
Simultaneous Assessment of Bolus Transport and Contraction Parameters in Multiple-Swallow Investigations

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A better understanding of scintigraphic findings may lead to a wider acceptance of esophageal transit studies. The purpose of this study, therefore, was to correlate standard manometric parameters with the quantitative and qualitative characteristics of liquid and semi-solid bolus transport. Twenty-nine patients were simultaneously investigated with esophageal scintigraphy and manometry. Single-swallow and sum-image data of six consecutive swallows were analyzed. No significant relationship between transit time and the velocity of the peristaltic wave could be identified, which suggests that factors other than peristaltic velocity (e.g., pharyngeal pump) essentially modulate esophageal transit. There was also no linear correlation between esophageal emptying and peristaltic amplitudes. Emptying was normal in patients with amplitudes >30 mmHg and reduced in those with amplitudes <30 mmHg. This suggests that a threshold pressure >30 mmHg is necessary to propel a test bolus adequately. Patterns in condensed images have been shown to specifically reflect the events in corresponding manometric recordings. Normal and different pathologic types of peristalsis presented analogous findings in both modalities. Thus, an analysis of the relationship between bolus transport and contraction parameters in simultaneous studies increases understanding of quantitative and qualitative scintigraphic results.

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Radionuclide measurement of esophageal transit has been proposed as a sensitive screening test for the assessment of esophageal motor dysfunction (1-3). However, its diagnostic role is still under discussion (4-9), even though some drawbacks of previous methods have been resolved by recent developments. Condensed images have been used to aid in the interpretation of esophageal scintigraphy and some investigators prefer this approach over other methods (10-13). Multiple-swallow protocols employed to compensate for the intra-individual variation between

repetitive swallows have been shown to enhance diagnostic accuracy (14,15).

The acceptance of esophageal scintigraphy as a useful clinical test might increase with a better understanding of its results. As previously suggested (16), this may be attained by correlating scintigraphic with simultaneously assessed manometric data. However, experience with such studies is still limited, with respect to the number of patients investigated, the bolus consistency used and the number of swallows correlated by both modalities (6,17,18). In particular, the results of multiple-swallow investigations and patterns in condensed images have not been correlated with manometric findings so far. Therefore, in this study, scintigraphy and manometry were simultaneously performed to compare the quantitative and qualitative characteristics of liquid and semi-solid bolus transport with standard manometric parameters. A multiple-swallow protocol was used (15), which permitted the evaluation of six consecutive swallows during a single investigation.

MATERIALS AND METHODS

Patients

Twenty-nine patients referred to the Division of Nuclear Medicine for the investigation of esophageal function were prospectively studied with simultaneous scintigraphy and manometry. There were 15 males and 14 females (age range, 34 to 71 yr, mean, 52 yr) suffering from diseases which are commonly associated with esophageal motor dysfunction: manifest or suspected connective tissue disease (n = 13), gastroesophageal reflux disease (n = 6), achalasia (n = 3), insulin-dependent diabetes mellitus (n = 3), unexplained dysphagia (n = 3) and noncardiac chest pain (n = 1).

The patients were investigated after an overnight fast. Studies with liquid and semi-solid test boluses were performed consecutively. If necessary, the patients were asked to clear residual esophageal activity between the two investigations by drinking unlabeled water in an upright position.

In addition, scintigraphic studies were repeated after removal of the catheter.

Esophageal Scintigraphy

The acquisition and processing protocols for the evaluation of multiple consecutive swallows were described previously (15).

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Acquisition. Patients were studied in the supine position with an LFOV gamma camera connected to a commercially available computer system (Siemens MicroDelta, Germany). Esophageal transit studies were performed with six radiolabeled liquid and semi-solid test boluses each. The transit of liquid bolus was studied with water (10 ml per swallow, labeled with approximately 10 MBq of ^{99m}Tc -sulfur colloid). Semi-solid bolus investigations were performed with a baby paste prepared according to a standardized protocol: 20 g instant Alete Milch-Fertigbrei[®] were dissolved in 40 ml water and administered in portions of 10 g per swallow labeled with approximately 5 MBq of ^{99m}Tc -sulfur colloid.

During dynamic data acquisition (240 frames; 0.8 sec/frame; byte mode; 64×64 matrix), a radiolabeled test bolus was administered every 30 sec. The patient was asked to ingest the bolus by one single deglutition and then to avoid swallowing for 30 sec until the next bolus was offered.

Processing. From each dynamic study, a condensed image was created, showing the six consecutive swallows in a space-time matrix. Condensation was confined to a user-defined ROI comprising the esophagus from the pharynx to the lower sphincter. The method and algorithms used for image condensation were described previously (11,13). In the raw version of a condensed multiple-swallow image, the single swallows were standardized with respect to their starting points, arranged consecutively, and added to a condensed sum image, which comprises the representative information of the entire study.

For quantitative evaluation, time-activity curves were derived from the sum and all six single-swallow images. The curves were generated by plotting the count rates of the columns assembled in each image. The count rate of each column was obtained by

addition of its single pixel data. Esophageal emptying was expressed in percent of the peak activity and was calculated 12 sec after the swallow was initiated (15). Values $<80\%$ were considered pathologic. As explained previously (15), in particular cases, esophageal emptying of a single swallow may exceed the value of 100%, for example, if residual activity from a preceding swallow will be cleared with the following one. Global esophageal transit time was determined as the time from the starting point of a swallow until esophageal activity fell to 10% or less of the peak activity. Due to consecutive swallowing at 30-sec intervals, however, only transit times of 20 sec or less could be defined numerically. Transit times exceeding 20 sec were referred to as >20 sec and excluded from regression analysis with manometric parameters.

In the simultaneous studies, quantitative data were evaluated for each single-swallow and the corresponding sum image. Qualitative evaluation of esophageal function was performed by analyzing the bolus behavior in condensed images. A representative example of regular semi-solid bolus transport in a multiple-swallow study is shown in Figure 1.

