Tokai J Exp Clin Med., Vol. 51, No. 2, pp. 89-98, 2026

Effect of a Reduced Frame Rate for Videofluoroscopic Swallowing Studies on the Recognition of Aspiration in Adult Patients

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(Received January 26, 2026; Accepted March 12, 2026)

The aim of this study was to clarify the effects of reduced frame rates in videofluoroscopic swallowing studies (VFSS) on aspiration assessment. The consecutive key frames (CKFs), that is, the range of key frames that are essential for penetration-aspiration scale (PAS) scoring of abnormal laryngeal penetration (ALP) and aspiration, was defined using retrospective 30-frames/second (fps) VFSS records for 50 adult dysphagia patients at an acute care university hospital. The results showed that the CKFs was larger in 24 aspiration patients than in 26 ALP patients, and its distribution was wider. The minimum CKFs that included no trace of residual liquid (TRL) was 8 for aspiration. When reducing the frame rate in seven steps to 3.75 fps, the complete disappearance of CKFs with no TRL was seen in only four ALP patients. With partial disappearance of CKFs, the PAS scoring of ALP and aspiration even with a reduction to 3.75 fps agreed consistently and almost completely with that at 30 fps, and high reliability was obtained. This study was exploratory, but 3.75 fps was the lower limit that satisfied the criteria in analyses after defining the acceptable level for frame rate reductions in assessing aspiration.

Key words: frame rate, swallowing, silent aspiration, penetration-aspiration scale, intensive care unit

INTRODUCTION

The mechanisms underlying the occurrence of dysphagia in the intensive care unit (ICU) are not completely understood [1], but factors may include disuse muscle atrophy, sarcopenia, decreased muscle strength associated with malnutrition [2, 3], cognitive disorders that make following instructions difficult [4], gastroesophageal reflux, lack of breathing and swallowing coordination [5], as well as direct injury by endotracheal and tracheostomy tubes. For endotracheal tubes in particular, changes in sensation from post-extubation laryngeal injury or tubes have been reported [6]. Post-extubation dysphagia (PED) from long-term endotracheal intubation is reported to occur in a wide range (3–62%) of cases [7]. The risk of occurrence increases with increasing duration of intubation [8] and tube diameter [9, 10]. The rate of occurrence of post-extubation silent aspiration (SA) specifically is reportedly 17–25% [11–13], and handling of PED is therefore considered important.

The bedside swallowing evaluation (BSE) [14] used by speech-language pathologists (SLPs), the post-extubation dysphagia screening (PDS) [15] used by nurses, and the Yale Swallow Protocol (YSP) [16] that can be used by both SLPs and nurses are all well known internationally as non-instrumental assessments that can be performed soon after extubation in the ICU to evaluate aspiration risk. These assessments emphasize evaluations using a 3-ounce water swallow test (3 oz. WST) [17], but much remains contentious about aspiration evaluation using this test alone [18, 19]. Thus, underestimation and overestimation of SA are issues that need to be addressed, and reliable means of detecting SA at the bedside in the ICU are needed. Though instrumental assessments with a videofluoroscopic swallowing study (VFSS) or a fiberoptic endoscopic examination of swallowing (FEES) are considered necessary for conclusive proof of SA, performing these diagnostic imaging examinations for all ICU patients is impractical. Difficulties with a VFSS, for example, include the need for multiple medical personnel, including a doctor, since the patient must be transported to the fluoroscopy room, and any problems that occur must be dealt with, such as problems with the machines that are connected or the overall condition of the patient. Issues with a FEES include patient burden from the series of procedures using a nasotracheal intubation tube, and the risk of patient agitation or bleeding, although it has an advantage over a VFSS in that it can be performed at the bedside.

One aspect that makes a VFSS, which is a fluoroscopy procedure, superior to a FEES in assessing aspiration is that there is no whiteout period. For example, aspiration cannot be determined with a FEES when all aspirated material reaches the subglottic airway during

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whiteouts whose duration depends on various parameters [20–22]. Moreover, even if aspirated material remains in the subglottis after whiteout, the posterior wall of the subglottic airway becomes a blind spot, and aspiration cannot be assessed.

Therefore, the aim of the present study was to devise a practical method for assessing aspiration with new equipment that can detect SA with high reliability at the bedside. Specifically, the goal was to introduce a system into clinical use in which a dynamic digital radiography function is added to a conventional mobile, general purpose radiography machine (Mobile-DDR), the major challenge for which was the construction of a bedside aspiration assessment system that functions under radiation and workflow constraints [23]. With regard to technical constraints on radiography conditions, the optimal frame rate for assessing aspiration is a particular issue that needs to be prioritized.

