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REVIEW ARTICLE

Hyoid bone displacement as parameter for swallowing impairment in patients treated for advanced head and neck cancer

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Abstract Reduced hyoid displacement is thought to contribute to aspiration and pharyngeal residues in head and neck cancer (HNC) patients with dysphagia. To further study hyoid elevation and anterior excursion in HNC patients, this study reports on temporal/kinematic measures of hyoid displacement, with the additional goal to investigate correlations with clinical swallowing impairment. A single-blind analysis of data collected as part of a larger prospective study was performed at three time points before and after chemoradiotherapy. Twenty-five patients had undergone clinical swallowing assessments at baseline, 10-weeks, and 1-year post-treatment. Analysis of videofluoroscopic studies was done on different swallowing consistencies of varying amounts. The studies were independently reviewed frame-by-frame by two clinicians to assess temporal (onset and duration) and kinematic (anterior/superior movement) measures of hyoid displacement (ImageJ), laryngeal penetration/aspiration, and presence of vallecula/pyriform sinus residues. Patient-reported oral intake and swallowing function were also evaluated. Mean maximum hyoid displacement ranged from 9.4 mm (23 % of C2–4 distance) to 12.6 mm (27 %) anteriorly, and from 18.9 mm (41 %) to 24.9 mm (54 %) superiorly, depending on bolus volume and consistency. Patients with reduced superior hyoid displacement perceived significantly more swallowing impairment. No correlation between delayed or reduced hyoid excursion and aspiration or residue scores could be demonstrated. Hyoid displacement is subject to variability from a number of sources. Based on the results, this parameter seems not very valuable for clinical use in HNC patients with dysphagia.

Keywords Head and neck neoplasms · Dysphagia · Hyoid bone · Kinematics · Elevation · Displacement · Aspiration · Chemoradiotherapy

Introduction

Dysphagia, aspiration, or even the inability to swallow, is one of the most disabling adverse effects of treatment with concurrent chemoradiotherapy (CRT) for advanced head and neck cancer (HNC). Inefficient or unsafe swallowing may lead to severe consequences that may alter patients' nutritional status and quality of life. Although multiple swallowing abnormalities are likely present in patients with dysphagia, reduced hyolaryngeal elevation (hyoid bone displacement) is thought to be one of the prime contributors of impaired swallowing [1–4]. During the pharyngeal phase of swallowing, the hyoid bone usually elevates and moves anteriorly under the tongue base by contraction of the suprahyoid muscles, to initiate superior laryngeal movement and cricopharyngeal sphincter opening [5]. Unfortunately, in HNC patients, hyoid displacement is often considerably reduced, as a result of radiation-induced

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damage to anatomical structures involved in swallowing [3, 6, 7]. Consequently, reduced vertical excursion of the hyolaryngeal complex may lead to incomplete airway closure with an associated risk of aspiration, whilst reduced hyoid displacement in the anterior direction will lead to reduced opening of the upper oesophageal sphincter, resulting in pyriform sinus residues, thus also increasing the risk of laryngeal penetration and/or aspiration [4].

Videofluoroscopy (VFS) has become the gold standard for objective evaluation of swallowing function, with the hyoid bone as anatomical point of interest. Several authors have reported on hyoid excursion by biomechanical analysis with VFS [8–10]. According to the literature, hyoid movement can be influenced by various factors such as body height [4], age and gender [11–14], aetiology of dysphagia [15], and bolus characteristics [16, 17]. Unfortunately, the measurements are not always easy and reproducible, and are prone to measurement errors [18, 19]. It is, therefore, not surprising that conflicting results of association between hyoid movement and aspiration are published [9, 10]. Given the fact that hyoid excursion is widely variable in healthy adults [20], it is currently recommended to measure hyoid displacement in anatomically normalised units, i.e. in percentage of the distance between vertebra C2 and C4. In this way, magnification artefacts or sex-based differences attributable to variations in measurement technique are reduced [10].