Esophageal Manometry

Esophageal manometry was performed with a seven-lumen tube, 5.0 mm external diameter, which was passed through the patient's nose and then swallowed. Each lumen of the catheter assembly had a side hole of 1.0 mm diameter and was continuously perfused with water at 1.0 ml/min by a low-compliance pneumohydraulic pump (Mui Scientific, Ontario, Canada). Pressure rise with total occlusion of a side hole was >250 mmHg/sec. First, a conventional manometry was performed with the sonde

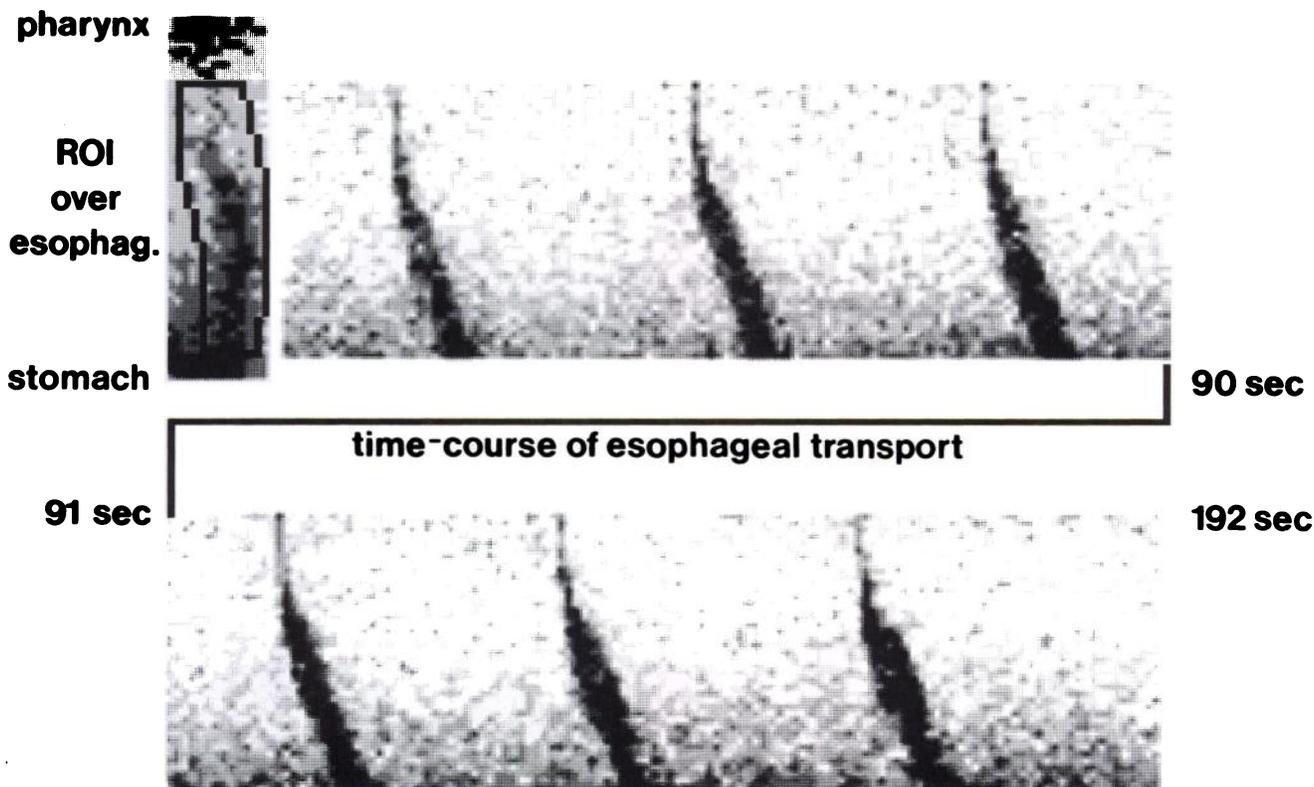


FIGURE 1. Display of the condensed image from a multiple-swallow investigation. This example shows regular transit of a semi-solid test bolus in each of the six consecutive swallows investigated.

having four side openings distally in order to ensure that the lower esophageal sphincter position could be determined exactly. A special sonde was then inserted with the openings placed 0.5, 1, 4, 9, 14, 18 and 22 cm above the lower esophageal sphincter. Esophageal intraluminal pressure was transmitted to a pressure transducer (Statham) and displayed on a chart recorder (Hellige Recomed, Germany). Pressure amplitudes (mmHg) of each recording site were measured from the mean baseline pressure to the peak of the peristaltic wave. In some patients, the proximal opening of the catheter assembly was located in the upper esophageal sphincter, and recordings from this lumen were therefore excluded from further evaluation. The arithmetic mean of the remaining six recordings was used to define a mean peristaltic amplitude for each single swallow. Peristaltic velocity (cm/sec) was calculated from 18 to 0.5 cm above the lower esophageal sphincter. However, due to hypo-aperistalsis (amplitudes <10 mmHg) or recording artifacts (as caused by breathing), this parameter could not be obtained for each single swallow. From the arithmetic mean of the single-swallow data, an average peristaltic amplitude and velocity was calculated for each multiple-swallow investigation.

Manometric findings were interpreted according to visual and quantitative criteria as outlined by Richter and colleagues (19). In the present investigation, mean values of peristaltic amplitudes <30 mmHg were prospectively defined as pathologic (19).

Statistical Analysis

The esophageal contraction amplitude (cut-off limit prospectively set at 30 mmHg) was used as gold standard for defining normal and abnormal tubular esophageal function. Patients with simultaneous contractions ($n = 3$) exclusively had an average pressure amplitude <30 mmHg and were therefore not evaluated as a separate group. According to these criteria, the sensitivity and specificity of scintigraphic findings were calculated. The relationship between scintigraphic (esophageal emptying, transit time) and manometric (peristaltic amplitude and velocity) data was analyzed by linear regression with the level of significance set at 0.05.

RESULTS

Scintigraphic Versus Manometric Findings

Manometric findings of liquid and semi-solid bolus investigations were normal in 19 patients and pathologic in 9 patients. In one patient, esophageal manometry showed normal results for the liquid bolus, but pathologic results for the semi-solid bolus study. The manometric findings and the corresponding results of the simultaneous esophageal scintigraphy are summarized in Table 1. Concordant findings were observed in 83% of studies with liquid boluses and in 76% of studies with semi-solid boluses, respectively. The predictive value of a negative test was 89% for liquid and 88% for semi-solid bolus studies. The predictive value of a positive test was 70% for liquid and 62% for semi-solid bolus studies.

Quantitative Evaluations

The quantitative scintigraphic and manometric findings are summarized in Figures 2 and 3.

The relationship between transit time and the velocity of peristaltic wave propagation is shown in Figure 2. For

TABLE 1
Findings in Simultaneous Esophageal Manometry and Scintigraphy

	Scintigraphy			
	Liquid		Semi-solid	
	Negative	Positive	Negative	Positive
Negative	17	3	14	5
Manometry				
Positive	2	7	2	8
Sensitivity*	77.7%		80.0%	
Specificity*	85.0%		73.7%	

* Manometry taken as gold standard.

single swallows, in neither liquid (Fig. 2A) nor semi-solid test boluses (Fig. 2B) could a significant linear correlation between transit time and peristaltic velocity be identified. Within the range investigated (patients with transit times >20 sec and those with simultaneous contractions were excluded from regression analysis), an inverse linear trend was found. Sum-image data revealed comparable relationships (Fig. 2C,D).