The radiation dose can be reduced by decreasing the recording frame rate using pulsed X-ray irradiation [24]. However, sacrificing diagnostic capability to achieve this reduced radiation dose is not justified [25]. For comprehensive aspiration assessment using a VFSS, a frame rate of at least 30 fps is recommended internationally [26–29]. However, a Mobile-DDR, which is a general-purpose system, has the disadvantage of having an upper limit of only 15 fps [23].

Assuming two consecutive frames A and B recorded at 30 fps, if the frame rate is reduced to 15 fps, either frame A or frame B is lost, and such lost frames are complemented with consecutive A, A or B, or B frames. Bonilha *et al.* reduced the frame rate from 30 fps to 15 fps in penetration-aspiration scale (PAS) [30] scoring, and ejected laryngeal penetration (PAS 2) was mistakenly judged to be no laryngeal penetration in one of five adult patients who swallowed a thin liquid [31]. When the key frame essential for determination is only one frame at 30 fps, the key frame is completely lost when the rate is lowered to 15 fps, which may lead to an incorrect assessment. However, if there are two or more consecutive key frames, they are not completely lost, and it would seem that this would not lead to an incorrect assessment.

Mulheren reported that no significant difference was seen in PAS assessment even when the VFSS frame rate was reduced from 30 fps to 15 fps in 20 abnormal adult dysphagia patients at an acute hospital [32]. This supports the possibility that, when performing a 30-fps VFSS with adult dysphagia patients, at least two consecutive key frames are essential for PAS scoring, and assessments of laryngeal penetration and aspiration are unlikely to be affected by lower time resolutions.

In this exploratory study, therefore, the consecutive key frames (CKFs) was clarified by defining the range of key frames essential for PAS scoring of abnormal laryngeal penetration and aspiration for a VFSS recorded at 30 fps. The minimum CKFs not including trace of residual liquid (TRL) that enables PAS scoring was also evaluated. Then, by reducing the frame rate in a stepwise fashion, a comparison was made between cases where CKFs were partially lost and cases where they were completely lost, and the effect of reducing the frame rate on aspiration assessment was evaluated.

The purpose of the study was to investigate the frame rate in swallowing assessments specifically for aspiration, not the frame rate for conventional comprehensive swallowing assessments using a VFSS. If the cutoff value for aspiration could be clarified, that information could also be broadly useful in clinical settings to avoid unnecessary radiation exposure. This is thought to be especially important at the bedside for severely ill patients with many constraints, and clarifying the effects of a reduced frame rate on aspiration assessments would be a preliminary step in verifying the optimal frame rate for determining aspiration.

METHODS

The present retrospective, cross-sectional study was conducted in accordance with the Declaration of Helsinki and was approved by the Medical Ethics Committee of Tokai University (21R-203). Consent was taken to have been obtained from all patients using the opt-out method (information provided on posters in the hospital at the clinical research institution and on institutional webpages).

VFSS was performed using a stationary, digital, general purpose, fluoroscopic X-ray system (Ultimax-i DREX-UI80; Canon Medical Systems, Otawara, Japan) for 97 patients who were admitted to Tokai University Hospital between August 1, 2020 and July 31, 2021. Of them, patients in whom laryngeal penetration and aspiration could not be determined from imaging due to visualization issues were excluded, leaving 74 patients who met the following inclusion criteria (Table 1): 1) adult (age > 20 years); 2) results from testing for the diagnosis of dysphagia; 3) standard imaging with continuous irradiation recorded at 30 fps (picture archiving and communication system; PACS); 4) swallowing of a liquid with a barium sulfate concentration of 30 mass% prepared specifically for VFSS by the Nutrition Department (no limitations on physical properties such as viscosity resulting from preparation with or without a thickening agent); and 5) pharyngeal-stage impairment on a profile view in a relaxed sitting position.

Two doctors and one SLP with over 30 years of experience in VFSS assessment rated the swallow with the worst PAS score [29] in the VFSS for each of the 74 subjects. When there were multiple liquid swallowing recordings for a single subject, the recording with the worst PAS assessment for which there was agreement among the three assessors was selected.

Discrepancies in PAS scores were handled by convening the SLP and the two physicians who rated and reviewed the recording and attempted to reach agreement.

