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Automated Assessment of Test of Masticating and Swallowing Solids Using a Neck-Worn Electronic Stethoscope: A Pilot Study

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ABSTRACT

Background: The Test of Masticating and Swallowing Solids (TOMASS) is a validated screening tool for assessing masticatory and swallowing functions. However, the conventional TOMASS relies on operator-dependent methods, which limit its objectivity and efficiency. The neck-worn electronic stethoscope (NWES), a contact sensor positioned on the back of the neck, has recently been developed to automatically detect and monitor swallowing actions through deep learning-based analysis of collected sound data.

Objective: This study piloted a semi-automated assessment approach using a NWES to objectively measure TOMASS parameters and examine the influence of age and gender.

Methods: A total of 123 healthy adults (mean age: 58.7 ± 18.5 years) consumed two crackers while audio data recorded using a NWES and visual data were collected by smartphone. Measurements included discrete bite count, swallow count, oral processing and swallowing time (OPST), and first OPST (1st-OPST). Statistical analyses were conducted to assess gender- and age-related changes and differences.

Results: The NWES enabled objective and precise TOMASS measurements. Age-related prolongation of OPST and 1st-OPST was observed, particularly in men ($p < 0.001$). Women exhibited fewer age-related changes in OPST, although swallow count tended to decrease with age ($p < 0.001$). Regarding gender differences, younger women demonstrated higher bite (2.3 [interquartile range (IQR): 1.0–3.0] vs. 1 [IQR: 1.0–2.0], $p = 0.042$) and swallow counts (2.5 [IQR: 2.0–2.5] vs. 2 [IQR: 1.0–2.0], $p = 0.026$) compared with men.

Conclusion: The NWES appeared suitable as an objective, efficient tool for automated TOMASS evaluation. Age-related changes in masticatory and swallowing performance differed according to gender, highlighting the need for tailored assessments. Future research on NWES-based TOMASS measurements should include diverse populations and extension to dysphagia and masticatory dysfunction.

1 | Introduction

The physiological mechanisms underlying bolus transport from the oral cavity to the pharynx differ substantially between the ingestion of liquids and solid food [1]. Whereas a liquid bolus is typically held in the oral cavity until the voluntary initiation of swallowing, chewed solid food particles are progressively transported to the oropharynx, which often remains open during mastication. The bolus may even reach the vallecula prior to the onset of swallowing [1]. These distinct transport patterns indicate that the evaluation of abnormal liquid or solid intake should be conducted separately in reflection of the underlying physiological differences.

Various screening protocols for dysphagia have been developed using water swallowing tests [2]. These typically involve instructing patients to swallow some amount of liquid, followed next by clinical observation for signs such as coughing or wet voice, which may indicate aspiration or penetration. In contrast, assessments of masticatory function have emerged from dental research and clinical settings, utilising test materials such as gummy jellies, peanuts, or silicone test tubes [3–5]. Patients are typically instructed to chew the material as directed and expel it for analysis. Although these tests are widely used in dental and dysphagia clinical settings, there remains a lack of standardised screening methods to assess the natural process of eating that combines both the masticatory and swallowing functions involved.

The Test of Masticating and Swallowing Solids (TOMASS) is one of the few available screening tools to evaluate the mastication and swallowing processes for solid food [6]. The TOMASS measures the number of discrete bites and swallows, as well as the total time required to consume a piece of cracker. The validity of this test has been established in healthy adults, older adults, children, and patients with dysphagia [6–12]. Although the TOMASS can reliably evaluate the process of mastication and swallowing, its measurement relies on visual observation and palpation to count bites and swallows, with timing measured manually using a stopwatch [6]. These actions depend heavily on the operator's skill, have variable objectivity, and are time-consuming. Additionally, conventional TOMASS measurements often rely on manual timing and visual observation to detect the first bite and onset of swallowing, which may introduce ambiguity and limit reproducibility.

The neck-worn electronic stethoscope (NWES) is a novel device that utilises real-time audio activity processing algorithms and deep learning techniques to analyse sound information obtained through electronic cervical auscultation. This smartphone-based device is worn around the neck and uses a piezoelectric vibration sensor constructed as a contact microphone to automatically detect swallowing sounds during the consumption of food, liquid, or saliva. The feasibility of the NWES for swallowing a liquid bolus has been reported in healthy individuals [13, 14] and in a small sample of patients with dysphagia [15]. However, there have been no reports validating the NWES for eating solid food. This study serves as a preliminary investigation into the feasibility of using the NWES to detect sounds associated with the processes of mastication and swallowing.

