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RESEARCH ARTICLE

Real-time MRI of swallowing: intraoral pressure reduction supports larynx elevation

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The reduction in intraoral pressure during swallowing has previously been linked to bolus transport, although no such relation has yet been proven. The purpose of this work was to evaluate the time course of intraoral pressure during swallowing using simultaneous real-time magnetic resonance imaging (MRI) and dynamic pressure recordings. Real-time MRI based on highly undersampled radial fast low-angle shot (FLASH) and regularized nonlinear inverse reconstruction was performed at 3 T using a standard head coil and a mid-sagittal section covering the entire oral cavity. Voluntary swallowing (10 mL of pineapple juice or saliva) was monitored for about 30 s in 11 normal subjects at spatial and temporal resolution of $1.3 \times 1.3 \times 8\ \mathrm{mm}^3$ and 40 ms, respectively. Simultaneously, the intraoral atmospheric pressure was recorded at a resolution of 10 ms during the entire course of deglutition. Quantitative measures of bolus transport, larynx elevation and submental muscle changes were obtained from the image series. As a key result, negative intraoral pressure accompanied laryngeal elevation during swallowing in all subjects. A reduction in submental muscle length during swallowing was also observed. No correlations of maximum negative pressure with larynx elevation and submental muscle change were found. In conclusion, intraoral pressure reduction during swallowing is not connected to oral bolus transport, but supports laryngeal elevation by palatal fixation of the tongue.

KEYWORDS

intraoral pressure, larynx elevation, real-time MRI, swallowing

1 | INTRODUCTION

The physiology of the human swallowing process has not yet been fully clarified. For example, to date, intraoral manometry of the isometric tongue pressure or atmospheric pressure in the oral cavity[1,2] has been discussed exclusively within the context of oral bolus transport. Pushing the bolus is seen as the tongue's main task and a gradient of negative atmospheric intraoral pressure has been suggested to support bolus transport.[3,4] However, a pressure gradient has never been proven experimentally and the functional context of a negative intraoral pressure during swallowing still remains an open question. An unambiguous identification of the time course of events during swallowing therefore requires an intraoral atmospheric pressure measurement in synchrony with dynamic visualization of the functional anatomy during deglutition.

Previous methods chosen to monitor swallowing processes present with specific drawbacks unable to resolve the above-mentioned uncertainty. X-Ray videofluoroscopy visualizes the course of deglutition, but suffers from a limited display of soft tissues, a lack of quantitative dimensional measures and the issue of radiation exposure. Ultrasonography is not well suited for the most instructive sagittal view of the oropharyngeal tract, which is necessary to describe the process of deglutition.[5] Finally, flexible endoscopic evaluation of swallowing (FEES) cannot depict the oral phase and has a ‘white out’ during crucial swallowing events.[6,7].

More recently, advances in the development and application of real-time magnetic resonance imaging (MRI)[8] have allowed for arbitrary noninvasive and repetitive views of the oropharyngeal tract and its functional anatomy, as demonstrated, for example, in studies of the articulators during normal speech at an in-plane resolution of

Abbreviations used: FEES, flexible endoscopic evaluation of swallowing; FLASH, fast low-angle shot; FOV, field of view; fps, frames per second; MRI, magnetic resonance imaging; NLINV, nonlinear inversion; RF, radiofrequency; ROI, region of interest

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1.5 mm and temporal resolution of 33 ms.[9] This new method offers novel insights into the process of deglutition and has already been proven to be a highly valuable diagnostic tool for swallowing and dysphagia.[10–12] The present study aims to combine real-time MRI recordings at a resolution of 40 ms or 25 frames per second (fps) with intraoral manometry to newly investigate the role of intraoral pressure changes during the complete course of swallowing. The simultaneous recordings of both measures are expected to provide better insight into the role of negative intraoral pressure in healthy subjects.