Penetration-aspiration scale

1) Material does not enter the airway;
2) Material enters the airway, remains above the vocal folds, and is ejected from the airway;
3) Material enters the airway, remains above the vocal folds, and is not ejected from the airway;
4) Material enters the airway, contacts the vocal folds, and is ejected from the airway;
5) Material enters the airway, contacts the vocal folds, and is not ejected from the airway;
6) Material enters the airway, passes below the vocal folds, and is ejected into the larynx or out of the air-

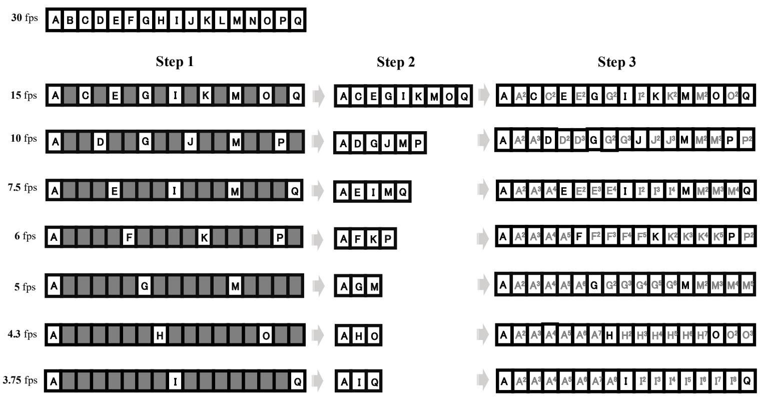

Fig. 1 Video clips created at progressively reduced frame rates: three steps in the video clip creation procedure
fps: frames per second.
Step 1: Seven video clips are prepared with stepwise reductions in the frame rate, which was 30 fps in the original VFSS, for each of the 50 subjects.
Step 2: Each video clip prepared as Step 1 is reconstructed with the remaining frames.
Step 3: Each video clip reconstructed in Step 2 is time-corrected to 30 fps to interpolate the deleted frames.

way;
7) Material enters the airway, passes below the vocal folds, and is not ejected from the trachea despite effort; or
8) Material enters the airway, passes below the vocal folds, and no effort is made to eject it.

Assessment results on which the three assessors agreed were taken as the gold standard, and they were classified as PAS 1–8 (1, n = 15; 2, n = 9; 3, n = 6; 4, n = 10; 5, n = 10; 6, n = 7; 7, n = 6; and 8, n = 11).

The primary outcome in this study was the smallest CKFs with no TRL to enable PAS scoring of aspiration in 30-fps video clips. The secondary outcome was the smallest CKFs with no TRL to enable PAS scoring of laryngeal penetration that was considered abnormal in 30-fps video clips. PAS 1 and 2 patients were unnecessary for these outcomes and so were excluded.

The 50 patients with PAS scores of 3–8 with abnormal laryngeal penetration and aspiration were included in this study.

Determining the continuous key frames with no trace of residual liquid of 30-fps video clips

The range of liquid dynamic images for which PAS scoring was considered to be possible with agreement of the three assessors who determined the PAS gold standard with 30-fps VFSS (that is, the CKFs, where 1 frame is 1/30 sec) was determined. If there was disagreement on the starting frame, the most earliest frame was selected. If there was disagreement on the ending frame, the most latest frame was selected. Then, the first and last frames of the frame range were carefully determined in PAS 3–8 cases, as described below.

For PAS 3, the first frame in which liquid in the airway was confirmed was the start frame, and the end frame of the pharyngeal phase and airway response was defined as the end frame.

For PAS 4, the first frame in which liquid was confirmed to be in contact with the vocal folds was defined as the start frame, and the last frame in which liquid was confirmed to be on the vocal folds was defined as the end frame.

For PAS 5, the first frame in which liquid was confirmed to be in contact with the vocal folds was defined as the start frame, and the frame at the end of the pharyngeal phase and airway response was defined as the end frame.

For PAS 6, the first frame in which liquid inflow was confirmed under the vocal folds was defined as the start frame, and the last frame in which liquid was confirmed to be below the vocal folds was defined as the end frame.

For PAS 7, the first frame in which liquid inflow was confirmed under the vocal folds was defined as the start frame, and the frame at the end of the pharyngeal phase and airway response was defined as the end frame.

For PAS 8, the first frame in which liquid inflow was confirmed under the vocal folds was defined as the start frame, and the frame at the end of the pharyngeal phase was defined as the end frame.

In addition, whether there were still images of the fluid that would allow determination of undrained laryngeal entry and undrained aspiration until the end of imaging was determined. This was done because, even if key frames are lost, PAS 3, 5, 7, and 8 may be correctly scored if there is TRL in subsequent images.

The smallest CKFs with no TRL of aspiration and the smallest CKFs with no TRL of laryngeal penetration considered to be abnormal were obtained from the PAS score distribution based on the CKFs that enabled PAS scoring at 30 fps and TRL.