In HNC patients with dysphagia, Wang and colleagues [3] recently assessed hyoid displacement in irradiated nasopharyngeal cancer patients. Hyoid excursion, especially in the anterior direction, was found to be significantly reduced compared to the control group. Correlation patterns between kinematic measures and swallowing impairment, however, were not investigated. Similarly, two other case studies reported on reduced hyoid displacement in HNC patients [7, 21]. Percentages of restricted or reduced hyoid movement ranged from 42 to 97 %, depending on primary tumour site. Correlations were again not investigated. The present study reports on hyoid displacement parameters in an advanced HNC patient cohort treated with CRT. The primary aim was to report on temporal and kinematic measures related to hyoid displacement in this patient cohort. The secondary aim was to investigate correlations with persisting (clinical) swallowing impairment, and to assess the possible value of these parameters for clinical care.

Materials and methods

Patient population

Patients were diagnosed with advanced (stage III and IV) squamous cell carcinoma of the head and neck region and treated with concurrent chemoradiotherapy (CRT) at The Netherlands Cancer Institute from 2006 to 2008. Each patient received 100 mg/m^2 Cisplatin as a 40 min IV infusion on days 1, 22, and 43. Intensity-modulated radiotherapy (IMRT) of 70 Gy in 35 fractions was administered over 7 weeks starting concurrently with chemotherapy [22]. In an attempt to prevent swallowing sequels following treatment, all patients had participated in a clinical trial on preventive and continued post-treatment swallowing rehabilitation [23]. Informed consent was obtained from all individual participants included in the study.

Twenty-five patients had undergone objective and subjective swallowing assessments until 1-year post-treatment

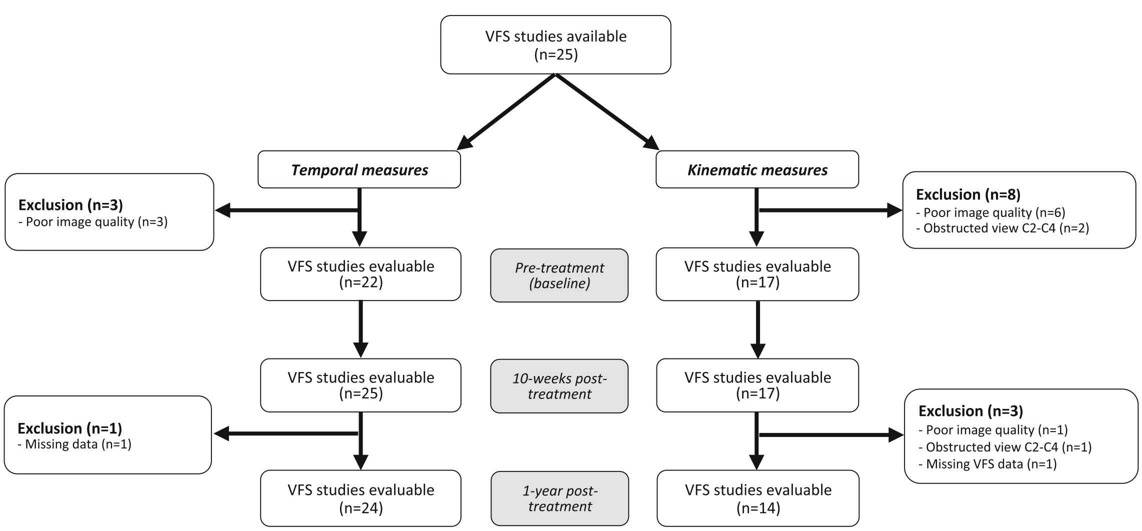

Fig. 1 Consort flowchart of the available patient data

and were included in the present study. Patients were analysed at baseline (approximately 2 weeks before treatment onset), at 10-weeks post-treatment, and at 1-year post-treatment. An overview of the analysed patients is demonstrated in Fig. 1. Regarding temporal analysis, some VFS studies were excluded due to poor quality or missing data, resulting in a dataset of 22, 25, and 24 swallow studies, for analysis at baseline, at 10-weeks post-treatment, and at 1-year post-treatment, respectively. Regarding kinematic analysis, in eight patients poor VFS image quality or obstructed view of target structures precluded precise evaluation of hyoid displacement. At 1-year post-treatment, three more swallow studies had to be excluded due to poor image quality ($n = 1$), obstructed view of vertebra C2–C4 ($n = 1$), or missing data ($n = 1$). This resulted in 17 patients for analysis at baseline and at 10-weeks post-treatment and 14 patients for analysis at 1-year post-treatment.

