Dysphagia (2014) 29:685–691
DOI 10.1007/s00455-014-9562-5

ORIGINAL ARTICLE

Frequency of Stage II Oral Transport Cycles in Healthy Human

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Received: 28 March 2013 / Accepted: 23 July 2014 / Published online: 21 August 2014

Abstract Stage II transport (St2Tr) is propulsion of triturated food into the pharynx for storage before swallowing via tongue squeeze-back against the palate. To clarify the phenomenology of St2Tr, we examined the effects of food consistency and the number of chewing cycles on the number of St2Tr cycles in a chew-swallow sequence. We recorded chew-swallow sequences in lateral projection with videofluoroscopy of 13 healthy volunteers eating 6 g of hard (shortbread cookie), and soft foods (ripe banana and tofu) with barium. We counted the number of chewing and St2Tr cycles from food intake to terminal swallow. We used the Friedman test for bivariate analyses and negative binomial regression for multivariable analyses. On bivariate analysis, food consistency had a positive association with the number of chewing cycles ($P = 0.013$), but not with the number of St2Tr cycles ($P = 0.27$). Multivariable analysis, however, revealed a greater number of St2Tr cycles with hard than soft food ($P \leq 0.01$) and a trend toward negative correlation between the numbers of St2Tr and chewing cycles ($P = 0.083$). The number of chewing cycles needed to clear the mouth differs among food consistencies as demonstrated previously. Greater numbers of both St2Tr and chewing cycles were elicited with the hard than with the soft foods. Given the trend toward negative correlation, the association between the number of St2Tr cycles and that of chewing cycles deserves further study.

Keywords Deglutition · Deglutition disorders · Mastication · Swallowing · Fluoroscopy · Food · Tongue · Oral cavity

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Introduction

The processes of drinking and eating are different in many ways. Intake of liquids is traditionally described as a four-stage process including oral preparatory, oral propulsive, pharyngeal, and esophageal stages [1]. This model is not readily applicable to eating solid foods because of the complex coordination of chewing and swallowing and because chewed solid food commonly accumulates in the pharynx for five or more seconds prior to pharyngeal swallow onset [2, 3]. Normal ingestion and swallowing for solid foods require food intake, mastication, oral food transport, and swallowing. Oral food transport begins with stage I transport (St1Tr), the movement of food from the incisors to the postcanine teeth for chewing. During mastication and bolus preparation, portions of triturated (chewed) food are propelled from the oral cavity to the pharynx via stage II transport (St2Tr); its mechanism, however, is quite different from St1Tr [2, 4].

The motion pattern, “tongue squeeze-back movement (TSM)” mechanism [5], is important for bolus transport during St2Tr and the oral propulsive stage of swallowing [2, 3, 6]. It is accomplished by the anterior tongue contacting the palate and the area of tongue–palate contact expanding posteriorly to “squeeze” food back through the fauces. The fundamental difference between TSMs in St2Tr and in oral propulsive stage is timing of the following pharyngeal swallow; for St2Tr, food accumulates in the oropharynx for five or more seconds while chewing continues with no pharyngeal stage [2, 3], on the other hand, for the oral propulsive stage of swallow, TSM similarly drives the bolus to the pharynx, but the pharyngeal stage follows with little delay. Although tongue movements in St2Tr and swallowing have been described previously [2, 7], the phenomenology of St2Tr and the TSM mechanism in relation to food consistency has not been fully explored.

Mastication is essential for eating solid food. The number of chewing cycles needed to prepare food for swallowing depends on many factors (e.g., number of functional teeth, salivary flow, jaw adductor strength, and characteristics of food [8]).Individuals who use a greater number of chewing cycles for one food tend to use more chewing for other foods as well [9]. Moreover, the number of chewing cycles is dependent on the initial consistency of the food ingested [8, 10, 11]; dry, hard foods require more chewing than moist or soft foods of the same volume [11].

Food consistency influences other ingestive behaviors, as well [12–14]. High-viscosity liquid requires longer oral and pharyngeal transit times [15]. The timing of swallow initiation differs with food consistency; swallows occur earlier with liquids than triturated solid food. Furthermore, a bolus of triturated hard food stays in the valleculae for a longer time before swallowing than does soft food [16]. However, the effect of food consistency on the number of St2Tr cycles has not been reported.