The relationship between esophageal emptying and the amplitude of peristaltic contraction is summarized in Figure 3. Single-swallow findings are displayed in Figure 3A for liquid and in Figure 3B for semi-solid bolus studies. No linear correlation between emptying and the amplitude of contraction was identified. Sum-image data (Fig. 3C,D) compensate for the intra-individual variation between single swallows and therefore depict the relationship between the latter parameters more precisely. Mean amplitudes >30 mmHg always (except for a few cases in the simultaneous studies) led to normal esophageal emptying (>80%). Regression analysis between emptying and amplitudes >30 mmHg showed no linear relationship. The correlation coefficient was $r = 0.29$ ($p = 0.08$) in simultaneous studies and $r = 0.02$ ($p = 0.92$) in studies after removal of the catheter, respectively. In most cases with amplitudes <30 mmHg, esophageal emptying was impaired (<80%). The correlation of emptying with amplitudes <30 mmHg did not reveal a linear relationship either. The correlation coefficient was $r = 0.23$ ($p = 0.35$) in the simultaneous investigations and $r = 0.29$ ($p = 0.28$) in studies after removal of the catheter. Similar results were obtained if patients with simultaneous contractions ($n = 3$) were excluded from regression analyses. In patients with amplitudes <30 mmHg, simultaneously assessed esophageal emptying (liquid: $57\% \pm 28\%$, semi-solid: $53\% \pm 22\%$; values are mean \pm s.d.) was significantly lower ($p < 0.01$, Student's *t*-test), compared to the corresponding data in patients with amplitudes >30 mmHg (liquid: $91\% \pm 9\%$, semi-solid: $85\% \pm 18\%$).

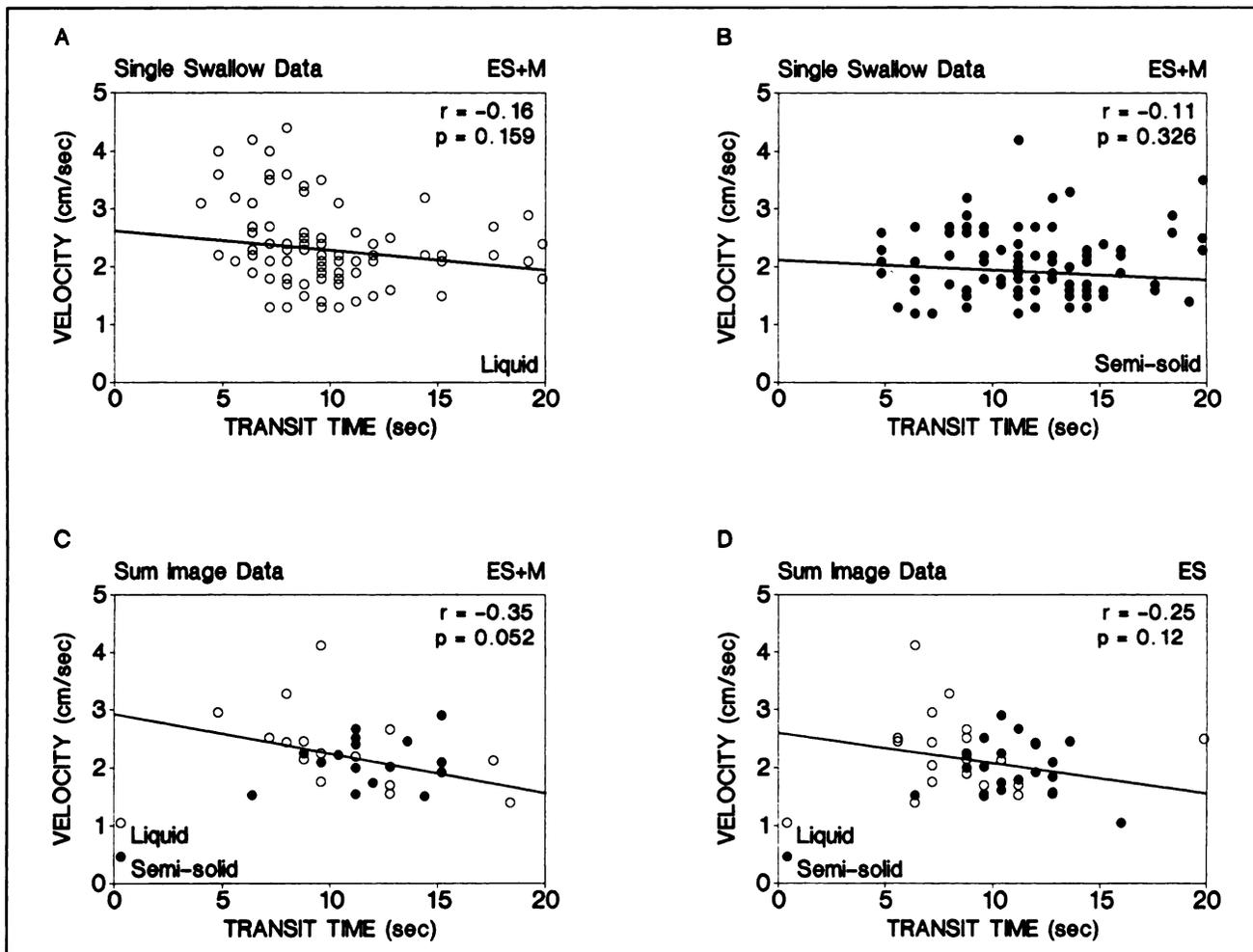


FIGURE 2. Relationship between transit time and velocity of peristaltic wave propagation in simultaneous esophageal scintigraphy and manometry (ES + M). The data show an inverse linear trend but no significant correlation. Single-swallow findings of liquid (A) and semi-solid (B) bolus investigations. Sum-image data of simultaneous studies (C) and those of a study (ES) repeated immediately after removal of the manometric tube (D).

Qualitative Evaluations

The comparison of condensed image patterns with the amplitude and progression of peristaltic waves as seen on manometric recordings revealed a close relation. Normal bolus behavior and various deviations occur coincidentally in both modalities. As shown in Figures 4–7, the patterns in condensed images display analogous findings to corresponding manometric recordings in normal swallowing, repetitive and aberrant swallows, deglutitive inhibition, intermittent phenomena, simultaneous contractions or focal functional disturbances.

