The American Journal of Gastroenterology
Copyright © 1999 by Am. Coll. of Gastroenterology
Published by Elsevier Science Inc.

Vol. 94, No. 2, 1999
ISSN 0002-9270/99/$20.00
PII S0002-9270(98)00728-X

Clinical reviews

Multiple Intraluminal Electrical Impedancometry for Recording of Upper Gastrointestinal Motility: Current Results and Further Implications

H. N. Nguyen, M.D., J. Silny, Professor, and S. Matern, Professor

Department of Internal Medicine III (Gastroenterology, Hepatology and Endocrinology), University Hospital, University of Technology RWTH-Aachen; and Helmholt Institute for Biomedical Engineering, University of Technology RWTH-Aachen, Aachen, Germany

This review focuses on current aspects of the novel technology of multiple intraluminal electrical impedance measurement. It presents methodological features, summarizes current results, and discusses potential implications for further research. The impedance technique assesses a bolus transport and its associated peristalsis. Validation studies showed a good analogy between physically deduced impedance characteristics and characteristics derived from cineradiography and manometry. From the impedance tracings, it is possible to distinguish between resting states, bolus transit, and wall contraction. Characteristics of a peristaltic wave can be obtained. In human studies, esophageal and small intestinal peristaltic patterns can quantitatively and qualitatively be assessed. A high resolution recording of bolus movements with interesting details of transport and mixing can be obtained. On the basis of several prior characterized impedance tracings duodenal contractile patterns have been classified, and the interdigestive and postprandial states characterized. For reflux evaluation the impedance technique was especially useful for the detection of nonacid gastroesophageal reflux, which is not detectable by pH monitoring. In summary, the main impact of the impedance technique is its capability to characterize esophageal and intestinal chyme transport. Important data on luminal chyme transport have been obtained. This technique is developing into an interesting investigative tool to complement standard techniques for study of upper GI motility, in particular for basic research. (Am J Gastroenterol 1999;94:306–317. © 1999 by Am. Coll. of Gastroenterology)

Received June 4, 1998; accepted Sep. 18, 1998.

INTRODUCTION

One of the most important functions of the gastrointestinal tract (GIT) is the transport of food and fermented material from one digestive stage to another. This is based on propulsive mechanisms distributed along the whole length of the organ. Using intraluminal manometry important advances have been made in understanding both normal and abnormal gastrointestinal motility. This technique is already established as a main diagnostic modality in the esophagus (1–4). In the small bowel it is now moving into clinical focus (5, 6).

For the most part, the study of esophageal bolus transport has centered on interpretations of intraluminal manometry alone, radiography alone, or manometric data collected concurrent with videofluoroscopy. Intraluminal manometry measures force per unit area on ports fixed within the lumen and records the contractile patterns in a number of narrow segments of the muscular tube. Based on the spatiotemporal sequence of events, the integrity function of the esophagus can be deduced because the underlying motor physiology has been clearly defined (5). On the other hand, radiological imaging procedures visualize the position and contour of a marked bolus in a rough time sequence, and thereby provide information about geometrical variations of the esophageal lumen with time. On principle, manometric means are used to characterize certain aspects of the contraction patterns, whereas fluoroscopic methods show the bolus transport that results from this motor activity. Thus, these techniques can be regarded as complementary techniques by which different aspects of bolus transport can be verified (7–9). Applying synchronous videofluoroscopy and manometry, the complex relationship between muscle contraction, intrabolus forces, and bolus transport can be investigated (8, 10–13). Simultaneous application of both techniques, however, requires considerable technical support as well as experience and expertise in their performance and interpretation. There are also limitations to these techniques: radiography is insensitive to contractions occurring in esophageal segments devoid of bolus fluid, whereas manometry is insensitive to contractions that do not occlude the lumen. Another important finding is that intrabolus and extrabolus pressures seem to have different properties (12), and therefore may limit the interpretation of manometric pressures pertaining to associated bolus transport.