2 | MATERIALS AND METHODS

This study was approved by the institutional review board of the University Medical Center Göttingen and all participants gave written informed consent before MRI. Eleven healthy volunteers (seven men, four women; age, 26.5 ± 4.9 years; range, 19–34 years) were recruited from the local university. MRI was conducted on a commercial 3-T MRI system (Prisma Fit, Siemens Healthcare, Erlangen, Germany) using the standard 64-channel head coil. For manometric measurements, a pressure sensor ('GMSD 2 BR', Greisinger Electronic GmbH, Regenstauf, Germany) was connected to a computer through a USB-adapter ('GDUSB', Greisinger Electronic GmbH). The pressure sensor measured relative pressure within the range of −150 to 262 mmHg with a resolution of 0.075 mmHg. The relative pressure was recorded using in-house acquisition software. The pressure recordings were acquired at 100 Hz (every 10 ms) during the MRI measurement. A trigger signal from the MRI scanner was used to synchronize real-time MRI acquisitions and pressure recordings.

2.1 | Real-time MRI

Real-time MRI was based on highly undersampled radial fast low-angle shot (FLASH) acquisitions with image reconstruction by temporally regularized nonlinear inversion (NLINV).[8,13,14] T_1-weighted radiofrequency (RF)-spoiled images were continuously acquired with the following parameters: TR = 2.10 ms; TE = 1.33 ms; flip angle, 8°; field of view (FOV), 192 × 192 mm^2; in-plane resolution, 1.3 × 1.3 mm^2; slice thickness, 8 mm. The use of 19 spokes yielded a temporal resolution of 40 ms, corresponding to 25 fps. Any series of five successive frames of the dynamic acquisition employed complementary sets of 19 spokes (i.e. sequentially and uniformly shifted against each other). Online image reconstruction was realized with a highly parallelized version of the NLINV algorithm[15] and a 'bypass' server ('sysGen/TYAN Octuple-GPU', Sysgen, Bremen, Germany) equipped with eight graphical processing units (GeForce GTX 580, TITAN, Nvidia, Santa Clara, CA, USA). This server was fully ('invisibly') integrated into the reconstruction pipeline of the commercial MRI system to avoid the need for any user interference.

2.2 | Study protocol

During MRI, subjects lay in the supine position. For pressure measurements, a small tube with an internal diameter of 1 mm was placed between the tongue and hard palate. This tube (length, 7 m) was connected to the pressure sensor which was placed outside the MRI chamber to avoid any impact of the magnetic field on the pressure measurement.

For bolus application (10 mL of pineapple juice), a second tube was connected to a syringe and placed into the mouth. In order to avoid any loss of relative pressure recordings during the swallowing process, the subjects were instructed to perform swallowing with closed lips. In addition, familiarization with MRI and swallowing in the supine position was accomplished by allowing 5–10 min of practice before the actual measurements, whilst lying on the patient table, but outside the magnet. The protocol consisted of a single bolus application to be swallowed, followed by several 'dry' swallowing maneuvers (saliva) by each subject. The single bolus was given manually from a specialist (MD) who ensured the safety and soundness of the procedure. The protocol for each measurement (duration, 30 s) consisted of an initial rest phase (5 s), bolus collection in the oral cavity (5 s) and voluntary swallowing of the entire bolus.

For each subject, five measurements were performed in sagittal, transverse and coronal orientation, including two sagittal repetitions. As a result of inadequate bolus information from large movements of the laryngo-pharyngeal tract in the longitudinal and sagittal direction, the measurements on the transverse and coronal orientations were subsequently discarded. Furthermore, one sagittal measurement was chosen for the analysis to ensure both appropriate MRI visualization of the swallowing process and reliability of the observed pressure change by excluding compromised events caused by imperfect closure of the lips.

2.3 | Data evaluation

Every 30-s measurement resulted in 750 real-time images and 3000 synchronized pressure measurements. Figure 1 shows an example comprising selected frames of a real-time MRI movie which correspond to specific phases of the swallowing process. For each image, the area of the oral bolus (cm^2), the elevation of the larynx (mm) and the length of the submental muscle (mm) were manually quantified in the sagittal plane using the region of interest (ROI) tool from the DICOM-viewer Osirix® (Pixmeo SARL, Bernex, Swiss). The extent of the bolus was determined by surrounding the contrasted area in the oral cavity in every single frame from the onset of bolus filling to the end of its appearance. The elevation of the larynx was measured between the most caudal and most cranial location of the 'epiglottic petiole', and the length of the submental muscle was measured from its minimum to maximum extension during swallowing. For data analysis, the maximum negative pressure was chosen, as most subjects performed a single major swallow as well as one or more smaller swallows to clear the bolus. In all cases, the evaluation focused on the main swallowing event which was accompanied by the maximum negative pressure.