DISCUSSION

Since radionuclide measurement of esophageal transit has been established to assess esophageal motor function, scintigraphic findings have been compared with manometric data to evaluate the diagnostic role for scintigraphic techniques (1–9). Whereas sensitivity and specificity of

the scintigraphic approach were taken into consideration by most investigators, only a few made a closer comparison of the parameters obtained by either method (6,17,18,20–22). In particular, experience with simultaneously performed studies, which enable correlations of transit with contraction parameters in individual swallows, is still limited (6,17,18). However, this approach seems essential to further improve the understanding and interpretation of scintigraphic findings.

To our knowledge, this is the first simultaneous scintigraphic and manometric study that: (a) investigates the passage of liquid and semi-solid test boluses, (b) correlates the quantitative data of multiple swallows in both modalities and (c) compares condensed image patterns with corresponding manometric recordings.

In our investigation, the sensitivity and specificity of esophageal scintigraphy is within the spectrum reported earlier (5,6,8,9). However, our data have to be interpreted with caution. First, the low sensitivity (liquid: 77.7%, semi-

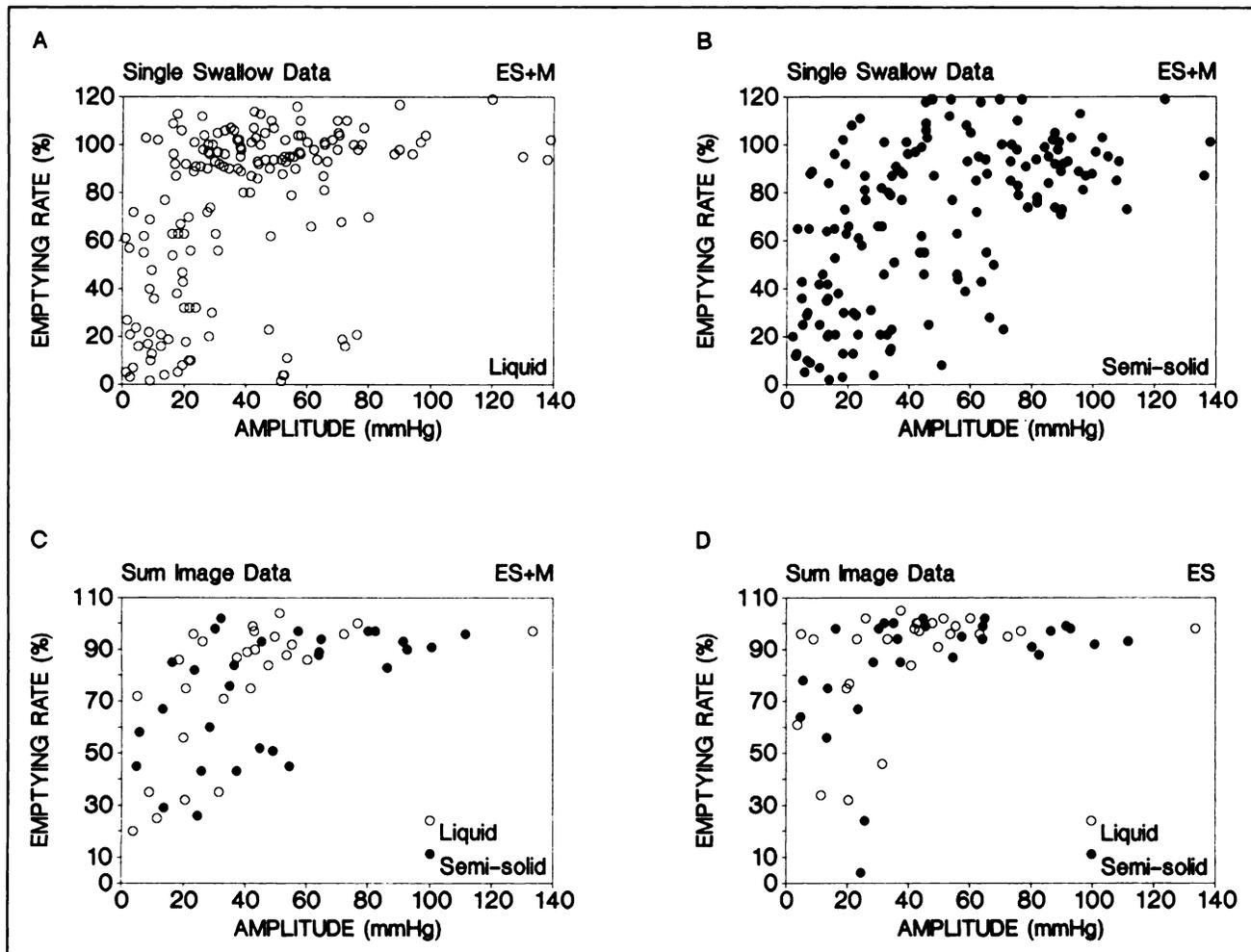


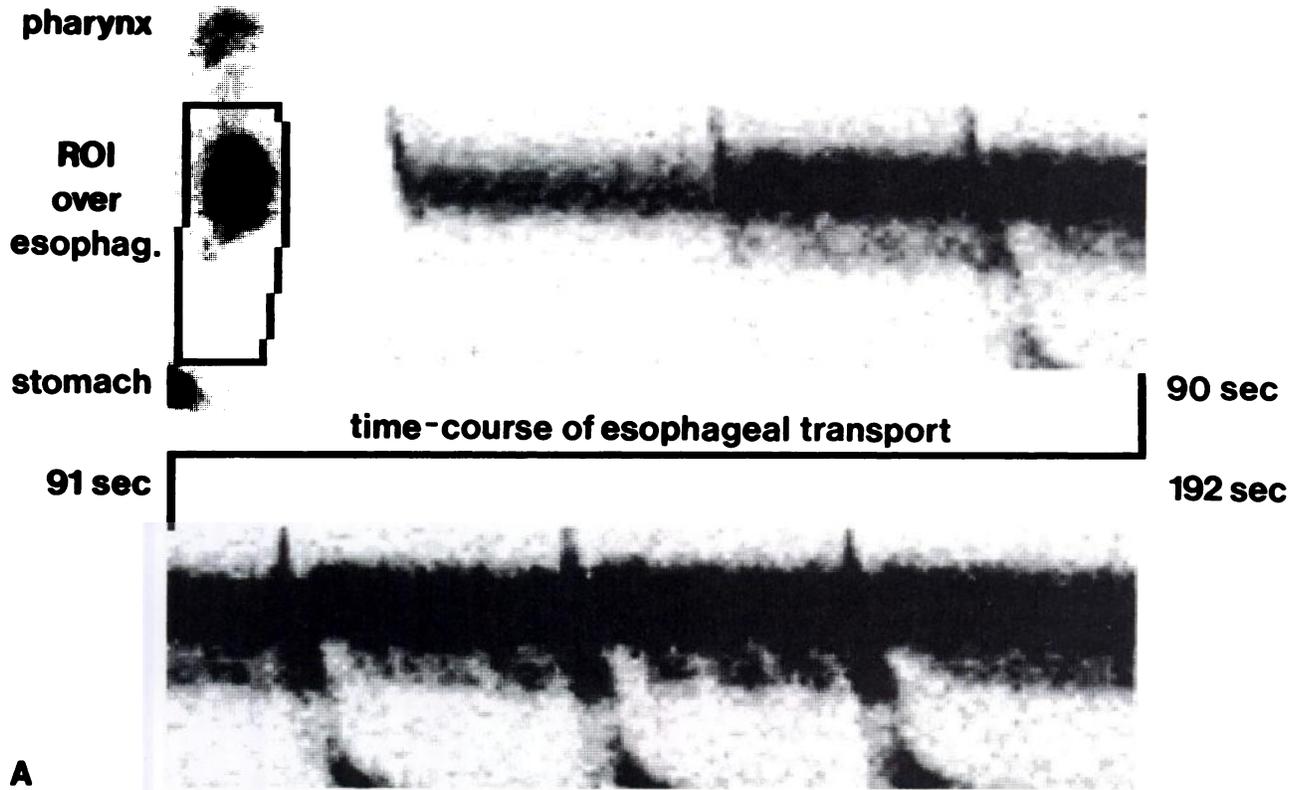
FIGURE 3. Relationship between esophageal emptying and the amplitude of peristaltic waves in simultaneous scintigraphic and manometric studies (ES + M). No linear correlation is detected. Single swallow findings of the liquid (A) and semi-solid bolus (B) investigations. Sum-image data of the simultaneous studies (C) and those (ES) after removal of the tube (D).