Objective swallowing assessment

Patients had undergone a standardised lateral VFS protocol, imaging the lips, oral cavity, cervical spine, and proximal cervical oesophagus. An experienced speech language pathologist, clinical investigator, and a laboratory assistant performed all studies. Patients were seated upright and were asked to swallow different consistencies of varying amounts (3 and 5 cc thin liquid; 3 cc paste; and solid Omnipaque coated cake), delivered orally by a spoon or cup. Patients were instructed to sip and wait for a verbal cue from the clinical investigator before swallowing. A coin of ten eurocents was fixed on the chin as reference distance to correct for magnification. All VFS studies were recorded at 25 frames per second and matched (together with an external microphone) with an external computer via a frame grabber (Terratec). Subsequently, the studies were saved for movie editing by Magix (free download at http://magix-movie-edit-pro.en.softonic.com), and digitally captured with VirtualDub. Each VFS study was then reviewed in real-time, slow motion, and frame-by-frame, and rated on clinical, temporal, and kinematic measures independently by the two experienced researchers.

Clinical measures

According to the protocol, penetration aspiration scale (PAS) scores and more than normal post-swallow residue scores (located at the tongue base, vallecula, or pyriform sinuses) were independently assessed. The PAS is a validated 8-point scale (score 1: material does not enter the airway, to score 8: material enters the airway, passes below the vocal folds, and no effort is made to eject) with the lowest score referring to normal swallowing functioning, whereas higher scores refer to more severe swallowing disability [24]. Aspiration status was determined using a binary reduction of the PAS, with any single swallow with a score of ≥ 3 resulting in classification of the patient as an aspirator [9]. The overall 'presence of residue' score was also assessed, ranging from 0 (no residue) to 3 (residue above and below the hyoid bone, with minimal residue in only the piriform sinus judged as normal) [25, 26].

Temporal measures

Hyoid elevation onset and duration was reported in seconds, comparable to the methods described by Kendall et al. [27]. In short, B1 represents the first movement of the head of the food bolus from a stable or 'hold' position that passes the posterior nasal spine and results in all or part of the bolus entering the oropharynx. H1 represents the first superior–anterior movement of the hyoid bone that results in a swallow. H2 symbolises the point at which the hyoid bone reaches its maximum displacement during the swallow. The onset of hyoid elevation relative to the onset of pharyngeal transit (hyoid elevation start time) was calculated as $H1 - B1$. The time required for the hyoid bone to reach maximal elevation (maximum hyoid elevation time) was calculated as $H2 - H1$.

Kinematic measures

Two picture frames (stills) of each VFS swallow study were generated to assess spatial measures of hyoid movement; one showing the resting position of the hyoid bone, and the other showing maximum displacement. The resting position was marked as the moment just before the bolus was propelled from the oral cavity towards the pharynx. The point of maximum displacement was defined as the point just before the hyoid bone began its descent to a resting position [28, 29].

Both stills were individually opened with the program ImageJ 1.32 for structural movement tracing (http://imagej.nih.gov/ij/). The following structures were traced in each frame: the anterior–inferior corner of vertebra C4 (for the remainder of this article: 'C4'), the anterior–inferior corner of vertebra C2 ('C2'), the anterior–superior corner of the hyoid bone, and the length of the scaling reference coin (known length 19.75 mm), as used for calibration. A coordinate system was defined with the vertical y-axis running from C2 through C4, and the horizontal x-axis running perpendicular to this line through C4. All picture frames were rotated to a true vertical/90° angle. The angle of the line between C2 and C4 was used to rotate the image to the 90° angle. ImageJ provided calculated values of each point (x, y), and the following formulas were used to measure anterior and superior hyoid displacement:

Fig. 2 Two lateral VFS images showing *1* the resting position of the hyoid bone (*right*), and *2* the hyoid bone during maximum displacement (*left*). The relevant points are marked during frame-by-frame tracing. With the known length (19.75 mm) of the scaling reference coin, as used for calibration, the C2–C4 distance was measured as 51.76 mm. Hyoid displacement was then calculated absolute (in mm) and in anatomically normalised units (% of C2–C4 distance). Anterior displacement was measured here as $(x_2{-}x_1) - (C4x_2{-}C4x_1) = (182.06{-}155.76) - (230.99{-}213.85) = 9.16$ mm (17.7 % of C2–C4 distance). Similarly, superior displacement was measured as (206.14−195.15) − (176.88−186.62) = 20.77 (40.1 % of C2–C4 distance)