Video clips prepared with stepwise reductions in the frame rate

The following three steps, shown in Fig. 1, were performed using video editing software (Adobe Premiere Pro; Adobe Inc., San Jose, CA, USA). In step 1, video clips 1–7 were prepared with stepwise reductions in the frame rate, which was 30 fps in the original VFSS, for each of the 50 subjects.

1) 15 fps: 1/30 frame was kept, and the next 1/30 frame was deleted. This was repeated.
2) 10 fps: 1/30 frame was kept, and the next 2/30 frames were deleted. This was repeated.
3) 7.5 fps: 1/30 frame was kept, and the next 3/30 frames were deleted. This was repeated.
4) 6 fps: 1/30 frame was kept, and the next 4/30 frames were deleted. This was repeated.
5) 5 fps: 1/30 frame was kept, and the next 5/30 frames were deleted. This was repeated.
6) 4.3 fps: 1/30 frame was kept, and the next 6/30 frames were deleted. This was repeated.
7) 3.75 fps: 1/30 frame was kept, and the next 7/30 frames were deleted. This was repeated.

In step 2, each video clip prepared as above was reconstructed with the remaining frames. In step 3, each video clip reconstructed in Step 2 was time-corrected to 30 fps to interpolate the deleted frames. For example, at 3.75 fps, the range of 7 frames from B to H after the remaining frame A was deleted, and instead, all 7 frames were interpolated entirely with frame A before the deleted frame. The video clips were all saved in MPEG-2 format.

Assessment of the blinded video clips with the different frame rates was randomly assigned to 7 SLPs with at least 5 years of clinical experience with dysphagia. Since it would be difficult to exclude only language information that could affect PAS scoring from the sounds recorded together with the videos, sound sources were not included in the individual video clips (50 patients). Sound source information related to airway response was entered in advance on the PAS record sheet and provided to each assessor. The assessors were not told that PAS 1 and 2 had been excluded, and they assigned PAS scores of 1–8, including slow motion and stop motion replay, with no time limitations set for the assessment. The videos were viewed on a 21.5-inch monitor with a resolution of 4096 × 2304.

Changes in PAS scores with complete disappearance of consecutive key frames with no trace of residual liquid

PAS scoring results for patients in whom CKFs with no TRL completely disappeared with the stepwise frame rate reduction from 15 fps to 3.75 fps were compared with the PAS scoring results for video clips at 30 fps.

Validity and reliability of PAS scores with reduced frame rates

All patients, excluding those for whom key frames with no TRL had completely disappeared, were assessed. After validity evaluation, inter-rater reliability was evaluated at 15 fps, 10 fps, 7.5 fps, 6 fps, 5 fps, 4.3 fps, and 3.75 fps after a gap of 3–4 days, and intra-rater reliability was evaluated after a further gap of 3–4 days.

Sensitivity, specificity, positive predictive value, and negative predictive value of aspiration detection

The sensitivity, specificity, positive predictive value, and negative predictive value for detection of aspiration (PAS 6–8) were evaluated at 15 fps, 10 fps, 7.5 fps, 6 fps, 5 fps, 4.3 fps, and 3.75 fps in all 50 patients.

In this exploratory study, the acceptable levels of frame rate reductions in aspiration assessment were set to a sensitivity of ≥ 90%, with emphasis on preventing overlooking of aspiration, and a specificity of ≥ 80% to limit false positives. The lowest frame rate that satisfied these criteria was taken to be the lower limit for the provisional reduced frame rate that is acceptable in aspiration assessment.

Statistical analysis

Statistical analyses were performed using SPSS version 28 (IBM; Armonk, NY, USA), with values of $P < 0.05$ considered significant.

The weighted Kappa coefficient was used for assessing inter-rater and intra-rater reliabilities. Weighted kappa coefficients were interpreted to show reliability as follows [30]: 0.21–0.40, fair; 0.41–0.60, moderate; 0.61–0.80, substantial; and 0.81–1, almost perfect.

This was a retrospective study, and the participants included in the analysis were all consecutive patients who were admitted during the period set for the study and met the inclusion criteria. Thus, this group consisted of 50 patients. Taking the expected agreement (kappa coefficient) to be 0.8–0.9, the estimated accuracy (half-width of 95%CI) with $n = 50$ was roughly ± 0.15 – ± 0.12. This is thought to fall within a range (± 0.2) that does not go significantly beyond the interpretation category for level of agreement as an exploratory investigation. In the actually collected data, even with about 10% missing data, this estimated accuracy was roughly ± 0.16 – ± 0.13; therefore, the number of patients in this study was judged to be valid.