solid: 80%) may be due to the limited number of patients ($n = 10$) with esophageal dysfunction in this study. In a larger group of patients investigated in our department ($n = 47$), the sensitivity of esophageal scintigraphy was 95%. Second, specificity (liquid: 85%, semi-solid: 73.7%) is partially compromised by an irritating effect of the manometry catheter; all patients with negative manometric and positive scintigraphic findings in the simultaneous study had negative scintigraphy after the catheter was removed, thus raising specificity to 100%.

In our study, an inverse linear trend could be identified between transit time and the velocity of the peristaltic wave, but there was no significant correlation. In contrast, Richter and coworkers (18) found a significant relationship between both parameters. However, their patient population was different, the number of patients and swallows investigated was considerably smaller, and their studies were only performed with liquid boluses. We also investigated semi-solids, which particularly yielded weaker correlations. O'Sullivan and co-workers (17) found that

regional transit time does not reflect peristaltic propagation. Spiegel and colleagues (21) also did not observe significant pairing between the velocity of the contractile wave and esophageal emptying time. These casuistic observations are confirmed and extended by our data. Missing correlations suggest that esophageal bolus transport is also essentially mediated by factors other than peristaltic velocity. As previously shown (2,23,24), the pharyngeal pump may be one major mechanism. The pharyngeal ejection force propels the leading edge of a liquid bolus to the gastroesophageal junction immediately, leaving minimal work to be done by peristalsis. More viscous boluses are only propelled over the proximal half of the esophagus, thus requiring more intense peristaltic action to complete transport over the distal half (24). Thus, transit of viscous boluses might reflect peristaltic velocity more adequately, particularly in the distal esophagus. Since our approach only considered global esophageal parameters, we were not able to support this hypothesis in the present study.