In the present study, we examined the numbers of chewing, St2Tr, and total TSM cycles and their associations in a chew-swallow sequence (from food intake to terminal swallow) in healthy volunteers eating a hard food and two soft foods. We speculate that the sensory characteristics of the bolus in the oral cavity drive the initiation of TSM, as they do other oral behaviors, including mastication and swallowing. In this light, we hypothesize that the number of St2Tr cycles and total number of TSM cycles in a chew-swallow sequence will differ with initial food consistency. A secondary hypothesis is that the numbers of St2Tr and TSM cycles also vary with the number of chewing cycles, since this alters the consistency of the bolus delivered to the pharynx.

Methods

Participants

Fourteen healthy participants (mean 22 years, range 21–24 years, 9 women and 5 men) were recruited for this study. Before starting the experiment, a dentist did a clinical examination to exclude the presence of disorders of the temporo-mandibular joint or asymmetry of mastication. All had normal (Class 1) dental occlusion. None reported any history of cough, voice change, dysphagia, a major medical problem, orthodontic treatment in childhood, trouble eating or swallowing, or laryngopharyngeal or gastroesophageal reflux disease. Videofluoroscopy (VF) of a 5 ml liquid barium swallow was performed for each participant in both lateral and anterior–posterior position to confirm normal swallowing function. The protocol was approved by the Institutional Review Board of our institution. Each participant gave verbal and written informed consent prior to experimental procedures.

Data Collection

We attached small radiopaque markers on the participant’s teeth. The markers, small lead disks with 4 mm in diameter and 0.5 mm thick, were glued to the buccal surfaces of the upper and lower canines and first molars on the left side with dental cement. Fine wire electromyographic (EMG) electrodes were placed in several muscles; the EMG findings were not reported in this study.

VF was performed in lateral projection using a 12-inch image intensifier at 90 kV. Collimation was configured to obtain the image of the entire mouth and pharynx; the borders of the image were approximately the lips anteriorly, hard palate superiorly, posterior pharyngeal wall posteriorly, and cervical esophagus inferiorly. Video output was recorded using a digital video (DV) cassette recorder at 30 frames/s; a time signal was imprinted to each frame of the video. Radiation exposure time was limited to a maximum of 5 min.

Each participant was seated comfortably in a VESS Chair (C Midwest Medical LLC, Milwaukee, WI, USA) and was asked to move his or her head as little as possible during recording. The recordings were performed, while each subject consumed three samples of solid food: 6 g each of hard cookie (Pure Butter Shortbread, Walkers Shortbread Inc.), raw peeled ripe banana (soft food), and firm tofu (soft food). Banana and tofu were selected as soft foods since they differ in other respects: Banana is cohesive, while tofu is homogeneous but not cohesive. Each sample was dusted with barium sulfate (Varibar, EZ-EM Inc., Westbury, NY, USA) to enhance its radiopacity. Foods were placed in the participant’s mouth by the

Fig. 1 Graphic example of chew-swallow sequence. The sequence starts from food intake. After finishing stage I transport, first chewing starts from maximum jaw opening and ends at next maximum jaw opening. Stage II transport (St2Tr) is tongue squeeze-back movement with clear bolus propulsion beyond the posterior nasal spine, which occurs during chewing. The sequence ends when the food is cleared from the oral cavity. We counted the numbers of chewing (*boxes with dot line*, 11 times in this figure), St2Tr (*boxes with bold solid line*, two times), and swallowing cycles (*boxes with long ash dot line*, two times)