RESULTS

PAS score distribution based on the consecutive key frames and trace of residual liquid to enable PAS scoring at 30 fps

Table 2 lists PAS 3–8 patients in the order of the smallest CKFs that reflects the range of key frames essential in PAS scoring of abnormal laryngeal penetration and aspiration. All 24 aspiration patients (PAS 6–8) had a larger CKFs and a wider distribution of key frames than all 26 patients with abnormal laryngeal penetration (PAS 3–5).

Even when all CKFs were lost, an "×" mark was given to patients in whom not even the trace of residual liquid (TRL) that makes PAS scoring possible could be obtained.

The results showed that the smallest CKFs with no TRL to allow PAS scoring was 2 frames for PAS 4 with laryngeal penetration overall, 8 frames for PAS 6 with aspiration overall, and 15 frames when limited to PAS 8 with SA. All three conditions were obtained with the patients swallowing a thin liquid (that is, with no added thickener).

Changes in PAS scores with complete disappearance of the consecutive key frames with no trace of residual liquid

With frame rate reductions, the CKFs with no TRL needed to determine PAS scores disappeared completely with PAS 4 only. The total number of patients was 0 at 15 fps, 1 at 7.5 fps, 3 at 6 fps, 3 at 5 fps, 4

Table 1 Characteristics of patients who met the inclusion criteria

	n = 74
Mean age (SD) (y)	75.0 (13.6)
Male/female	58/16
Pneumonia	24
(aspiration pneumonia/other)	(17/7)
Malignant neoplasm	15
(oral cancer/esophageal cancer/lung cancer/other)	(5/5/4/1)
Cerebrovascular disease	11
Neurodegenerative disease	6
Heart disease	4
Brain injury	3
Connective tissue disease	3
Spinal cord injury	2
Vocal cord paralysis	2
Other	4

Table 2 PAS score distribution on VFSS at 30 fps: CKFs and TRL to enable PAS scoring

PAS 3 (N = 6)		PAS 4 (N = 10)		PAS 5 (N = 10)		PAS 6 (N = 7)		PAS 7 (N = 6)		PAS 8 (N = 11)	
CKFs	TRL	CKFs	TRL	CKFs	TRL	CKFs	TRL	CKFs	TRL	CKFs	TRL
9	○	2	×	4	○	8	×	43	○	10	○
11	○	2	×	5	○	11	×	50	○	12	○
12	○	3	×	5	○	15	×	57	×	15	○
20	○	5	×	5	○	17	×	66	×	15	×
21	○	9	×	6	○	84	×	102	○	25	○
23	○	14	×	11	○	100	×	136	×	27	×
		14	×	15	○	134	×			33	×
		14	×	21	○					58	○
		15	×	27	○					74	○
		23	×	50	○					87	○
										111	×

When CKFs are completely lost, ○: residue that makes PAS scoring possible remains, ×: residue that makes PAS scoring possible does not remain, CKFs: consecutive key frames; TRL: trace of residual liquid; PAS: penetration-aspiration scale; VFSS: videofluoroscopic swallowing study.

at 4.3 fps, and 4 at 3.75 fps. Specifically, frames in which fluid reaching the glottis could be recognized completely disappeared, and PAS 4 could no longer be assigned, but frames remained in which liquid was ejected without reaching the glottis after laryngeal penetration. As a result, all assessors mistakenly judged all four PAS 4 patients as PAS 2.

Validity and reliability of PAS scores with reduced frame rates

Table 3 shows the differences in 30-fps PAS scores and PAS scores with frame rate reductions in 46 patients, excluding the four PAS 4 patients in whom CKFs with no TRL had completely disappeared. Table 4 shows the validity and reliability of PAS scoring when key frames had partially disappeared in the same 46 patients. Frame rates of 15 fps, 10 fps, 7.5 fps, 6 fps, 5 fps, 4.3 fps, and 3.75 fps all nearly completely agreed with 30-fps PAS scores.

When the incorrect assessments for all reduced frame rates from 15 fps to 3.75 fps for each of the PAS scores (3–8) shown in Table 3 were totaled, the rate of incorrect assessments was 12 of 42 patients (28.6%) for PAS 3, 10 of 42 patients (23.8%) for PAS 4, 14 of 70 patients (20.0%) for PAS 5, 12 of 49 patients (24.5%) for PAS 6, 0 of 42 patients (0%) for PAS 7, and 3 of 77 patients (0.04%) for PAS 8.

Sensitivity, specificity, positive predictive value, and negative predictive value for aspiration detection

The sensitivity, specificity, positive predictive value, and negative predictive value for the detection of aspiration (PAS 6–8) in the 50 patients are shown in Table 5. At 15 fps, 10 fps, 7.5 fps, 6 fps, 5 fps, 4.3 fps, and 3.75 fps, sensitivity was 91.7–100%, specificity was 88.5–96.2%, positive predictive value was 88.5–96.0%, and negative predictive value was 92.3–100%.