Amplitudes <30 mmHg led to reduced emptying,



A

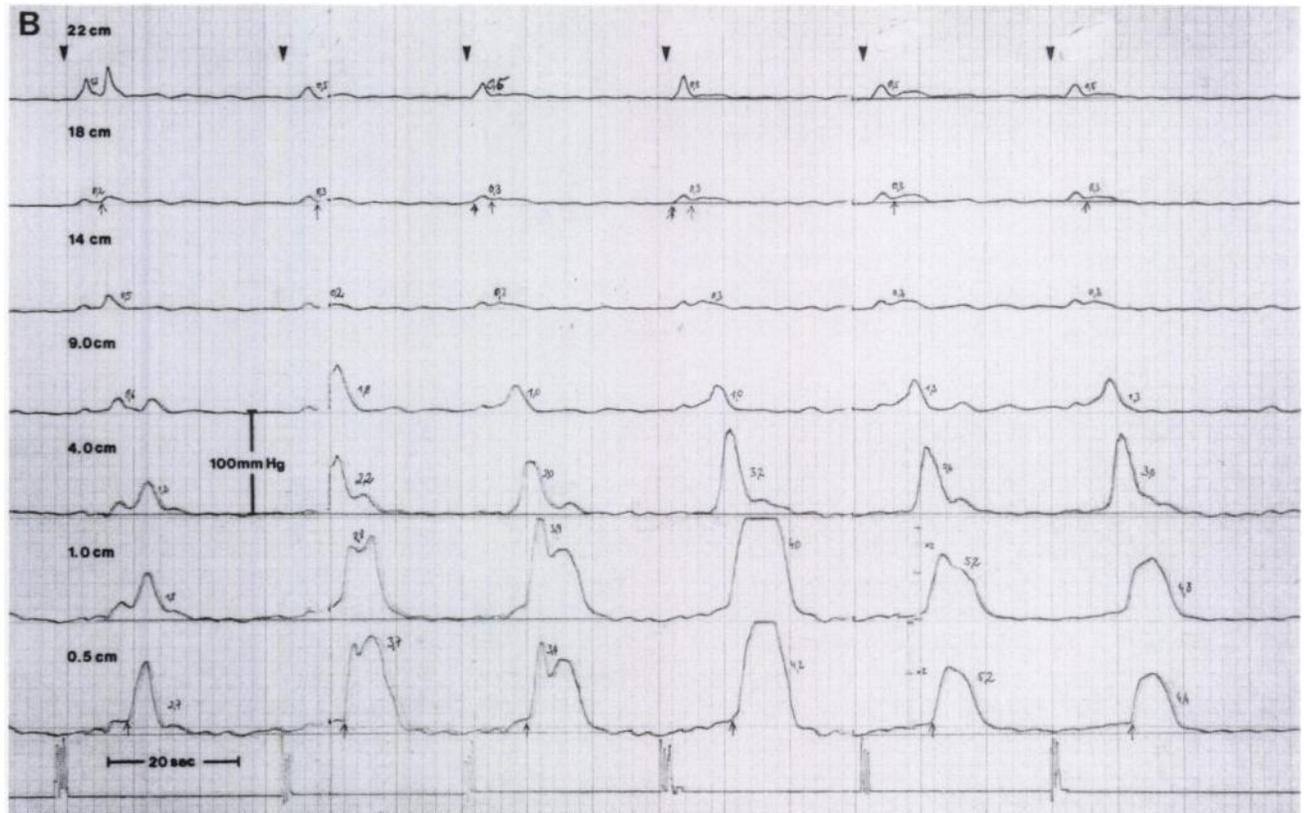
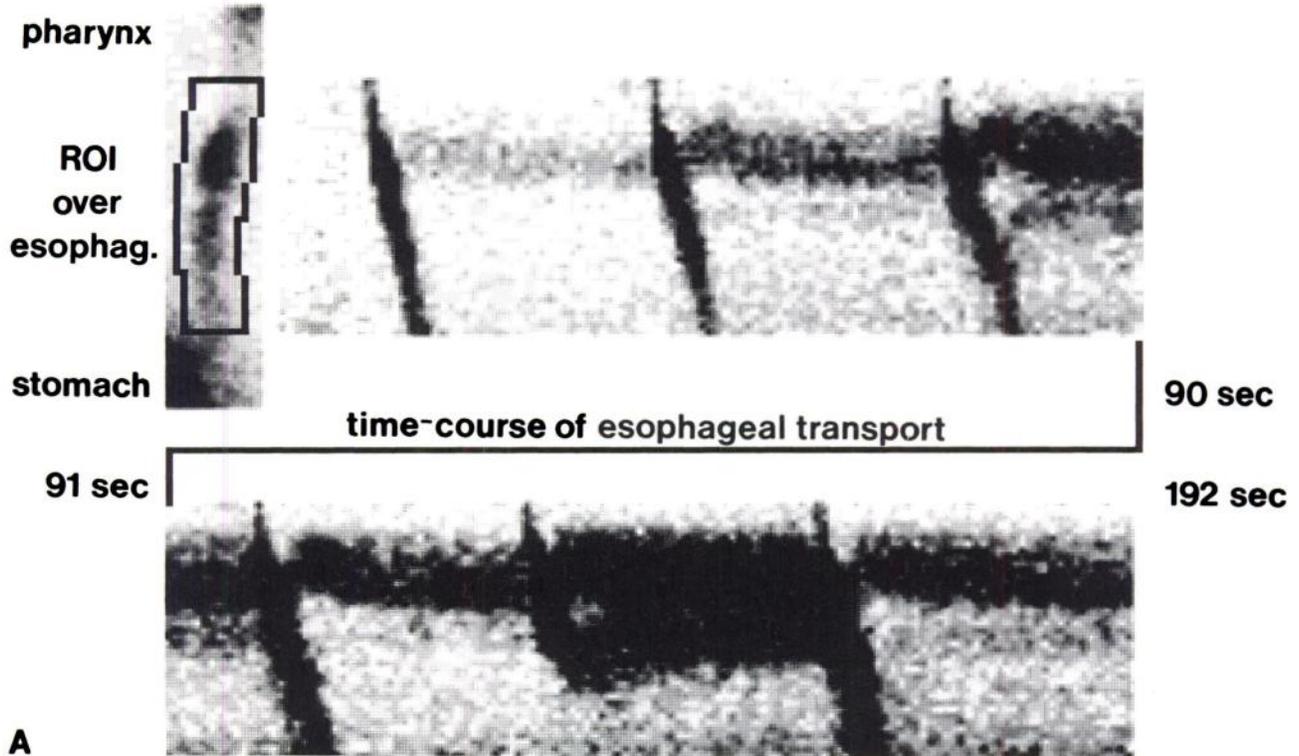


FIGURE 4. The condensed image shows delayed emptying of the proximal esophagus in each single swallow (A). After (parts of) the bolus have passed this segment, regular transport through the distal half is seen. The manometric recording displays (B) in each of the six swallows markedly reduced amplitudes in the corresponding portion of the esophagus. Amplitudes in the distal esophagus are regular.