Anterior displacement: $(x_2 - x_1) - (C4x_2 - C4x_1)$, and superior displacement: $(y_2 - y_1) - (C4y_2 - C4y_1)$, where x_1 and y_1 are the starting (rest frame) coordinates of the hyoid bone, x_2 and y_2 are the compared image coordinates (maximum excursion coordinates), $C4x_1$ and $C4y_1$ are the coordinates of the anchor point in the rest frame, and $C4x_2$ and $C4y_2$ are the coordinates of the anchor point at maximum excursion [28, 29]. Subsequently, hyoid displacement was transformed into anatomically normalised units, i.e. in percentage of the distance between vertebra C2 and C4 [10]. This process was subsequently completed for each different consistency and amount of each single VFS swallow study on all three different time points. As an example, two lateral VFS images with the marked points are shown in Fig. 2.

Subjective swallowing assessment

Patients' perceived swallowing function was assessed at the various assessment points with questions from a larger study-specific questionnaire, addressing specific HNC issues such as pain, oral dysfunction, speech problems, swallowing dysfunction, and interrupted social interaction. The 17 study-specific questions regarding diet, swallowing, and chewing are shown in "Appendix I" [30]. Especially, the questions regarding swallowing function (questions 11–14) were taken into consideration. Each item was scored on a 3-point scale, and total subjective impairment scores were calculated using the sum score of these questions (maximum score: 11).

Reliability analysis

All VFS clinical and temporal assessments were done in consensus by the first author and an experienced speech language pathologist (SLP). The VFS kinematic measures were calculated by another trained researcher, with 15 % of all measurements randomly repeated to measure intrarater reliability, and 15 % within 1 month randomly reviewed by the first author, as a measure of interrater reliability. Test–retest reliability was measured with two-way random intraclass coefficients [ICC(2,1)] for consistency. For intrarater reliability, anterior and superior displacement showed an ICC(2,1) 0.76 and 0.80, respectively. For interrater reliability, these coefficients were 0.79 and 0.83 for anterior and superior displacement, respectively, showing acceptable agreement.

Statistical analysis

All measured temporal and kinematic data per assessment point were averaged across patients according to bolus size and direction of displacement. Data were described as means with standard deviations. Wilcoxon signed rank test was used to test statistical differences for various hyoid displacement parameters between baseline and 10-weeks post-treatment, and between baseline and 1-year post-treatment. Second, correlations with subjective swallowing impairment (study-specific questions) were calculated with the Spearman's rank test. All data were collected and analysed in SPSS (Chicago, Illinois; version 23.0), and a significance level of $p < 0.05$ was used.

Results

Details on the clinical characteristics of the study population are presented in Table 1. Pretreatment, 2/17 patients (12 %) were diagnosed with dysphagia according to the binary classification from the PAS scores obtained from VFS assessment. At 10-weeks and 1-year post-treatment these numbers were 3/17 (18 %) and 2/14 (14 %), respectively. More than normal residue above and below the hyoid bone was present in 16/17 (94 %) patients at baseline, in 8/17 (47 %) patients at 10-weeks post-treatment, and in 13/14 (93 %) patients at 1-year post-treatment. Regarding patients' perceived swallowing impairment at baseline, 6/17 patients (35 %) reported swallowing issues based ≥2 positive answers on the study-specific questions regarding swallowing function. At 10-weeks and at 1-year post-treatment, these numbers were 53 and 29 %, respectively.

Temporal measures

Both hyoid elevation start time (the onset of hyoid elevation relative to the onset of pharyngeal transit; H1−B1) and maximum hyoid elevation time (H2−B1) were calculated, separated per consistency and assessment point. At baseline, 10-weeks and at 1-year post-treatment, 22, 25, and 24 patients, respectively, were evaluated. As can be seen in Table 2, hyoid elevation start time ranged from −0.14 ± 0.28 s for a 5 cc thin liquid swallow to 0.16 ± 0.43 s for a solid swallow. Maximum hyoid elevation time varied from 0.47 ± 0.21 to 0.96 ± 0.94 s for these consistencies. The onset of hyoid elevation relative to the onset of the swallow, and the time required for the hyoid bone to reach maximal elevation, seemed to increase with increases in bolus size or consistency although these changes were statistically not significant (Wilcoxon signed rank test; $p > 0.05$ for the various assessment points). There were also no significant changes over time for hyoid elevation start time and maximum hyoid elevation time ($p > 0.05$ for all consistencies).