To address the limitations of the conventional TOMASS test, this study explored a novel evaluation method using a NWES to automate TOMASS measurements and enhance objectivity. In addition, while the impact of age and gender on masticatory and swallowing functions has been previously investigated [16, 17], their influence on TOMASS measurements with a NWES has not been fully examined. Accordingly, this study also explored the effects of age and gender on TOMASS test outcomes.

2 | Materials and Methods

2.1 | Participants

The participants for this study were recruited through advertisements in local newspapers and community-wide communications. A total of 123 healthy adults who consented to participate were included. The study was conducted with approval from the Ethics Committee of Tokyo University of Science (D2021-015) and University of Tsukuba (2022R710). The inclusion criteria for this study were age 20 years and older, no history or current symptoms of dysphagia, and no cognitive impairments. Candidates were excluded if considered inappropriate by the research team. All participants provided self-reported data regarding age, gender, number of teeth, and the presence or absence of dentures by a written questionnaire.

2.2 | TOMASS Test

First, the patient donned a NWES around the anterior neck between C2 and C5 (Figure 1). Sound information was recorded on a smartphone (Nexus 5X, Android 8.1.0, LG electronics) via a wired connection, and the recorded data were securely uploaded to cloud storage (Microsoft Azure, Microsoft). We also captured close-up video footage using the smartphone's camera to verify cracker pick-up and consumption.

The TOMASS measurements were conducted in accordance with the original methodology [6]. Two pieces of commercially available crackers (3 g per cracker, 47 × 47 × 3 mm, Nabisco Premium Crackers, Mondelez Japan) were provided for each participant. These crackers have been validated for use in TOMASS protocols in a previous study [6]. Both cracker chewing data were used for the statistical analysis. Participants were instructed to eat one cracker at a time, repeating the process twice, and to verbally indicate completion by saying "Finished." While the subject consumed the cracker, the NWES recorded swallowing sound signals as the smartphone video recorded the process.

2.3 | Data Reduction

Recorded audio data from the NWES and video data from the camera were manually integrated by a human coder by aligning the audio-video data corresponding to the utterance "Finished" using analysing software (ELAN version 6.6, Max Planck Institute for Psycholinguistics) to synchronise and annotate the audio and video recordings (Figure 2).

