcome limitations of those experienced *in vivo*. Testing in the physical domain also overcomes limitations of mathematical modelling as outlined earlier.

The aim of creating such a device is to rigorously test the relationships between constitution, ingredients, phase characteristics, particle breakdown, lubrication and pre-swallow manipulation on the mechanical effort and flow mechanics that the biological system may encounter. These relationships will then be interpreted to identify trends which can be exploited in the development of functional foods of variable acceptance for both healthy and dysphagic

populations. The breakdown pathway and manipulation effects of the oral phase need to be subsequently related to the form which is presented to healthy persons and patients alike.

The robotic swallowing device is proposed to link the observations of phenomena in the biological system with quantitative rheological metrics. This will be reflected in the measurement of dynamic parameters related to fields of rheology, tribology, and texture. The current research initiative opens up an alternative technique for evaluation of swallow efficacy and safety of novel food formulations outside of the human body. The biomimetic robotic approach complements additional research techniques in the medical, mathematical and engineering fields by addressing limitations of the current knowledge (Table 2). The synergy of findings from these techniques shall lead to improved understanding of the swallowing process in man. It is proposed that this will lead to better understanding of food alteration and in turn, result in improved prescription practice in the medical field.

5   Robotic modelling

Research into the robotic modelling of human swallowing has, to date, had little impact in the food technology and medical fields in the way of food design. This has been limited by the over simplification of actuation techniques caused by mechanical discretisation of the actuation behaviour and the lack of interpretable sensory information. A number of devices of pharyngeal and esophageal origin have been developed with a range of purposes from medical training to peristaltic pumping (Miki et al., 2010; Noh et al., 2011; Kobayashi et al., 2005; Kobayashi

and Tokyo University of Science, 2006; Minato et al., 2006). These devices present preliminary insight into novel modes of actuation for three-dimensional occlusive motions. However, the methods are currently limited by; their force transduction techniques (some being of a non-distributed nature), having skeletal structures which cause regions to exhibit little or no occlusive motion, and/or lack of attention to variability of wave tail geometry. In addition to this the transduction of transport performance parameters has been largely avoided. In response to these limitations, and further inspiration from the biological process, a set of engineering specifications have been developed.
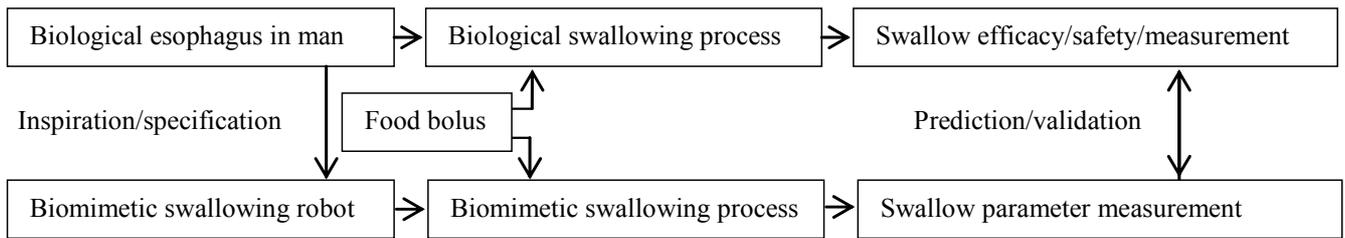
5.1   Biological inspiration

The current research is inspired by the esophageal region of the swallowing tract where the actuation behaviour has been characterised as peristaltic. Esophageal transport is achieved by a propagating wave of conduit occlusion which imparts force at the rear of the bolus. The behaviour of this process has been well reviewed in the medical field (Goyal and Chaudhury, 2008; Miller, 2008) and represents a region where actuation is more continuous and regular. The relationship between bolus formulation parameters and intra-bolus pressure has been investigated extensively by manometry (Clouse et al., 1998; Ghosh et al., 2006, 2008). This process is typical in the diagnosis of swallowing dysfunction and can be used to develop strategies towards prescription of TMF. It is proposed that robotic techniques may be used to quantify the differences in actuation effort for fluids of different rheological properties. Certainly aspects of the biological system such as compliance and varying wave geometry need to be addressed.

Table 2   Methods of evaluating swallow efficacy of bolus formulation

Method of investigation	Bolus morphology	Nature of swallowing process	Advantages	Disadvantages
In vivo experimentation	True food bolus	Biological	Extremely good knowledge of swallow efficacy	Puts patients at risk of health complications
			Patient-based	Intra- and inter-swallow variability. Not reproducible
Mathematical modelling	Numerical or analytical model	Finite element or analytically modelled peristalsis	Many formulations and actuation processes may be evaluated	Requires modelling of both the bolus and actuation system
			No ethical issues	
			Repeatable	
Robotic modelling	True food bolus	Biomimetic via robotic device	True bolus materials may be evaluated	Requires approximation of biological peristaltic principles
			Accurate evaluation of shear rate and history effects	Limited family of wavelengths may be investigated
			No ethical issues	Challenging to implement
			Repeatable	

**Figure 2** Relationship between current food investigation fields

The achievement of a biologically-inspired swallowing device will aid in the prediction of swallow efficacy and safety of food formulations externally to the human body. The process specification and validation elements (Figure 2) are crucial to the biomimetic motivation. These represent closure of the knowledge loop in order to elicit predictions of the biological behaviour by the robotic device.