To compare swallowing events within and across subjects, all recordings were synchronized to the moment of oro-velar opening defining a zero time point. Subsequent averaging across subjects was performed to illustrate the temporal relationship of individual swallowing events and to allow for the calculation of respective mean values. Regression analyses between maximum negative pressure, larynx elevation and submental muscle change were performed using the Analysis Toolbox of Excel® (Microsoft, USA, Redmond, WA, USA) with $p < 0.05$ considered to be significant.

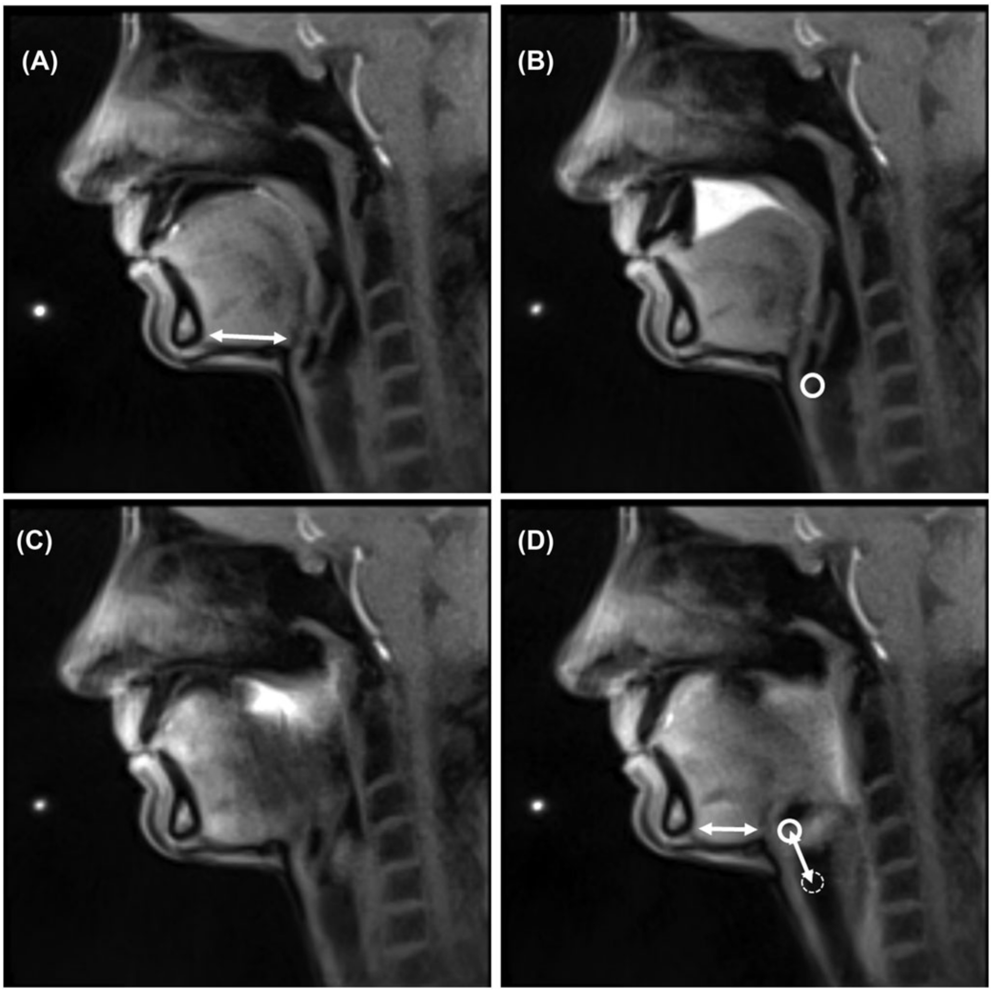

FIGURE 1 Selected frames of a real-time magnetic resonance imaging (MRI) movie of normal swallowing: A, start of bolus filling; B, end of bolus filling (4.72 s later) before elevation of the larynx; C, shortly after the start of voluntary swallowing (0.68 s later) with partial elevation of the larynx; D, end of bolus transport (0.40 s later) with full elevation of the larynx. (a, d) The length of the submental muscle is marked by a horizontal line with arrows. (b, d) The 'epiglottic petiole' is indicated by solid circles. (d) Laryngeal elevation is indicated by a line between the solid and dotted circles