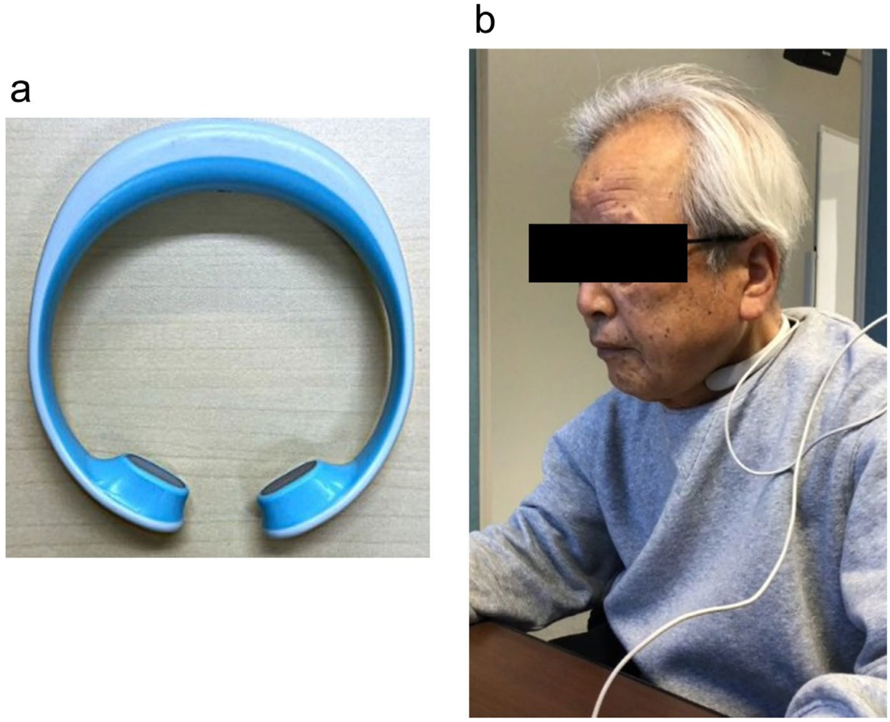

FIGURE 1 | Measurement procedure. A neck-worn electronic stethoscope consisting of a piezoelectric vibration sensor (a) was worn around the neck and connected to a smartphone (b). The vibration sensor was positioned on the anterior side neck to record audio data.

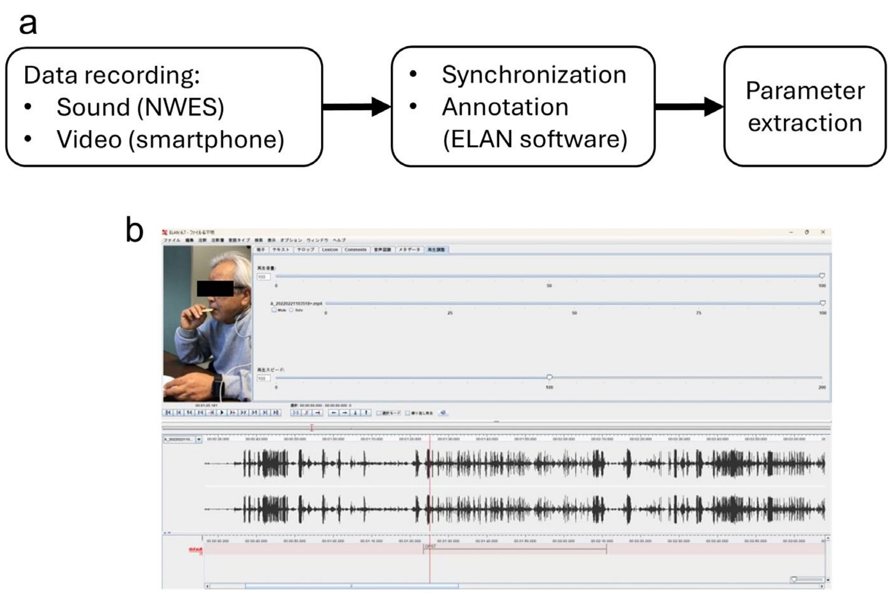

FIGURE 2 | Data analysis. (a) Flow diagram showing the analysis process. Audio was recorded using a neck-worn electronic stethoscope (NWES), and video was taken with a smartphone. The data were synchronised and annotated using dedicated software (ELAN) to extract Test of Masticating and Swallowing Solids parameters. (b) Recorded NWES audio data and video data were integrated and analysed using ELAN software. Example of annotated audio and video data using ELAN. The upper waveform represents audio data captured by the NWES, showing chewing and swallowing sounds. The lower panel displays manually annotated events, such as the first bite and subsequent swallows, synchronised with the audio and video timelines.

The following parameters were assessed by the software:

1. Discrete bite count: The total number of bites required to consume a single cracker was counted by the human coder using the video recordings.
2. Swallow count: The number of swallows required to finish a single cracker was counted using the video recordings and audio waveforms from the analysing software.
3. Oral processing and swallowing time (OPST): The duration from the initial sound of biting the cracker to the onset

of verbal indication of completion was measured using the video recordings and sound waveforms from the analysing software.

4. First oral processing and swallowing time (1st-OPST): The duration from the initial sound of biting the cracker to the onset of the sound associated with the first swallow was determined using the video recordings and sound waveforms from the analysing software.

All measurements were performed by a single experienced examiner. While age and gender information were not explicitly provided to the coder during the analysis, the synchronised video data included facial images (as shown in Figure 2b), which may have allowed the coder to infer participant characteristics.