Kinematic measures

Table 3a, b show the descriptive statistics for hyoid displacement (absolute in mm [A] and in 'anatomically normalised units' [4], i.e. % of C2–C4 distance [B]). As can be seen, mean maximum anterior and superior displacement ranged from 9.4 mm (23 % of C2–4 distance) to 12.6 mm (27 %), and from 18.9 mm (41 %) to 24.9 mm (54 %), respectively, depending on bolus volume and consistency.

Table 1 Clinical patient and tumour characteristics of the initially included patients ($n = 25$), the patients analysed at baseline and 10-weeks post-treatment ($n = 17$), and the patients analysed at 1-year post-treatment ($n = 14$)

	25 patients *n* (%)	17 patients *n* (%)	14 patients *n* (%)
Gender			
Male	19 (76)	14 (82)	12 (86)
Female	6 (24)	3 (18)	2 (14)
Mean age, year (range)	59 (39–77)	58 (39–77)	58 (39–77)
Tumour site			
Nasopharynx	3 (40)	3 (18)	2 (14)
Oral/oropharynx	12 (48)	8 (47)	7 (50)
Hypopharynx	10 (40)	6 (35)	5 (36)
Tumour stage			
Stage III	8 (32)	7 (41)	6 (43)
Stage IV	17 (68)	10 (59)	8 (57)
T stage			
T1	4 (16)	4 (24)	2 (14)
T2	7 (28)	4 (24)	4 (29)
T3	10 (40)	6 (35)	5 (36)
T4	4 (16)	3 (18)	3 (21)
N stage			
N0	3 (12)	2 (12)	2 (14)
N1	7 (28)	6 (35)	5 (36)
N2	11 (41)	7 (41)	5 (36)
N3	4 (16)	2 (12)	2 (14)

Table 2 Hyoid bone elevation onset and duration in seconds ±SD

	Bolus size				Valid *N*
	Thin liquid		Thick liquid	Solid cake	
	3cc	5cc	3 cc		
Baseline					
H1−B1	0.02 ± 0.37	−0.09 ± 0.18	0.03 ± 0.50	0.16 ± 0.43	22
H2−H1	0.67 ± 0.40	0.51 ± 0.14	0.69 ± 0.52	0.96 ± 0.94	22
10-weeks					
H1−B1	−0.08 ± 0.21	−0.14 ± 0.28	0.13 ± 0.58	0.10 ± 0.33	25
H2−H1	0.58 ± 0.25	0.47 ± 0.21	0.81 ± 0.60	0.92 ± 0.92	25
1-year					
H1−B1	−0.07 ± 0.20	−0.09 ± 0.24	−0.03 ± 0.35	0.08 ± 0.34	24
H2−H1	0.64 ± 0.17	0.74 ± 0.40	0.79 ± 0.39	0.87 ± 0.62	24

B1 the first movement of the head of the food bolus from a stable or 'hold' position that passes the posterior nasal spine and results in all or part of the bolus entering the oropharynx, *H1* the first superior–interior movement of the hyoid bone that results in a swallow, *H2* the point at which the hyoid bone reaches its maximum displacement during the swallow, *H1−B1* hyoid elevation onset relative to the onset of pharyngeal transit (=hyoid elevation start time), *H2−B1* hyoid elevation duration (=maximum hyoid elevation time), *SD* = standard deviation

No significant changes over time were noted for all parameters, except for a swallow of 5 cc thin liquid, in which displacement was significantly increased in the superior direction at 10-weeks post-treatment compared to baseline (Wilcoxon signed rank test; as % C2–C4: $p = 0.039$). This effect was predominantly seen in patients with a tumour in the oropharynx (change 5.9 mm; 12.3 %) and hypopharynx (change 5.7 mm; 13.3 %), and was absent in patients with a tumour in the nasopharynx (change −1.2 mm; −2.7 %).