Although this was an exploratory study, the level for the reduced frame rate in aspiration assessment defined as acceptable prior to the analysis was satisfied in all seven steps of reduced frame rates. The lower limit for the provisional reduced frame rate allowable for aspiration assessment was 3.75 fps.

Table 3 PAS scores with decreased frame rates versus 30 fps: comparison of results (N = 46)

15 fps (rows) vs. 30 fps (columns)

PAS	1	2	3	4	5	6	7	8
1								
2			2	1	1			
3			**4**		1			
4				**3**				
5					**7**			
6				1		**7**		
7							**6**	
8				1	1			**11**

10 fps (rows) vs. 30 fps (columns)

PAS	1	2	3	4	5	6	7	8
1			1					
2			1	2				
3			**4**		1			
4				**4**		1		
5					**7**	1		
6					1	**5**		
7							**6**	
8					1			**11**

7.5 fps (rows) vs. 30 fps (columns)

PAS	1	2	3	4	5	6	7	8
1								
2				2				
3			**6**			1		
4				**3**				
5					**9**	1		1
6				1		**5**		
7							**6**	
8					1			**10**

6 fps (rows) vs. 30 fps (columns)

PAS	1	2	3	4	5	6	7	8
1								
2								
3			**6**					
4				**5**		3		
5					**9**			
6				1		**2**		
7						2	**6**	
8					1			**11**

5 fps (rows) vs. 30 fps (columns)

PAS	1	2	3	4	5	6	7	8
1			1					
2								1
3			**5**					
4				**5**	1			
5					**8**			
6						**5**		
7						2	**6**	
8				1	1			**10**

4.3 fps (rows) vs. 30 fps (columns)

PAS	1	2	3	4	5	6	7	8
1								
2			2					
3			**2**					
4			1	**6**	2			
5			1		**7**			
6						**7**		
7							**6**	
8					1			**11**

3.75 fps (rows) vs. 30 fps (columns)

PAS	1	2	3	4	5	6	7	8
1								
2			1					
3			**3**					
4				**6**	1			1
5			2		**9**			
6						**6**		
7						1	**6**	
8								**10**

PAS: penetration-aspiration scale; fps: frames per second.

DISCUSSION

Studies of reduced image capture frame rates in previous VFSS were premised on comprehensive swallowing assessments. It is no exaggeration to say that the trend in recent years is on the appropriateness of reducing 30 fps to 15 fps, including not only in adults, but also in children [30−35]. In contrast, this study reduced the frame rate in a stepwise fashion with the purpose of swallowing assessments in cases of aspiration only. This is thought to be clinically meaningful in terms of the aim of achieving highly reliable SA detection at bedside.

In this exploratory study, the CKFs was defined as the range of key frames essential for abnormal laryngeal penetration and aspiration assessment in a 30-fps VFSS of 50 adult dysphagia patients as a fresh approach.

Table 4 Validity and reliability of PAS judgment by reduced frame rate without complete disappearance of CKFs and TRL to enable PAS scoring (N = 46)

	30 fps		Intra-rater reliability		Inter-rater reliability	
Frame rate (fps)	Weighted kappa coefficient	95%CI	Weighhted kappa coefficient	95%CI	Weighted kappa coefficient	95%CI
15	.814	0.691–0.938	.887	0.813–0.961	.829	0.746–0.912
10	.837	0.740–0.934	.889	0.811–0.968	.829	0.738–0.919
7.5	.829	0.707–0.951	.887	0.779–0.996	.821	0.708–0.935
6	.858	0.751–0.965	.844	0.754–0.934	.881	0.774–0.988
5	.810	0.655–0.965	.850	0.738–0.963	.822	0.675–0.970
4.3	.890	0.807–0.973	.923	0.849–0.997	.812	0.711–0.913
3.75	.875	0.768–0.983	.876	0.761–0.991	.806	0.681–0.932

PAS: penetration-aspiration scale; CKFs: consecutive key frames; TRL: trace of residual liquid; CI: confidence interval.

Table 5 Sensitivity, specificity, positive predictive value, and negative predictive value of aspiration detection (N = 50)

Frame rate (fps)	Sensitivity (%)	95%CI	Specificity (%)	95%CI	Positive predictive value (%)	95%CI	Negative predictive value (%)	95%CI
15	100	0.902–1.000	88.5	0.723–0.966	88.9	0.732–0.968	100	0.902–1.000
10	95.8	0.821–0.995	92.3	0.775–0.984	92.0	0.767–0.983	96.0	0.828–0.996
7.5	96.0	0.828–0.996	96.0	0.828–0.996	96.0	0.828–0.996	96.0	0.828–0.996
6	91.7	0.759–0.982	92.3	0.775–0.984	91.7	0.759–0.982	92.3	0.775–0.984
5	95.8	0.821–0.995	92.3	0.775–0.984	92.0	0.767–0.983	96.0	0.828–0.996
4.3	95.8	0.821–0.995	96.2	0.834–0.996	95.8	0.821–0.995	96.2	0.834–0.996
3.75	95.8	0.821–0.995	88.5	0.723–0.996	88.5	0.723–0.996	95.8	0.821–0.995

CI: confidence interval.