2.4 | Statistical Analysis

Categorical variables were expressed as the number and percentage, while continuous variables were presented as the median and interquartile range (IQR). Participants were stratified into four age groups: 20–39 years (Young group), 40–59 years (Middle group), 60–79 years (Young-old [Y-Old] group), and 80 years or older (Old-old [O-Old] group). The normality of data distribution was assessed using the Shapiro–Wilk test. For comparisons according to age group or gender, either the Kruskal–Wallis test or analysis of variance (ANOVA) was used depending on data distribution normality. The Dunn test with Bonferroni correction was employed for post hoc comparisons. Statistical analysis was conducted using IBM SPSS Statistics version 28.0 software (IBM Corporation). A p-value < 0.05 was considered statistically significant.

3 | Results

The characteristics of the 123 participants are presented in Table 1. Mean age was 58.7 ± 18.5 years, and 61 participants (49.6%) were female. The Young group consisted of 21 participants, the Middle group 39, the Y-Old group 43, and the O-Old group 20. Regarding tooth number, 7 participants (5.7%) were edentulous, 4 (3.3%) had 1–9 teeth, 8 (6.5%) had 10–19 teeth, and 104 (84.5%) had 20 or more teeth. Twenty-six participants (21.1%) reported using dentures.

Table 2 presents the descriptive statistics for each parameter categorised by age group and gender. The discrete bite count of men in the Y-Old group (2 [IQR: 1.5–3.0]) was significantly higher than in the Young (1 [IQR: 1.0–2.0], $p = 0.042$) and Middle (1 [IQR: 1.0–1.5], $p < 0.001$) groups. Men in the O-Old group also exhibited a significantly higher discrete bite count (2 [IQR: 1.0–3.0]) than those in the Middle group ($p < 0.001$). No significant differences were observed among age groups for women. Regarding gender differences, women had a significantly higher discrete bite count in comparison to men in the Young ($p = 0.042$) and Middle ($p < 0.001$) groups, with no remarkable differences in the Y-Old and O-Old groups.

In swallow count analysis, no significant differences were noted for men across age groups (Table 2). However, women in the Y-Old (1.5 [IQR: 1.0–1.5]) and O-Old (1 [IQR: 1.0–1.5]) groups demonstrated significantly lower swallow count compared with the Young (2.5 [IQR: 2.0–2.5]) and Middle (2 [IQR: 1.5–2.3]) groups (all $p < 0.001$). Gender comparisons indicated that women had significantly higher swallow count versus men (2 [IQR: 1.0–2.0]) in the Young group ($p = 0.026$), whereas men (2 [IQR: 1.0–3.0]) swallowed significantly more than women in the O-Old group ($p = 0.021$).

Regarding OPST, men in the O-Old group (36.1 [IQR: 31.5–44.3]) exhibited significantly longer OPST versus the other three groups (Young: 30.8 [IQR: 18.8–41.6], $p = 0.027$; Middle: 24.0 [IQR: 20.4–32.4], $p < 0.001$; Y-Old: 26.2 [IQR: 23.5–33.4], $p = 0.006$) (Table 2). No significant differences were observed among age groups for women. In gender comparisons, women in the Middle (37.9 [IQR: 34.8–45.9]) and Y-Old (36.5 [IQR: 29.8–42.4]) groups had significantly longer OPST values than men

TABLE 1 | Demographic information of participants ($N = 123$).

	Young group	Middle group	Young-Old group	Old-Old group
	($n = 21$)	**($n = 39$)**	**($n = 43$)**	**($n = 20$)**
Gender				
Male	11 (52.4%)	19 (48.7%)	21 (48.8%)	11 (55.0%)
Female	10 (47.6%)	20 (51.3%)	22 (51.2%)	9 (45.0%)
Number of teeth				
0 teeth	0 (0.0%)	0 (0.0%)	4 (23.5%)	3 (7.7%)
1–9 teeth	0 (0.0%)	0 (0.0%)	2 (5.1%)	2 (11.8%)
10–19 teeth	1 (4.8%)	0 (0.0%)	3 (7.7%)	4 (23.5%)
20 + teeth	20 (95.2%)	39 (100.0%)	34 (87.2%)	11 (64.7%)
Dentures				
Yes	0 (0.0%)	1 (2.6%)	15 (34.9%)	10 (50.0%)
No	21 (100.0%)	38 (97.4%)	28 (65.1%)	10 (50.0%)

TABLE 2 | Descriptive statistics for each parameter categorised by age group and gender.