Correlation with swallowing impairment

The number of patients showing penetration-aspiration on VFS assessments was low in the current study cohort (maximum three patients per assessment point), limiting the statistical power to investigate correlations between penetration-aspiration and hyoid displacement. The patients showing penetration or aspiration did not show reduced hyoid displacement compared to the group mean. No correlations between delayed and reduced hyoid excursion and residue scores could be demonstrated. Regarding investigation of correlations with patient-reported outcomes based on (sub) total scores of the study-specific questions regarding swallowing function (questions 11–14; "Appendix I"), superior hyoid displacement significantly correlated with subjective swallowing impairment for various consistencies and assessment points. Especially, superior displacement at baseline correlated well with swallowing function at 1-year post-treatment (see Table 4 for the *p* values for a 5 cc thin and 3 cc thick liquid swallow). In Fig. 3, this relationship for a 5 cc thin liquid swallow is illustrated in a scatter plot.

Discussion

The primary aim of the present study was to report on temporal and kinematic hyoid displacement parameters in HNC patients treated with chemoradiotherapy, with the secondary aim to investigate the correlations with objective and subjective swallowing impairment. Regarding the first aim, the onset of hyoid elevation relative to the onset of the swallow did not change significantly over time or with increases in bolus size or consistency, nor did the time required for the hyoid bone to reach maximal elevation. Maximum hyoid displacement—scaled in cervical/anatomical units (% C2–C4 distance)—ranged from 23 to 27 % in the anterior direction, and from 41 to 54 % in the superior direction. These results are somewhat lower in comparison with 'normative' data from the literature concerning patients referred for dysphagia assessment, with results ranging from 36 to 38 % anteriorly, and from 51 to 57 % superiorly [4, 9]. Although the predominant aetiology of dysphagia in those studies was neurogenic, whereby patients with a history of HNC were excluded, this possibly implicates that hyoid displacement in the current patient cohort was already limited at baseline, and might explain the lack of significant changes over time. Obviously, it is also quite difficult to demonstrated statistical differences in this small HNC sample. Regarding the second aim, we have not seen strong correlations between hyoid

Table 3 Hyoid bone displacement

	Bolus size				Valid N
	Thin liquid		Thick liquid	Solid cake	
	3cc	5cc	3 cc		
Absolute in mm					
Baseline					
Anterior mean ± SD	10.7 ± 3.4	12.0 ± 4.3	12.2 ± 4.3	11.6 ± 3.8	17
Superior mean ± SD	18.9 ± 8.0	20.3 ± 5.9	20.5 ± 8.4	19.3 ± 8.6	17
Follow-up 10-weeks					
Anterior mean ± SD	10.5 ± 4.3	11.4 ± 5.3	11.2 ± 5.0	12.6 ± 4.7	17
Superior mean ± SD	22.6 ± 8.3	24.9 ± 9.2	24.7 ± 9.1	23.0 ± 7.5	17
Follow-up 1-year					
Anterior mean ± SD	9.4 ± 4.3	9.9 ± 4.1	10.7 ± 4.4	12.5 ± 5.0	14
Superior mean ± SD	19.9 ± 7.6	23.3 ± 7.4	19.9 ± 7.7	21.9 ± 6.9	14
% of C2–C4 distance					
Baseline					
Anterior mean ± SD	23 ± 7	26 ± 9	26 ± 8	25 ± 8	17
Superior mean ± SD	41 ± 17	44 ± 12	45 ± 17	42 ± 18	17
Follow-up 10-weeks					
Anterior mean ± SD	23 ± 9	25 ± 11	25 ± 10	27 ± 10	17
Superior mean ± SD	49 ± 18	54 ± 19	53 ± 21	50 ± 16	17
Follow-up 1-year					
Anterior mean ± SD	20 ± 9	22 ± 9	23 ± 10	27 ± 10	14
Superior mean ± SD	43 ± 17	51 ± 16	43 ± 17	48 ± 15	14

SD standard deviation, *mm* millimetres, *cc* cubic centimetres

Table 4 Overview of Spearman's rank correlations between superior hyoid displacement at baseline and subjective swallowing impairment at 1-year post-treatment for a thin (5 cc) and thick (3 cc) liquid swallow

Superior displacement	Problems swallowing liquids	Problems swallowing soft foods	Problems swallowing solid foods	Swallowing more often	Total subjective score
Thin liquid swallow	0.41	0.41	0.73**	0.59*	0.72**
Thick liquid swallow	0.41	0.41	0.68**	0.55*	0.67**

* $p < 0.05$; ** $p < 0.01$

displacement and swallowing impairment, except for a significant association between reduced superior hyoid movement and subjective swallowing impairment based on four study-specific questions regarding swallowing function, which, however, was quite small.