A

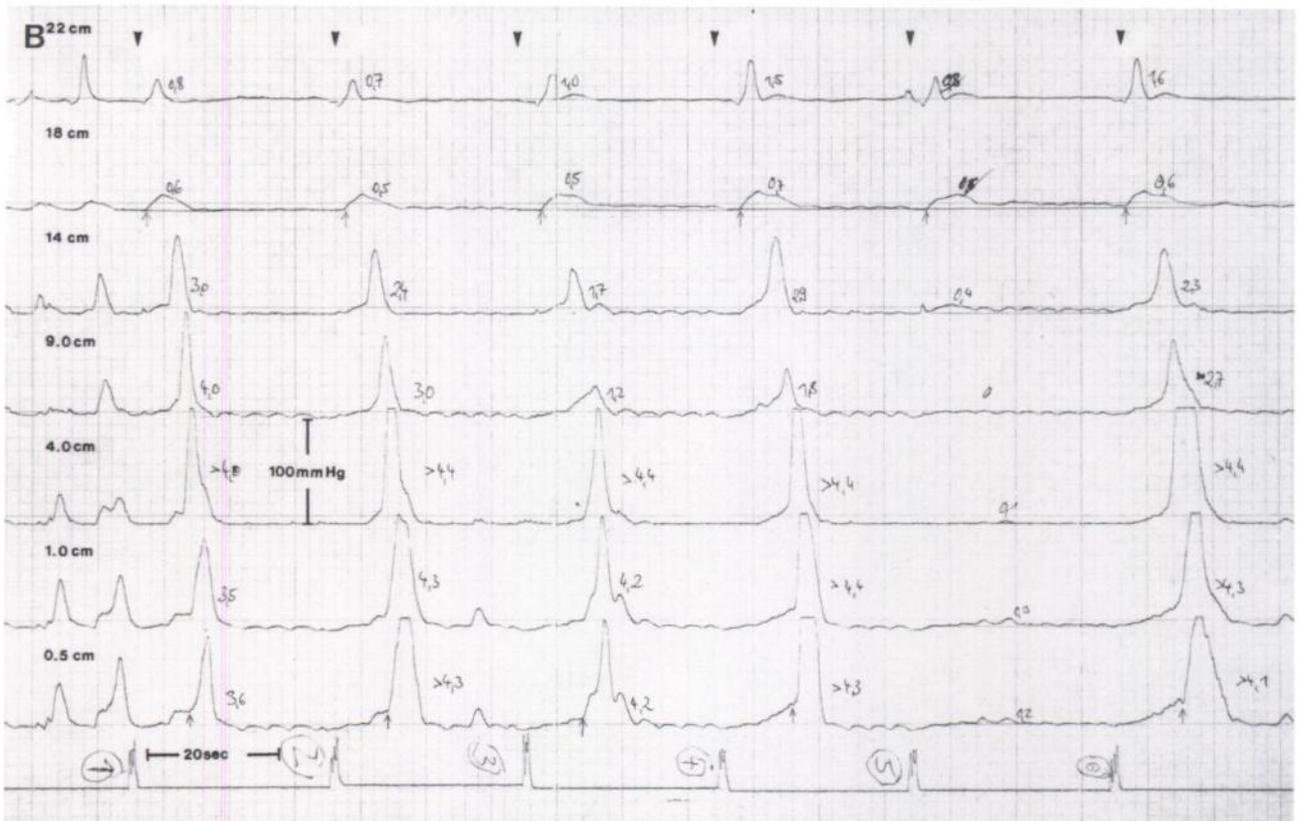
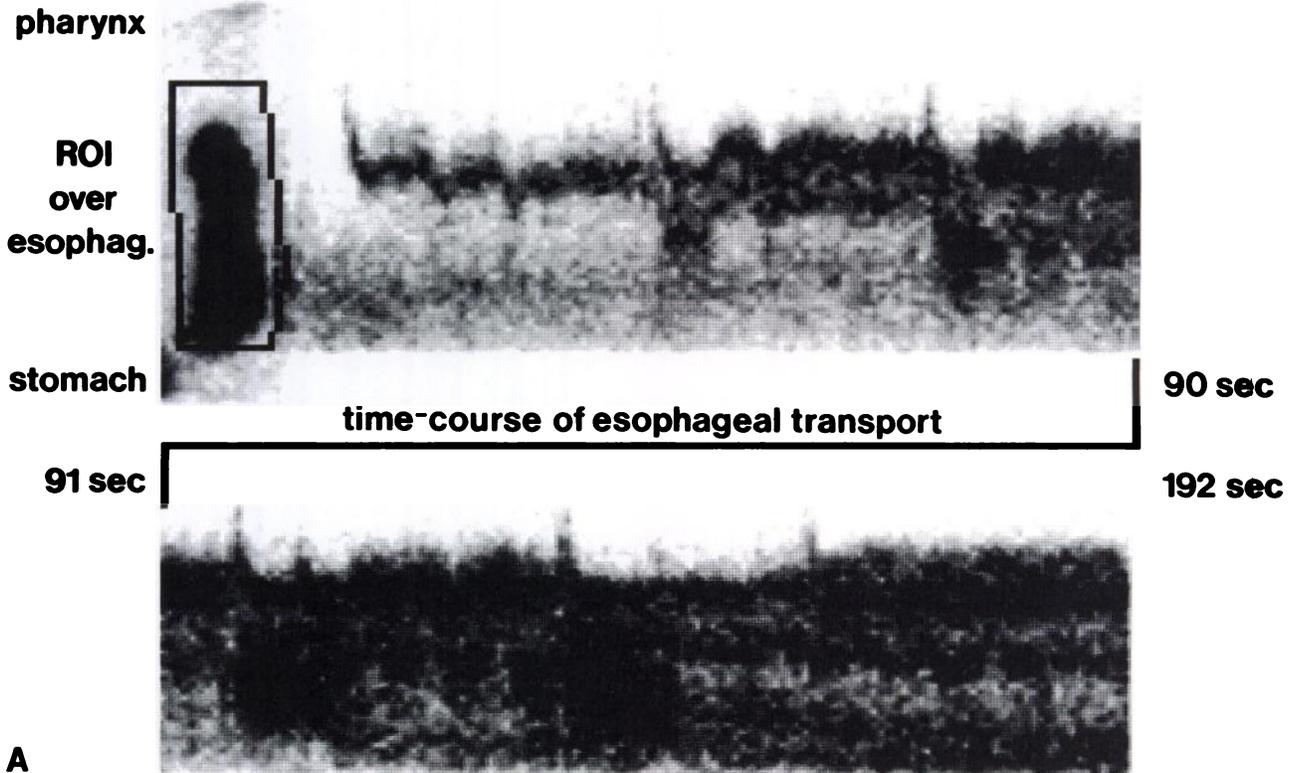


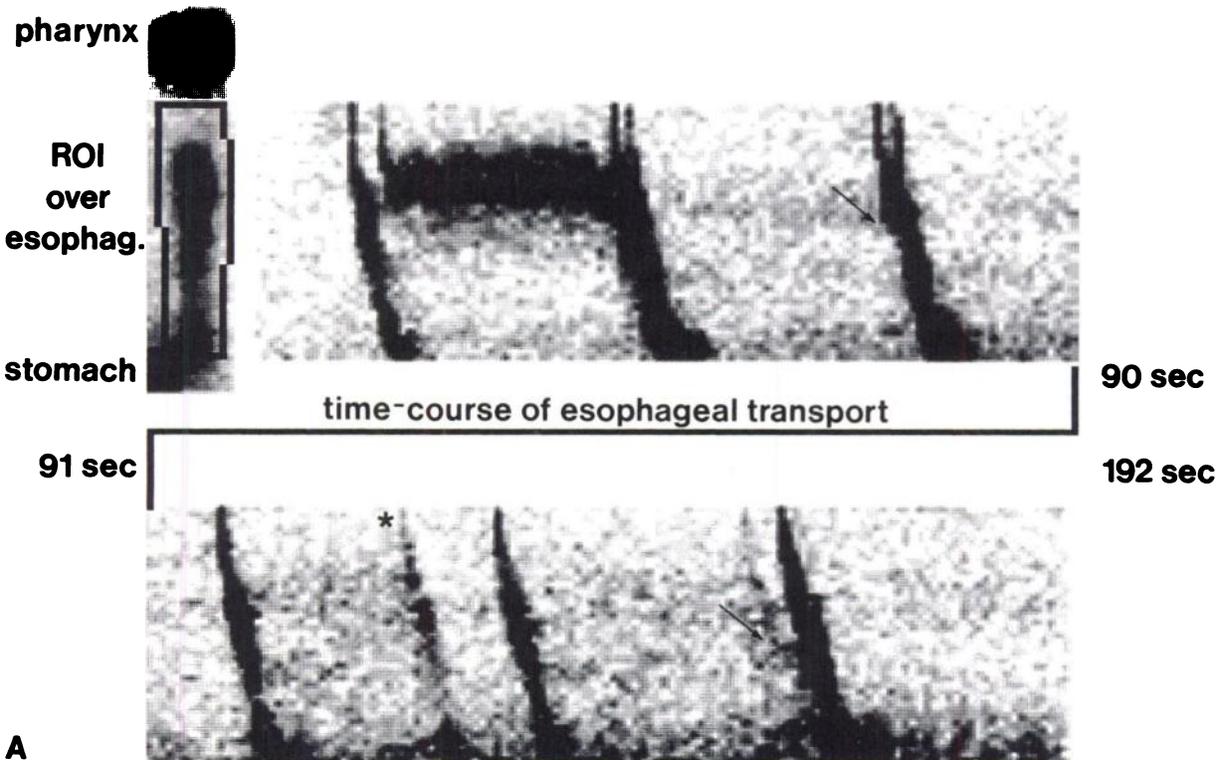
FIGURE 5. Segmental impairment of esophageal function in the proximal part, showing delayed emptying in the condensed image (A) and reduced amplitude in the manometric curve (B). The fifth swallow displays an intermittent phenomenon. The bolus is stuck in the proximal two-thirds of the esophagus; manometry shows almost no measurable amplitude in this particular swallow. The main portion of activity is cleared with the next swallow showing regular amplitudes in the distal esophagus again.