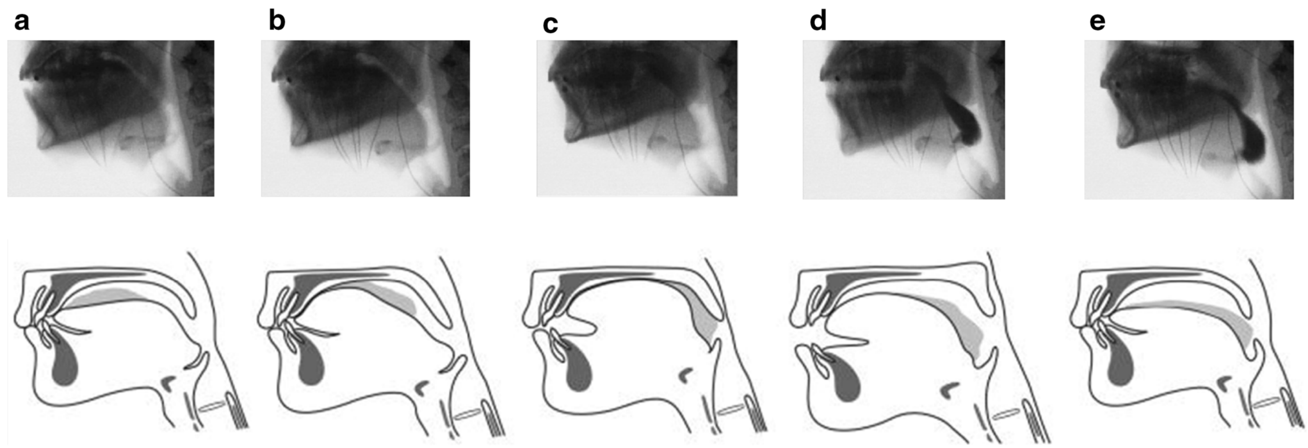

Fig. 2 Stage II transport in videofluoroscopic images and drawings. The tongue rises from the tip (**a**) and anterior surface, coming into contact with the anterior hard palate (**b**). This contact then spreads posteriorly, "squeezing" the food distally behind the contact (**c**). Then, the tongue is separated from the palate (**d**), and food bolus is positioned on the oropharyngeal surface of the tongue (**e**)

examiner. The participant was instructed to chew and swallow in his or her usual manner. Recording began immediately before food intake and finished after the final swallow with complete mouth clearance. No participant had difficulty completing the protocol.

Data Reduction and Data Analysis

VF recordings on DV cassettes were imported onto a desktop computer with digital image processing software (ImageJ, U.S. National Institutes of Health, Bethesda, MD, USA). The recordings were also reviewed in slow motion and were analyzed using the frame-by-frame stop-motion function of the software.

We counted all chewing, St2Tr, and swallow cycles during the recordings for each eating sequence, from food intake until the terminal swallow (Fig. 1). The number of St2Tr identified independently by five raters varied at first. Reanalyzing the images after discussion, we reached full agreement. The first chewing cycle was defined as beginning at the time of maximum jaw gape (jaw furthest open) just after the food was propelled to the postcanine region. Each chewing cycle ended, and the subsequent cycle started, at the time of the next maximum gape. St2Tr was defined as bolus propulsion by TSM. The anterior tongue contacts the palate at the alveolar ridge (Fig. 2a). The area of tongue–palate contact expands posteriorly (Fig. 2b), "squeezing" food back through the oral cavity and the faucial isthmus. Food is stored in the oropharynx on the pharyngeal surface of the tongue and in the valleculae for five or more seconds before swallow (Fig. 2c, d, e). We excluded cycles that included food transport but without definite TSM, because we could not be certain that these were truly St2Tr cycles and not posterior spillage from the oral cavity. We also calculated the number of TSM cycles for each participant by adding the number of St2Tr and swallowing cycles (since each swallowing cycle included an oral propulsive stage).

Statistics

To determine differences among the three foods, the data were first analyzed for normality. With a repeated measure using three food consistencies per participant, distributions of the number of chewing cycles, St2Tr cycles, and TSM cycles during whole sequences were analyzed with the Friedman test. To determine the association of both food consistency and the number of chewing cycles with the number of St2Tr cycles or TSM cycles in a chew-swallow sequence, we used a multivariable model. We performed

Table 1 Number of chewing cycles, St2Tr cycles, and swallowing cycles by participants

	Number of chewing cycles			Number of St2Tr cycles			Number of TSM cycles		
Participant	Cookie	Banana	Tofu	Cookie	Banana	Tofu	Cookie	Banana	Tofu
1	16	9	3	0	0	0	2	1	1
2	16	5	7	0	0	0	2	2	2
3	14	13	21	2	0	0	5	1	2
4	12	6	11	0	1	1	2	2	3
5	24	4	6	1	3	0	3	4	1
6	13	10	9	4	0	0	6	2	3
7	9	10	12	4	0	0	6	2	2
8	8	2	4	3	1	1	5	4	4
9	14	4	4	1	2	2	4	4	4
10	19	5	5	3	1	1	5	3	2
11	23	8	9	1	3	2	2	5	4
12	12	1[a]	7	5	8[a]	5	7	10[a]	7
13	18	8	6	6	1	3	8	2	5
Median	14	7	7	2	1	1	5	2	3
IQR	12–18	5–9	5–9	1–4	0–2	0–2	2–6	2–4	2–4