3 | RESULTS

Real-time MRI of 11 subjects resulted in a total of 35 swallowing events, i.e. 11 swallows with bolus and 24 swallows of saliva (one to four per subject). As an example, real-time MRI of the entire course of swallowing in a single subject is shown in Movie S1. Intraoral pressure measurements were obtained in all 11 subjects. Each single swallow was tightly accompanied by elevation of the larynx. In addition, larynx elevation was directly related to a negative intraoral pressure in eight of 11 cases for bolus swallowing and in 19 of 24 cases for saliva transport. Figure 2 depicts the time courses for bolus transport, laryngeal elevation and intraoral pressure for swallowing a bolus (left) or saliva (right). The diagrams refer to both a single subject (bottom row) and corresponding group results averaged across subjects (top row). Quantitative measures of intraoral pressure, duration of swallowing and percentage change of submental muscle length are summarized in Table 1.

A negative intraoral pressure was only seen during swallowing. Its appearance was in close temporal relationship to laryngeal elevation, but not to oral bolus transport. The latter was completed after one swallow in all subjects, despite intra-individual differences during the course of filling and emptying of the oral cavity. Laryngeal elevations were essential for and strongly connected to swallows with and without a bolus. However, the scatter plots depicted in Figure 3 support no significant correlation between the maximum negative pressure in the oral cavity and the extent of laryngeal elevation with the degree of submental muscle change. This finding is in line with the anatomical variability of the human oropharyngeal tract across subjects. A total of eight of 35 laryngeal elevations were seen without the appearance of negative intraoral pressures.

4 | DISCUSSION

This study combined intraoral pressure measurements with real-time MRI of swallowing and, for the first time, provides simultaneous information about the morphological and functional aspects of deglutition. The observation that every single swallow in all subjects is linked to elevation of the larynx clearly confirms its role as an essential precondition for swallowing.[6] In addition, however, this study demonstrates that every negative intraoral pressure is accompanied by larynx elevation, whereas no such negative pressure event is necessarily required for bolus transport.