Interestingly, in the current cohort study, hyoid displacement in patients with a tumour at the oropharynx and hypopharynx had slightly increased in the superior direction for a 5 cc thin liquid swallow at 10-weeks post-treatment compared to baseline. Though these differences were significant only for the 5 cc thin bolus, the higher values may reflect extra effort being exerted during these swallows. And if so, this could indicate that other issues, e.g. poor sensation, non-hyoid mechanical impairment, are present and responsible for the extra effort. For future studies it might be of interest to also look at overall transit times during swallowing, which can be prolonged with increased effort. Since we did not see this effect in the patients with a tumour located at the nasopharynx, it is also possible that the primary tumour, or pain due to the tumour, impaired the mobility of the hyoid bone at baseline in these patients, and that hyoid movement was 'restored' again after complete remission at 10-weeks post-treatment. However, there are much more parameters such as tumour

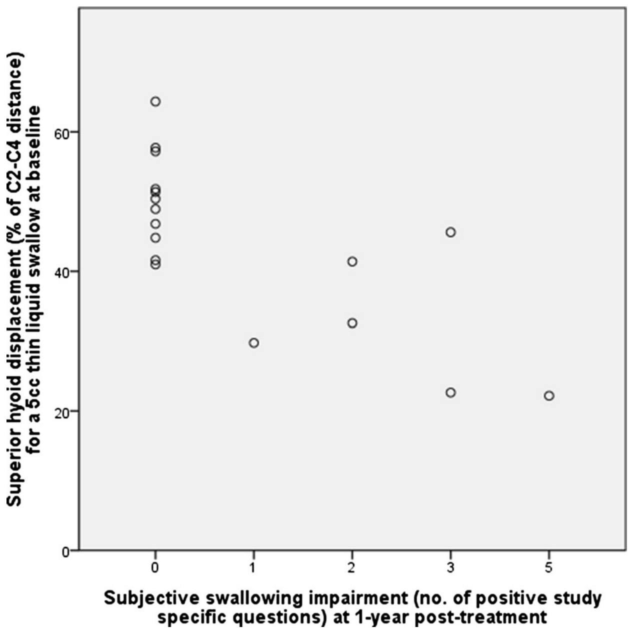

Fig. 3 *Scatter plot* of the relationship between superior hyoid bone displacement for a 5 cc thin liquid swallow at baseline (measured as % of the C2–C4 distance) and subjective swallowing impairment based on the study-specific questionnaire at 1-year post-treatment

volume, radiation dose effects and/or exercise therapy which might have played a role in this. In 2011, van der Kruis and colleagues revealed in their review a significant improved hyoid excursion in several studies following the treatment with swallowing manoeuvres and/or bolus modification [31]. A similar effect might be present in the current patient population: the participation in a preventive and continued post-treatment swallowing rehabilitation program might explain these favourable 10-weeks hyoid elevation outcomes [32]. This could maybe also explain the limited number of patients who had aspiration, and the lower rate of more than normal residue scores at 10-weeks post-treatment. Finally, patients who are cautious or fearful about swallowing safety, that is, who perceive greater difficulty, may elevate the hyoid early, as in the 'rest' or 'hold' position. If so, their hyoid displacement may be reduced, as compared to healthy subjects, or as compared to less fearful patients. Consequently, 'possible' hyoid displacement, or potential for hyoid displacement, may be difficult to determine in these cases.

Unfortunately, due to methodological issues (only four patients showing aspiration on VFS assessments), the hypothesis that patients with penetration or aspiration would show slower durations of hyoid movement and/or reductions in kinematic measures could not be statistically analysed. The significant association found between reduced superior hyoid movement and subjective swallowing impairment based on four study-specific questions regarding swallowing function was quite small. Possibly, other mechanical variables may have been impaired and accounted for patients' reported dysphagia. It is not exactly clear if hyoid elevation or anterior excursion is more important. Steele and colleagues (2011) reported significantly higher occurrence of penetration-aspiration in swallows where anterior movement was restricted [4]. However, Molfenter and colleagues (2014) found a trend towards lower maximum superior hyoid position and swallowing impairment [9]. In the current patient, cohort correlations between residue ratings and hyoid displacement were also lacking. Residue, however, might be explained by other, non-hyoid, mechanical variables. Further research with larger sample sizes is necessary to confirm these correlations.