This research initiative spans the three crucial aspects of esophageal swallowing; actuation, sensation and their coordination in process control. It is observed that these aspects are distributed in nature over the esophageal conduit, an intrinsically continuous radially contracting cylindrical surface. The muscular tube is not acted upon by rigid skeletal elements, rather a sequential assertion of cylindrical and longitudinal muscles. Thus, the nature of actuation is compliant and distributed. These concepts are communicated into the engineering domain through cross-boundary specifications.

5.2 Engineering specification

The specification of the process features and biological structure have been communicated in our earlier review of the swallowing system (Chen et al., 2012). The engineering requirements can be visualised as an axial occlusion that propagates in a moving actuation window (Figure 3). It is imperative that the discretisation of individual actuation units facilitates a compliant motion that is similar to the human case.

Figure 3 Propagation concept of discretised compliant peristaltic actuator
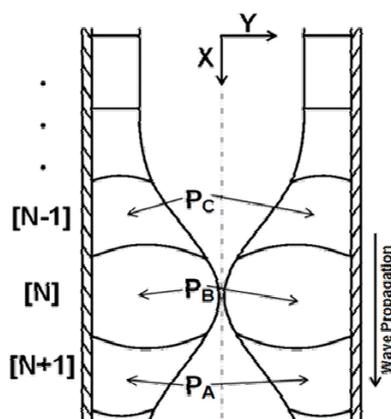
The defining characteristics of the esophageal phase of swallowing for engineering inspiration include:

1 geometrically faithful conduit distension, length, and actuation behaviour

2 sequential rostral-caudal occlusion of a continuous and compliant peristaltic nature

3 spatial-temporal achievement (geometry/manometry) of biologically captured swallowing process

4 concurrent sensation of bolus transit

The nature of tissues in the biological tract has inspired the concept of a soft-robotic device which exhibits intrinsic compliance in force transmission onto the bolus. This inspires a mechanical analogue of muscular actuation on the conduit in the biological domain. The feature of conduit occlusion, and its motion along the tract, must be continuous in nature such that all regions of the tract can totally occlude. This is respectful of the wave tail seal propagating the entire length of the conduit throughout manometry in the human body. This must be achieved in the biomimetic device. With reference to the process modelling the desire is to achieve biologically and mathematically inspired peristaltic trajectories of varying geometrical and manometric requirements. These are to be inspired from the current understanding of the esophageal swallowing process.

6 Congruence with the medical and food technology fields

Food technologists are interested in developing novel foods with predictable textural and flow characteristics to meet the demands of both healthy and dysphagic populations. The development of these types of foods has been challenging as current rheological measurements do not sufficiently relate fluid properties of the food bolus to the suitability for swallowing (Guinard and Mazzucchelli, 1996). Current research into texture modification in the food technology and medical contexts typically surrounds the use of conventional rheological and tribological measurements. These techniques have provided sufficient evidence to demonstrate weak trends in swallow elicitation and temporal features of the swallowing process.

This initiative addresses shortcomings of the current models and methods used to describe bolus formulations and their subsequent flow characteristics. In particular, the biomimetic shear field will be more realistic of that throughout human swallowing and the sensory interpretation will be conducted by methods that the body could reasonably measure and interpret. Thus, the transport paradigm consisting of the actuation, sensation, and control may all be inspired by aspects of the biological system. The interest is to mimic the process of swallowing such that manometric pressure profiles can be achieved which reflect the human swallowing behaviour.

The device will provide a platform on which bolus formulations can be tested for ease of swallowing, and will better demonstrate the flow characteristics as occur in man. It is proposed preliminarily that the device is tested on regular and medically prescribed food formulations for the safe and effective management of different forms of normal and dysphagic swallowing. This provides insight towards understanding the envelope of acceptable bolus formulations for human swallowing, and could be used to investigate properties of fluids that elicit the elusive swallowing trigger mechanism.

7   Conclusions

In the medical field, symptoms of the dysphagic swallowing process are typically mitigated by provision of TMFs. The current practice for prescription has been identified to lack a well-defined process, exemplified by the limited targeting of specific rheological effects. There is currently very little understanding towards the prediction of swallow efficacy for arbitrary bolus formulations. This arises from difficulty of isolating individual transport parameters in the biological system due to the uncontrollability of confounding factors.

The link between texture modification techniques and their resulting flow behaviour is proposed to be investigated by a biologically-mimicking swallowing robot. The process of esophageal swallowing, in man, serves as inspiration for the development of the novel food bolus investigation device. The interest is to clarify the effects of bolus constitution on rheological and tribological characteristics via a biomimetic transport process. The robotic technique facilitates exploration of the peristaltic swallowing function by empirical engineering methods. This new approach to food investigation and subsequent design is proposed to improve the rigor and scientific grounding of current food texture modification techniques.

The aspiration is to shed light on trends of transport behaviour that relate to controllable aspects of bolus formulation. It is proposed that this technique will improve the understanding of bolus interaction with the swallowing process. These methods can then be applied in the food technology and medical fields in a rigorous way to develop a protocol for the safe and effective use of TMF in the management of dysphagia. This has significant implications in the food technology and medical fields and advances knowledge of swallow-safety prediction for novel bolus formulations.

Acknowledgements

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