St2Tr stage II transport, *TSM* tongue squeeze-back movement, *IQR* interquartile range

[a] Excluded sequence

multivariable analyses because food consistency affects the number of both chewing cycles and St2Tr cycles; by multivariable analyses, we were able to discriminate the confounding effects of food consistency. A Poisson regression was planned a priori because dependent variables were counts and not continuous variables. Incident rate ratios (IRR) and 95 % confidence intervals (CI) were calculated for each predictor. Statistical analyses were performed using STATA version 11 (Stata Corporation, College Station, TX, USA). The critical value for *P* was set at 0.05.

Results

We excluded one participant (i.e., three chew-swallow sequences) because of a temporo-mandibular joint disorder seen on VF; thus 13 participants were included. We excluded one sequence (Participant 12, banana) as an outlier, because the frequency of St2Tr cycles was eight, greater than 3 standard deviations above the mean. A total of 38 chew-swallow sequences were analyzed (Table 1). For these sequences, the recorded swallows demonstrated no evidence of aspiration or other abnormality.

We determined mean, median, and variance in the number of chewing cycles, St2Tr cycles, and TSM cycles for each food consistency. The variances of the number of chewing cycles and St2Tr cycles were greater than the respective mean values. We chose negative binomial regression as a multivariable statistical tool because of its ability to handle the high variances in our dependent measures.

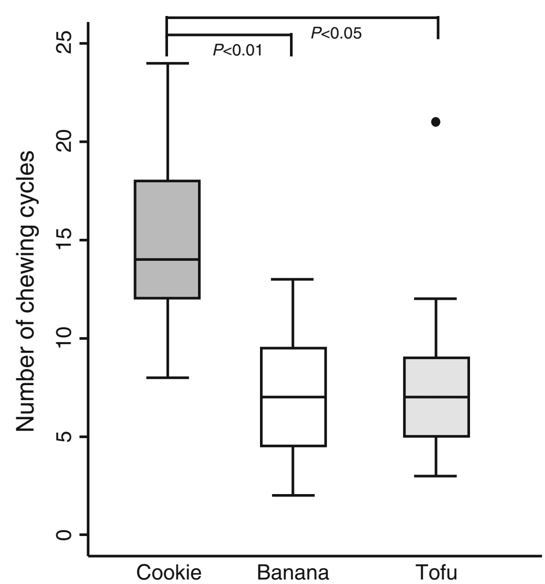

Fig. 3 Distribution of the number of chewing cycles during whole sequence. Cookie showed more chewing cycles than banana or tofu to swallow whole bolus ($P < 0.05$). The *bottom and top* of the box represent the *lower and upper* quartiles, respectively. The *line* in the box shows median value. The adjacent values, which separate the outliers from the rest of the data, are shown with the whiskers. The outliers, the *dots*, are the 25th or 75th percentiles plus 1.5 times the inter-quartile rage (IQR), which is the distance between the 25th and 75th percentiles

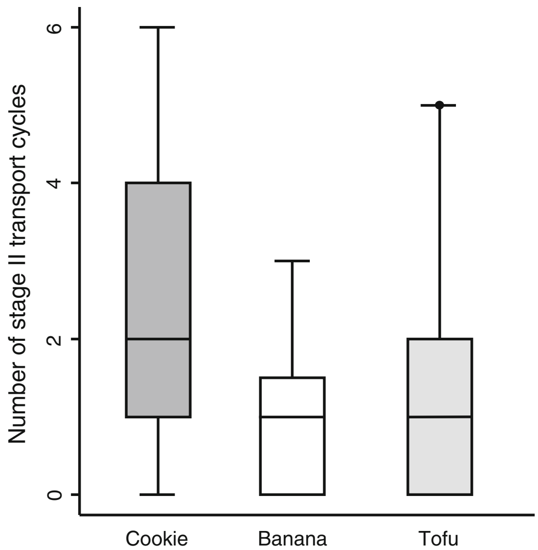

Fig. 4 Distribution of the number of stage II transport (St2Tr) cycles during whole sequence. Cookie tended to have more number of St2Tr cycles than either banana or tofu although it was not significant ($P = 0.27$)