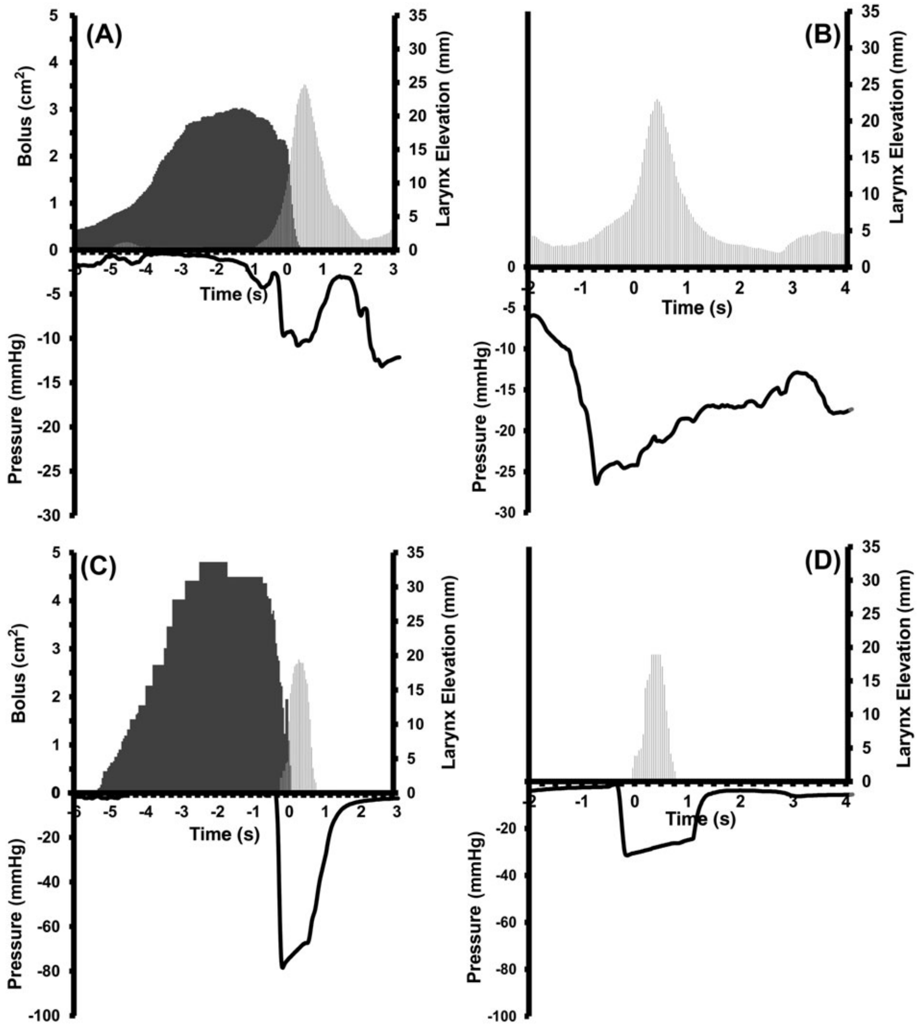

FIGURE 2 Bolus transport, laryngeal elevation and intraoral pressure during swallowing for a bolus (a, c) and saliva (b, d). (a, b) Mean values averaged across subjects (bolus, n = 11; saliva, n = 24). (c, d) Data for a single subject. All events were synchronized to the oro-velar opening (zero time)

TABLE 1 Intraoral pressure and real-time magnetic resonance imaging (MRI) findings during swallowing

Swallowing	Bolus (n = 11)	Saliva (n = 24)
Oral pressure (mmHg)		
Mean ± SD	−25 ± 26	−37 ± 33
Range	12 to −79	2 to −109
Duration (s)	4.6 ± 2.0	3.3 ± 2.0
Bolus (cm^2)	3.0 ± 1.4 (n = 35)	
Laryngeal elevation (mm)	27 ± 5	25 ± 5
Shortening of submental muscle (%)	−29 ± 6	−28 ± 9

SD, standard deviation.

Negative intraoral pressure was seen during maximum contact of the dorsum of the tongue against the hard palate. In this situation, the tongue is not pressed but sucked against the hard palate. This tongue fixation supports laryngeal elevation caused by a synergistic system of muscles consisting of lingual and infra-hyoid (external laryngeal) muscles chained by the hyoid bone. Swallowing without the use of the lingual muscle system, i.e. after laryngeal elevation without negative intraoral pressure, was observed in eight of 35 cases. In these events, the styloidal muscles (stylo-pharyngeal connected to the larynx,[16] stylo-glossal and stylo-hyoidal connected to the hyoid bone[17]) and submental muscles connected to the hyoid bone enabled elevation of the larynx, as sketched in Figure 4. These latter muscles represent the usual view of elevators of the larynx, as recently re-evaluated by conventional MRI.[18] These standard laryngeal elevators could be seen as synergistic or, in the case of lingual incompetency, compensatory to the lingual muscle system presented here.

A possible limitation of this study was the unavoidable use of a supine position for swallowing during real-time MRI. This may relieve laryngeal elevation caused by the altered impact of gravitation which, in turn, may contribute to the variability of negative intraoral pressures when compared with the rather constant pressure conditions in a sitting position.[2] In addition, the bolus itself may have affected the swallowing process in some volunteers, so that more physiological deglutition maneuvers may be expected during ('dry') swallowing of saliva. Finally, the observed inter-subject differences in performance restricted the MRI and pressure analysis to a single major swallow, which precluded a more standardized test–retest evaluation.

In conclusion, the purpose of the tongue during deglutition is not just to push the bolus, but to support laryngeal elevation in