For the obtained PAS score distribution and CKFs, as shown in Table 2, it was confirmed that, compared with all 26 patients with abnormal laryngeal penetration (PAS 3–5), the CKFs for all 24 aspiration patients (PAS 6–8) was larger and had a wider distribution. This result shows that aspiration is less susceptible than abnormal laryngeal penetration to the effects of partial or complete disappearance of the CKFs due to frame rate reduction. However, the characteristic of this distribution is that it was from a heterogeneous adult population of whom more than half had pneumonia or cancer, and verification in populations with different target diseases is necessary.

As shown in Fig. 1, when the frame rate of 30-fps video clips is reduced in seven steps, 15 fps corresponds to the disappearance of a single frame, and 3.75 fps corresponds to the disappearance of seven consecutive frames. Therefore, with video clips of seven or fewer key frames, it is possible that the key frames disappeared completely in the range of the reduced frame rates in the present study. As a result, the complete disappearance of CKFs could be confirmed only for abnormal laryngeal penetration. Specifically, there were four PAS 4 patients (CKFs 2, 2, 3, 5) and five PAS 5 patients (CKFs 4, 5, 5, 5, 6). However, the five PAS 5 patients had TRL, and even if CKFs disappeared completely, image information needed to judge PAS remained. Thus, of the 50 patients, video clips in which the images needed to properly assess PAS were completely lost in only four PAS 4 patients, and in abnormal laryngeal penetration, the minimum value for CKFs with no TRL could be identified as 2.

Next, in the 46 patients excluding these four, how key frame disappearance affected the accuracy of PAS judgments was assessed. The results, as shown in Table 4, indicated that if CKFs disappeared partially for reduced frame rates of 15–3.75 fps, there was almost complete agreement with 30 fps for PAS 3–8, and it was confirmed that high intra-rater reliability and inter-rater reliability were consistently obtained. Thus, it was confirmed that, unless CKFs disappear completely, the accuracy of PAS assessments for abnormal laryngeal penetration and aspiration was not adversely affected even with a reduction in frame rate to 3.75 fps.

In addition, in the same 46 patients, when the incorrect assessments for all reduced frame rates for each PAS score were totaled, and the percentage of incorrect assessments was examined, there was some divergence, with 0% for PAS 7, 0.04% for PAS 8, and more than 20% for PAS 3–6. Thus, in PAS scoring, even with the frame rate reduced to 3.75 fps, for unexpelled aspiration including silent aspiration, a particularly high assessment accuracy was supported.

Meanwhile, the minimum CKFs that makes it possible to assess aspiration with no TRL was identified to be 8 for PAS 6. In this study, the frame rate was reduced to 3.75 fps, at which seven consecutive frames disappear, but since the disappearance of eight consecutive frames corresponds to 3.33 fps, if the image loss is 267 ms or more, the CKFs of PAS 6 may disappear completely. Moreover, when limited to SA evaluation of PAS 8, the minimum CKFs with no TRL could be identified as 15. The disappearance of 15 consecutive frames corresponds to 2 fps, and so if there is image loss of 500 ms or more, CKFs may disappear completely. In the range of 15–3.75 fps, the CKFs of aspiration could be confirmed to disappear partially. Thus, at 3.75 fps, the complete disappearance of CKFs of aspiration could be avoided in all cases, and it was confirmed that mistaken PAS assessment did not occur.

In addition, since the analysis dataset was limited to abnormal cases, PAS 1–2 was not included. However, within a range in which the CKFs of aspiration do not disappear completely, as shown in Table 5, not only the sensitivity and positive predictive value of aspiration detection, but also the specificity and negative predictive value were consistently high, even with the frame rate reduced to 3.75 fps.

Although this was an exploratory study, the level for the reduced frame rate in aspiration assessment defined as acceptable prior to the analysis was satisfied by all of the analysis results, and the provisional lower limit was 3.75 fps.