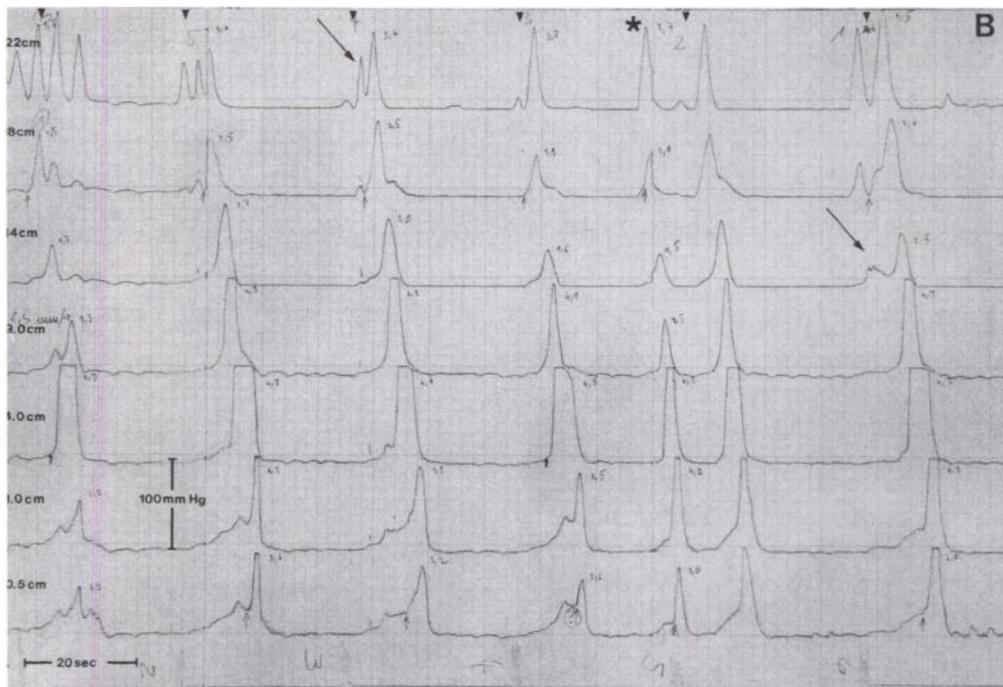
A



FIGURE 6. The condensed image (A) displays severely delayed emptying of almost the entire esophagus, clearly recognizing oscillatory bolus movements as well. Analogous to this observation, the manometric recording (B) apparently shows simultaneous contractions in this patient with achalasia.



A



B

FIGURE 7. This particular case summarizes a number of phenomena and artifacts with possible pitfalls for interpretation. The first swallow in the condensed image (A) is followed by another one shortly afterwards, which results in delayed emptying. The corresponding manometric recording (B) of this event was difficult to interpret, but possibly the swallow following the first, regular one was not peristaltic. Regular swallows 2, 3, and 6 showed the phenomenon of deglutitive inhibition in both modalities. In the manometric recording, the progression of the peristaltic wave is interrupted (at different levels) (→) by a following, regularly progressing peristaltic wave. The analogous finding in the condensed image is a brief interruption of bolus transport at the corresponding level, best seen in the third and sixth swallow (→). Between the fourth and fifth regular swallow, an aberrant swallow (*) is detected with regular manometric and scintigraphic characteristics. The condensed image shows that residual activity in the mouth of the patient from a preceding swallow suffices to register this event adequately.

whereas emptying was regular in patients with amplitudes >30 mmHg. These data suggest that above a certain level, esophageal transport (provided that propagative peristalsis is present) is independent of the peristaltic amplitude. This is in agreement with two previous reports (18,20), which showed no change in radionuclide transit with contractile amplitudes ranging from 30 to max. 500 mmHg. In most of our patients with amplitudes <30 mmHg, esophageal emptying was moderately to severely reduced. In contrast to Drane and co-workers (22), however, we were not able to confirm a linear correlation between emptying and pressure values ranging from 0 to 30 mmHg, which they observed in 11 patients with progressive systemic sclerosis.

Because our approach was limited to global quantitative data, it might be too insensitive to detect more distinct dependencies between transport and contraction parameters. Prospective studies that focus on a segmental analysis of quantitative findings in both modalities might further clarify potential relationships. Visual analyses of esophageal segments in condensed images and manometric recordings, as performed in this study, suggest that such an approach may be successful in quantitative data as well.

The benefits of condensed imaging techniques to precisely characterize the fate of a test bolus have been previously shown (11,12,15,16). Our investigation additionally demonstrates that patterns in condensed images specifically reflect the events in the simultaneous manometric recordings. Normal and abnormal swallowing have shown analogous findings in both modalities. These observations not only enhance the understanding and interpretation of various condensed image patterns, but also demonstrate that the major findings in manometric recordings are detectable with condensed images.

In conclusion, this study has shown that liquid and semi-solid bolus transport is independent of: (a) the propagation velocity of a peristaltic wave (except in cases of simultaneous contractions) and (b) the pressure amplitude above a threshold value of approximately 30 mmHg. Other factors such as the pharyngeal ejection force also mediate bolus transport. This influence is comprised within the scintigraphic data but not reflected in standard manometric findings. Condensed images have shown analogous findings to those in corresponding manometric recordings, thus accentuating their distinguished role for adequate depiction of esophageal events by a scintigraphic approach.

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