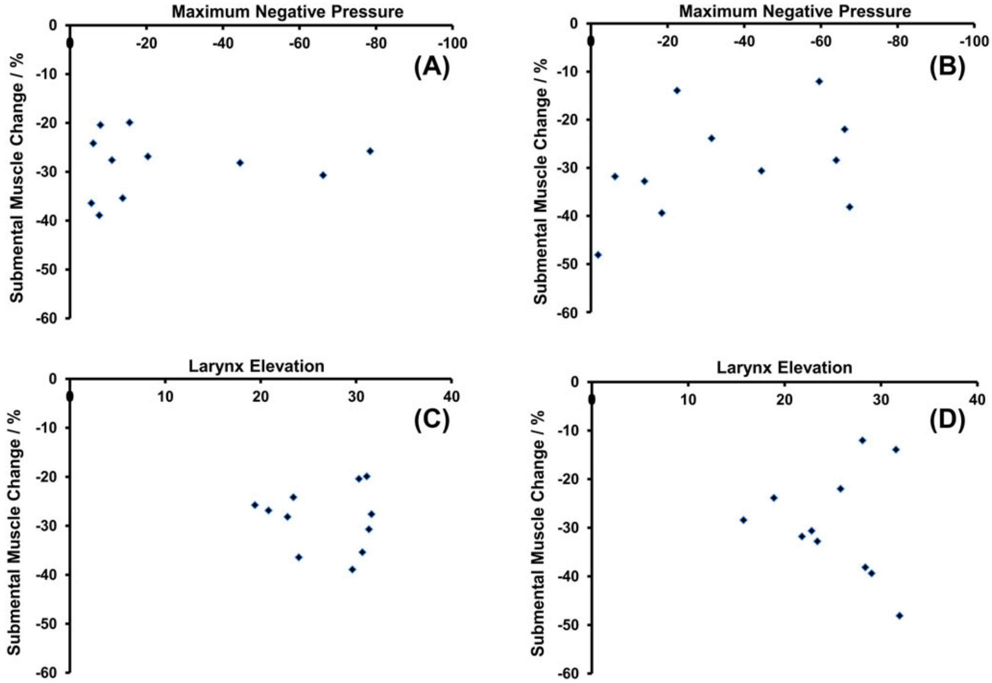

FIGURE 3 Maximum negative intraoral pressure (MNP) and larynx elevation (LE) reveal no significant correlation with submental muscle change (SMC) during swallowing of a bolus (MNP *versus* SMC, p = 0.78; LE *versus* SMC, p = 0.84) (a, c) and saliva (MNP *versus* SMC, p = 0.22; LE *versus* SMC, p = 0.73) (b, d)

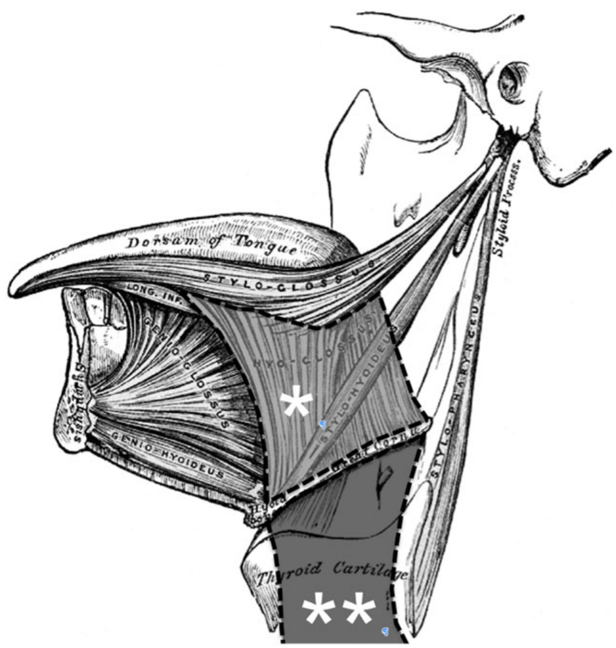

FIGURE 4 Modified lingual muscle system after Gray[17] with the hyoglossus* and the thyro-hyoid muscle**. They act in concert with the styloidal (stylo-glossus, stylo-hyoideus and stylo-pharyngeus muscle) and mental muscles (genio-glossus and genio hyoideus muscle) as the usually considered elevators of the larynx[17]

order to facilitate swallowing. Our finding of tongue fixation to the hard palate by suction complements, rather than contradicts, the conventional view on the styloidal and submental muscle system generally thought to ensure laryngeal elevation during swallowing. In dysphagia caused by structural or functional intraoral lesions, this knowledge could lead to a better understanding of the pathophysiology, and potentially improve the search for the best therapeutic strategy and rehabilitation.

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SUPPORTING INFORMATION

Additional Supporting Information may be found online in the supporting information tab for this article.

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