	Young group (n = 21)			Middle group (n = 39)			Young-Old group (n = 43)			Old-Old group (n = 20)			Age group p-value**
	Median	IQR		Median	IQR		Median	IQR		Median	IQR		
Discrete bite count													
Men	1	(1.0–2.0)	*	1	(1.0–1.5)	*	2	(1.5–3.0)		2	(1.0–3.0)		< 0.001[bde]
Women	2.3	(1.0–3.0)		2.5	(1.8–3.0)		2.8	(2.0–3.0)		2.5	(1.5–3.0)		0.552
Swallow count													
Men	2	(1.0–2.0)	*	1.5	(1.0–2.0)		1.5	(1.0–2.0)		2	(1.0–3.0)	*	0.339
Women	2.5	(2.0–2.5)		2	(1.5–2.3)		1.5	(1.0–1.5)		1	(1.0–1.5)		< 0.001[bcde]
OPST (sec)													
Men	30.8	(18.8–41.6)		24.0	(20.4–32.4)	*	26.2	(23.5–33.4)	*	36.1	(31.5–44.3)		< 0.001[cef]
Women	34.4	(29.3–43.3)		37.9	(34.8–45.9)		36.5	(29.8–42.4)		37.5	(32.8–42.9)		0.403
First OPST (sec)													
Men	17.3	(15.1–31.0)		20.0	(16.4–22.7)	*	23.3	(21.9–25.8)	*	27.4	(24.2–32.9)		< 0.001[ce]
Women	14.9	(11.1–22.0)		27.7	(22.5–34.4)		27.6	(23.8–34.0)		29.8	(27.4–40.2)		< 0.001[abc]

Note: Superscript letters denote pairwise comparisons with $p < 0.05$ for a: Young vs. Middle, b: Young vs. Young-Old, c: Young vs. Old-Old, d: Middle vs. Young-Old, e: Middle vs. Old-Old, and f: Young-Old vs. Old-Old.
Abbreviations: IQR, interquartile range; OPST, oral processing and swallowing time.
*Statistically significant gender difference ($p < 0.05$).
***p*-values are from ANOVA or Kruskal–Wallis tests.

(both $p < 0.001$), with no remarkable differences in the remaining groups.

Concerning 1st-OPST, men in the O-Old group (27.4 [IQR: 24.2–32.9]) displayed significantly longer 1st-OPST versus the Young (17.3 [IQR: 15.1–31.0]) and Middle (20.0 [IQR: 16.4–22.7]) groups (both $p < 0.001$) (Table 2). Among women, 1st-OPST was significantly longer in the Middle (27.7 [IQR: 22.5–34.4], $p = 0.003$), Y-Old (27.6 [IQR: 23.8–34.0], $p = 0.001$), and O-Old groups (29.8 [IQR: 27.4–40.2], $p = 0.001$) versus the Young group (14.9 [IQR: 11.1–22.0]). Gender comparisons revealed that while women in the Middle and Y-Old groups had significantly longer 1st-OPST than men (both $p < 0.001$), no such differences were present for the Young and O-Old groups.

4 | Discussion

This pilot study demonstrated the feasibility of integrating audio and video data using a NWES and smartphone to objectively evaluate mastication and swallowing behaviours. By capturing the timing of chewing and swallowing through audio data, our investigation showed the potential of this approach for precisely measuring the TOMASS. These findings suggest the potential clinical applicability of NWES-based TOMASS measurements as a reliable screening tool to assess mastication and swallowing functions.

The NWES facilitated the precise detection of mastication onset and completion, as well as the number of swallows, through audio signals, while discrete bite counts were obtained from video data captured via a smartphone. In contrast to manual methods, which can be inconsistent in detecting the first bite or the initiation of swallowing, the NWES provides a more objective and standardised approach. However, further improvements are required to achieve complete automation.

Originally developed by Huckabee [6], the TOMASS relies on manual, operator-dependent measurements of bites, swallows, and time. In contrast, the present study employed a NWES to automate the collection of audio data from the pharyngeal region, thereby enhancing objectivity and efficiency. Despite the potential variability in mastication and swallowing behaviours across populations, the findings of this study were consistent with previous research [6, 16, 17], which supported its validity. These findings suggest that NWES-based TOMASS measurements may have potential for clinical application in the assessment of dysphagia and masticatory dysfunction, although further validation against established methods is warranted. A previous study [18] has explored the use of video analysis for TOMASS measurements. In contrast, the present study employs a neck-worn, audio-based device that allows for hands-free and real-time assessment of swallowing events, offering greater potential for clinical usability and scalability.