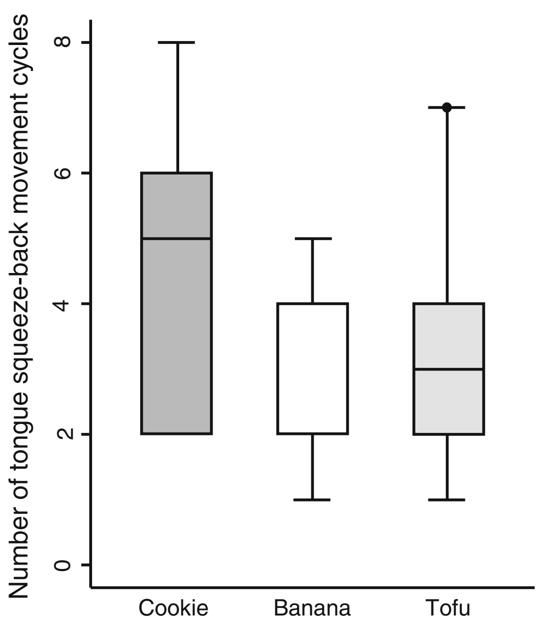

Fig. 5 Distribution of the number of tongue squeeze-back movement (TSM) cycles during whole sequence. Similar to the number of stage II transport cycles, cookie tended to have more number of TSM cycles than either banana or tofu although it was not significant ($P = 0.096$)

Bivariate Analyses for Numbers of Cycles

On bivariate analysis, food consistency had a significant association with the number of chewing cycles; there were more chewing cycles for hard than for soft foods ($P = 0.013$, Table 1; Fig. 3).

Table 2 Multivariable analysis model for the number of St2Tr cycles: effects of the number of chewing cycles and food consistency

		n	IRR (95 % CI)	*P* value
Number of chewing		38	0.92 (0.84–1.01)	0.066
Food consistency	Cookie	13	1	
	Banana	12	0.22 (0.071–0.67)	0.008
	Tofu	13	0.27 (0.095–0.76)	0.014
Model		38		0.049

St2Tr stage II transport, *IRR* incident rate ratio, *CI* confidence interval

Table 3 Multivariable analysis model for the number of TSM cycles: effects of the number of chewing cycles and food consistency

		n	IRR (95 % CI)	*P* value
Number of chewing		38	0.96 (0.92–1.01)	0.084
Food consistency	Cookie	13	1	
	Banana	12	0.56 (0.26–0.78)	0.004
	Tofu	13	0.53 (0.32–0.89)	0.015
Model		38		0.033

TSM tongue squeeze-back movement, *IRR* incident rate ratio, *CI* confidence interval

The numbers of St2Tr and TSM cycles did not vary significantly among foods on bivariate analyses (St2Tr cycles: $P = 0.27$, Table 1; Fig. 4; TSM cycles: $P = 0.096$, Table 1; Fig. 5).

Multivariable Analysis for Number of St2Tr Cycles

We performed a multivariable analysis to determine whether the number of St2Tr cycles was associated with food consistency after adjusting for the number of chewing cycles.

The multivariable analysis revealed that the number of St2Tr cycles in a chew-swallow sequence was significantly greater for hard than soft foods (banana: $P = 0.008$; tofu: $P = 0.01$ compared to cookie, Table 2) with no significant difference between banana and tofu ($P > 0.05$). After adjusting for the number of chewing cycles, there were four times more St2Tr cycles for cookie than banana, and three times more for cookie than tofu. The number of chewing cycles, however, was not significantly associated with the number of St2Tr cycles ($P = 0.066$), although there was a trend toward fewer St2Tr cycles in a sequence as the number of chewing cycles increased.