Although the raters in the current study used well-defined guidelines [28, 29] and—following several training sessions—maximum consensus was reached about the definitions of the measured spatial variables [19], intra- and interrater reliability [with an ICC(2,1) ranging from 0.76 to 0.83] was acceptable, and did not reach the level of 'excellent' reliability. Besides, all measurements and analyses were very time consuming; not only because of the pre-experimental training sessions, but also due to inefficiency/lack of computerisation in the current methods used. Software for automatic measurement and analysis extend of hyoid movement in the *x*–*y* coordinate system over time was unfortunately not available in our institute. Consequently, all swallow studies were individually analysed, and the provided *x* and *y* coordinates by ImageJ were manually entered to Excel/SPSS to calculate the maximum anterior and superior displacement values. For future perspectives it is, therefore, recommended to use automatic systems for analysis of hyoid displacement.

Conclusion

In this study, temporal and kinematic measures related to hyoid displacement in advanced HNC patients are reported up to 1 year after the treatment with concurrent chemoradiotherapy. Compared to normative data, hyoid elevation and anterior excursion was already limited at baseline. Since hyoid displacement is subject to variability from a number of sources, this parameter seems not very valuable for clinical use in HNC patients.

Compliance with ethical standards

Conflict of interest This study was made possible by Grants provided by Atos Medical (Sweden), the Verwelius Foundation (The Netherlands), and "Stichting de Hoop" (The Netherlands).

Ethical approval All procedures performed in studies involving human participants were in accordance with the ethical standards of the institutional and/or national research committee and with the 1964 Helsinki declaration and its later amendments or comparable ethical standards.

Appendix I: Selection of the translated Dutch study-specific questionnaire

A. Diet, swallowing and chewing complaints over the last week (17 questions)

1. Do you still have your own teeth?
   1 = yes 2 = yes, partially
   3 = no, I have a prosthesis 4 = no, and I don't wear a prosthesis
2. How often do you clean your teeth?
   1 = a couple of times a day 2 = once a day
   3 = less than once a day 4 = not at all
3. How do you experience your mouth opening?
   1 = normal 2 = a little bit limited
   3 = very limited 4 = I cannot open my mouth
4. What is your diet like?
   1 = I eat solid food 2 = I only eat soft (minced) food
   3 = I only eat liquid food 4 = I only have tube feeding
   5 = combination soft diet and tube feeding
5. Do you experience problems with eating, because of a limited mouth opening?
   1 = not at all 2 = a little
   3 = rather 4 = quite a lot
6. Do you experience problems with speech, because of a limited mouth opening?
   1 = not at all 2 = a little
   3 = rather 4 = quite a lot
7. Do you have problems with chewing your food?
   1 = not at all 2 = a little
   3 = rather 4 = quite a lot
8. Do you have problems with moving solid food around in your mouth?
   1 = not at all 2 = a little
   3 = rather 4 = quite bad
9. Do you have problems with moving soft/minced food around in your mouth?
   1 = not at all 2 = a little
   3 = rather 4 = quite a lot
10. Do you have problems with moving liquid food around in your mouth?
    1 = not at all 2 = a little
    3 = rather 4 = quite a lot
11. **Do you have problems with swallowing solid food?**
    1 = not at all 2 = a little
    3 = rather 4 = quite a lot
12. **Do you have problems with swallowing soft/minced food?**
    1 = not at all 2 = a little
    3 = rather 4 = quite a lot
13. **Do you have problems with swallowing liquid food?**
    1 = not at all 2 = a little
    3 = rather 4 = quite a lot
14. **Do you have to swallow repeatedly to get rid of food?**
    1 = yes 2 = no
    3 = sometimes
15. Do you have to drink during a meal to ease food down?
    1 = yes 2 = no
    3 = sometimes
16. Do you have a normal amount of saliva (spit)?
    1 = much less 2 = a bit less
    3 = the same 4 = a bit more
    5 = much more
17. Can you keep your saliva in the mouth without leakage?
    1 = not at all 2 = a bit
    3 = fairly well 4 = quite easily

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