Our study also explored the influence of age and gender on TOMASS parameters, revealing significant differences for discrete bite count, swallow count, and OPST. An increasing trend was observed for most of these parameters with advancing age as well as among women compared with men. These results corroborated previous studies demonstrating smaller bite size and longer masticatory duration in women versus men, with both increasing with age [6, 16, 19]. The original TOMASS study also reported that men took fewer bites and required a shorter mastication time [8], likely due to higher muscle activity, to reduce chewing cycles and masticatory duration [19]. The observed age- and gender-related differences in masticatory and swallowing parameters were consistent with previous studies using the conventional TOMASS protocol, suggesting that NWES-based measurements might serve as a reliable alternative to manual assessments.

Gender-based differences were also evident in this study. In men, both OPST-1 and total OPST increased significantly with age. Only OPST-1 showed a significant age-related increase in women, with no such change in total OPST. While discrete bite count remained consistent across age groups in women, swallow count was lower at older ages. This suggested that older women adapted to age-related functional decline by increasing the number of masticatory cycles to form a bolus before initiating swallowing, thereby reducing the overall number of swallows. Our findings highlight the complex interplay among gender, age, and masticatory and swallowing behaviours.

Lastly, the observed increase in masticatory duration with age was consistent with earlier studies [6, 16, 19]. Older participants had fewer teeth and higher rates of denture use, both of which likely influenced masticatory function [10]. Indeed, past reports have demonstrated that the number of teeth or functional tooth units is a prominent factor in masticatory performance and TOMASS results [10, 19–21].

This study had several limitations. First, it was conducted exclusively with healthy participants, which limited its generalisability to individuals with dysphagia or masticatory dysfunction. Future research should include these populations to confirm the utility of NWES-based TOMASS measurements. Second, the study was conducted in a single region in Japan, and so the findings may not be generalisable to other populations. Additional research across diverse demographic and cultural groups is necessary to determine the broader applicability of this method. Third, while our investigation stratified generally healthy participants by gender and age, other potential confounding factors, such as oral health status and systemic conditions, were not fully accounted for and should be considered in future analyses. Another limitation is that the NWES has not yet been validated against gold standard instrumental assessments, such as videofluoroscopic swallowing study or fibreoptic endoscopic evaluation of swallowing. Future studies should include such comparisons to further establish the clinical validity of NWES-based measurements. Finally, although the NWES enables objective recording of swallowing sounds, the current approach still requires manual synchronisation and annotation of audio and video data, including bite count identification. This introduces a degree of subjectivity, which we plan to eliminate through future system automation.

5 | Conclusion

This pilot study demonstrated the feasibility of measuring the TOMASS using a NWES and smartphone. The simultaneous recording of visual and pharyngeal audio data using the NWES highlighted its potential application as an automated screening procedure for masticatory and swallowing dysfunction. Our findings also confirmed that masticatory and swallowing durations tended to increase with age, with distinct gender-based differences. Accordingly, NWES-based TOMASS measurements may serve as a valuable screening tool for detecting masticatory and swallowing abnormalities, particularly in clinical populations. Future research should focus on validating this method in individuals with dysphagia and exploring its potential to assess pathophysiological changes in eating function.

Author Contributions

K.M. and K.S. developed the concept for this study. K.M. and K.S. provided substantial assistance in data collection. A.S. and R.M. performed statistical analyses. A.S., R.M., and K.M. wrote the initial draft of the manuscript. All authors reviewed the manuscript and approved its final version.

Ethics Statement

This study was approved by the Research Ethics Committee of Tokyo Medical and Dental University (D2021-015) and University of Tsukuba (2022R710) and was conducted in accordance with the Declaration of Helsinki of 1975, as revised in 2008 and 2013. The individuals included in the study provided informed consent.

Conflicts of Interest

The authors declare no conflicts of interest.

Data Availability Statement

Data on the results of this study are available from the corresponding author upon request.

Peer Review

The peer review history for this article is available at https://www.webofscience.com/api/gateway/wos/peer-review/10.1111/joor.70030.

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