Multivariable Analysis for Number of TSM Cycles

We also performed multivariable analysis in which the total number of TSM cycles was dependent variable. The total number of TSM cycles was defined as the number of

St2Tr cycles plus the number of swallows in a recording, since each swallow included an oral propulsive stage with TSM mechanism. The findings mirrored the results of the multivariable analysis for St2Tr cycles; the number of TSM cycles was significantly associated with food consistency (banana: $P = 0.004$; tofu: $P = 0.015$ compared to cookie and $P > 0.05$ compared with banana, Table 3) but not with the number of chewing cycles ($P = 0.084$). The number of TSM cycles was approximately two times greater for cookie than for the soft foods, after adjusting for the effect of the number of chewing cycles.

Chewing Cycles and St2Tr Cycles by Participant

Inter-individual variability in the numbers of chewing cycles and St2Tr cycles per chew-swallow sequence was substantial (Table 1) but was not analyzed statistically due to high heterogeneity of the data.

Discussion

The numbers of chewing, St2Tr, and TSM cycles in a chew-swallow sequence were clearly higher for hard food than for soft foods in our study. Greater number of mastication cycles for hard food has been shown previously [8, 10, 11]. After correcting for the number of chewing cycles, initial food consistency was significantly associated with the number of St2Tr cycles and the number of TSM cycles (including oral propulsive stage of swallow) needed to clear the mouth. There was a non-significant trend toward fewer St2Tr cycles as the number of chewing cycles increased.

We suggest that receptors in the tongue and the palate collect the sensory information about bolus consistency during TSM when the bolus is squeezed between the tongue and the palate. It is known that there are some sensory inputs from the oral cavity during mastication [17–19]. Tongue contact with the hard palate during TSM is longer than during mastication or other food intake behaviors. It follows, then, that more sensory information about the compressed bolus might be collected from both the tongue and the hard palate. TSM may be followed by another chewing cycle or by a pharyngeal stage of swallowing. We suggest that information about the bolus is sent to the medullary swallowing center during TSM. If the bolus has not been sufficiently reduced to permit safe swallowing, further mastication will follow. This TSM behavior is called “St2Tr.” Conversely, if the bolus has been well triturated and is considered ready for swallowing, a pharyngeal swallow is initiated.

The higher number of chewing cycles results in smaller food particles and more mixing with saliva producing a bolus that is less viscous and presumably easier to transport from the oral cavity to the pharynx. This could potentially explain the reduced number of St2Tr cycles in sequences with greater numbers of chewing cycles, which was a trend but not statistically significant in this study.

We think that some people tend to have more St2Tr and some have less. The number of participants in this study was appropriate for testing the primary hypothesis but was inadequate for a statistical analysis of the differences in the number of St2Tr among participants (Table 1). It is known that there are substantial between-participant differences in the number of chewing cycles [9]. It has been shown that St2Tr is subject to modification by volition [6]. We need further studies with larger groups of participants to clarify whether this reflects meaningful biological differences among individuals.

Participants consumed 6 g samples of each food in the present study. Prior research in our laboratory showed this size was sufficient to consistently elicit mastication [20, 21]. Although our data suggests that bolus characteristics may affect the number of St2Tr cycles, we did not analyze the physical characteristics of the foods in this study. Moreover, as the number of participants and trials were limited, the statistical power of the study may not have been sufficient to detect differences between banana and tofu. Further study is indicated, including analysis of food characteristics and larger sample.

We found that it was important to have a group discussion to confirm the criteria for St2Tr. Individual difference is common when evaluating oral phase in VF [22]. It is known that group discussion raises reliability in scoring a swallowing study [23]. Further study should be driven to improve reliability and accuracy.

Conclusion

These data suggest that the original food consistency affects the number of chewing and St2Tr cycles used to clear the oral cavity. There might be some sensory inputs during mastication and during TSM. The association between the bolus characteristics and the number of St2Tr cycles deserves future study. Since hard food requires more cycles of chewing and St2Tr, careful consideration should be given to food consistency when planning diets for people with an impaired oral function.

Acknowledgments The late Dr. Karen Hiiemae immensely contributed this work. We would like to thank Chune Yang for her extraordinary support and assistance. We appreciate the comments on the manuscript offered by Drs. Rebecca Z. German and Ianessa Humbert.

Conflict of interest This research was supported in part by NIH/NIDCD award No. R01-DC02123. We presented this study at the

20th Annual Meeting of Dysphagia Research Society, Toronto, Canada, March 7–10, 2012. All authors have no financial conflict of interests to disclose concerning the research.

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