The minimum CKFs with no TRL was 2, and theoretically it is possible that CKFs disappeared completely for all reduced frame rates of 10–3.75 fps. Thus, it was expected that, at 15 fps, the complete disappearance of CKFs was avoided in all cases, and no mistaken PAS assessments occurred at this frame rate. However, as a result of reducing the frame rate in a stepwise fashion from 15 fps to 3.75 fps, CKFs disappeared completely for reduced frame rates of 7.5–3.75 fps. This frame rate was lower than expected, but the reason that 10 fps was not included may have been that the key frames with a difference in the frame where omission started remained.

We reported the possibility of SLPs being able to evaluate the presence or absence of aspiration by bringing a Mobile-DDR to the bedside and imaging swallowing dynamics for a maximum of 20 seconds at 15 fps, and then using the replayable video on the Mobile-DDR monitor immediately afterward. This suggests that assessments by SLPs may be useful in rapidly evaluating aspiration at the bedside as a diagnostic aid to doctors [23]. In addition, the fact that reducing the frame rate to 3.75 fps in swallowing assessments was found to be acceptable means that the maximum imaging time can be extended without increasing the radiation dose to a level that is higher than that for imaging at a 15 fps frame rate. Unlike a VFSS, which is a comprehensive swallowing assessment, the use of a Mobile-DDR for the limited purpose of aspiration assessment is promising for standardizing interdisciplinary protocols for swallowing treatment at the bedside of seriously ill patients, in addition to FEES.

LIMITATIONS

Generalizability and Study Population

This was a retrospective, relatively small study at a single institution in a patient sample with a high degree of heterogeneity, and it was skewed toward elderly people mainly with pneumonia or malignant tumors. The distribution of CKFs in this group may be different from that in other clinically important groups, such as post-extubation ICU patients, young adults, and pediatric populations. Caution in interpreting the results is especially needed in populations with different pharyngeal phase durations or physical properties of the swallowed bolus. For example, infants and toddlers have shorter pharyngeal phase duration than adults, and it may be possible to decrease the CKFs more than in the present study [33]. Pharyngeal phase duration may be shorter even in children and other patients of small stature. The barium sulfate solution of 38% w/v used in the VFSS in the present study was adjusted to various viscosities, but since low-viscosity liquids have high fluidity, and their transfer is soon completed, it may be that CKFs can be reduced more than in the present study [31]. Transfer of liquid may also be completed quickly when a small volume is swallowed. With such decreases in CKFs, the lower limit of both the frame rate at which CKFs completely disappear and the frame rate that is allowable in swallowing assessments may be higher than in this study.

Use of Simulated Low Frame Rates

In the low-frame rate condition in the present study, images were not captured at a true low frame rate fluoroscopy setting. Rather, they were generated with post-processing of 30-fps recordings. The reason for adopting this approach was that, to accurately evaluate the effect of frame rate with respect to aspiration, it is necessary to capture aspiration with the same swallowing movements as in the recordings used for comparison. However, low-frame rate images generated in simulations may not perfectly reproduce the low-frame rate images obtained in actual imaging. This is because changes in imaging conditions, including X-ray pulse settings and dose, affect noise, motion blur, and image quality. With lower doses, for example, noise increases, and image quality becomes coarser.

Low-frame rate imaging conditions optimized for the diagnosis of aspiration, including the aim of avoiding unnecessary radiation exposure, are an important issue at the bedside of seriously ill patients under many restrictions.

Potential Rater-Related Bias

In this study, the gold standard with 30-fps PAS was established with the agreement of two doctors and one SLP with more than 30 years of experience in VFSS. Meanwhile, assessment of the blinded video clips with stepwise decreases in frame rate was randomly assigned to seven SLPs with at least 5 years of clinical experience evaluating dysphagia. In addition to the validity of each frame rate condition (comparison with the gold standard of 30 fps), inter-rater and intra-rater reliabilities were also assessed.

This ensures the rigor of the reference standard (30 fps), while at the same time being a design option based on differences in the purpose of testing the reproducibility of evaluations, for which the feasibility of implementation under radiation and workflow constraints was assumed. However, in addition to differences in the rater groups in establishing the reference standard and assessing the low frame rates, the possibility of an assessor effect (systematic bias) due to professional background and experience cannot be completely ruled out. The inability to strictly separate this from the effects of frame rate reductions is a limitation of this study.

In the future, it will be necessary to evaluate more directly the assessor effect, such as with cross-assessment in which multiple assessors (including people of different professional backgrounds and years of experience) conduct cross-sectional assessments of the same cases.

ACKNOWLEDGMENTS

This work was supported by a Grant-in-Aid for Scientific Research (C), MEXT KAKENHI Grant Numbers 22K11348 and 25K14541. Financial disclosure statements have been obtained, and no conflicts of interest have been reported by the authors or by any individuals in control of the content of this article.

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