In the small intestine, intraluminal manometry is an excellent technique to determine characteristics of the interdigestive state (14), as well as to differentiate between neuropathic and myopathic processes (5, 15, 16). However, detailed information on small intestine chyme transport, in particular after a meal, are still lacking. The causes are partly methodological limitations, as manometry measured only contractile activities exerted by the bowel wall on a sensor within the lumen, whereas information about transit of luminal contents cannot reliably be inferred from pressure changes. If contractions are lumen-occlusive, an accurate measurement of the contractile force at that locus can be obtained. In contrast, if contractions are not lumen-occlusive, the contractile force exerted by the smooth muscle is dissipated by the intraluminal contents. Thus, the resultant pressure within the cavity will depend not only on the nature of the contents, but also on the size of the cavity and that, in turn, depends on the distance between points at which the lumen is occluded. A prediction of the direction of the bolus movement is not possible. It is also important to remember that although pressure events within the bowel are customarily referred to as contractions, the pressure changes are not always proportional to the force exerted by the muscle wall (5).

Recently, other technologies have been applied to characterize the bolus transport in detail. In the esophagus, ultrafast computed tomography was used to determine the composition and the transit of a swallowed bolus (17), and intraluminal high frequency esophageal ultrasonography was introduced to evaluate esophageal wall motion and lumen diameter, as well as muscle thickness (18). In the small intestine, ultrafast echo-planar magnetic resonance was applied to visualize peristalsis and flow of luminal contents (19). These techniques, however, require high level technical support. In addition, the bolus transport can only be studied on a defined segment and at a defined moment, but detailed data on spatial and temporal resolution of bolus transport through the whole organ are still not available.

Multiple intraluminal electrical impedance is a new technological approach for quantitative assessment of peristalsis and chyme movement in the gastrointestinal tract (20). The impedance method used differs essentially from the epigastric electrical impedance recording treated by Sutton (21), as well as from the intraluminal approach of Fisher *et al*. (22). It is also different from another intraluminal impedance approach introduced by Gregersen for investigation of compliance in luminal organs (23, 24). During the last 5 yr, several studies have been performed using this technique, and considerable results with interesting data about esophageal and intestinal chyme transport have been obtained (25–34). The purposes of this article are 1) to illustrate this technique, 2) to summarize the current results, and 3) to implicate further directions for clinical and basic research using this technique.

PRINCIPLES OF THE IMPEDANCE PROCEDURE AND THEORETICAL CONSIDERATIONS

The method is based on the intraluminal measurement of electrical impedance between a number of closely arranged electrodes during a bolus passage using an intraluminal probe (Fig. 1, left side). Cylinder-shaped metallic electrodes are mounted on a thin plastic catheter. Each neighbouring electrode pair is connected to an impedance voltage transducer outside the body *via* thin wires running inside the plastic tube. The instantaneous output voltage of each transducer represents the average electrical impedance of the volume conductor around the catheter in the section between the measuring electrode pair at a given time.

The intraluminal electrical impedance is inversely proportional to the electrical conductivity of the luminal contents and the cross-sectional area. Compared with the muscular wall, air has a lower electrical conductivity and yields an impedance increase. In contrast, saliva or nutrients have a higher conductivity and therefore yield an impedance drop at the corresponding measurement segments. On the other hand, a luminal dilation (*e.g.*, induced by bolus entry or wall relaxation) results in impedance drops, whereas a luminal narrowing (*e.g.*, induced by wall contraction) causes impedance increase.

A peristaltic contraction wave pushing a bolus ahead of it can be divided at a given time in a simplified way into four phases, as recently confirmed by concurrent high frequency sonography and manometry (18): during the resting phase 1, the wall muscles are relaxed, and the organ walls lie smooth or folded together and swim on a thin fluid film. In phase 2 the organ wall is extended by the bolus. A fully contracted segment that pushes the bolus is associated with phase 3. In phase 4, the muscular tube is relaxed again and the organ walls can touch each other, and the fluid film, which is transported away with the bolus, is slowly built up again. Distribution of different physical characteristics, such as wall tension, lumen size, or pressure in the muscle tube, can be used for the quantitative description of the contraction wave. Unfortunately, by measuring changes of intraluminal pressure during a contraction wave we can recognize only phase 3, in which the organ is totally contracted.

Based on theoretical considerations and on results of *in vivo* as well as animal studies (20, 25, 26), a bolus passage over one measuring segment yields a typical impedance tracing with a maximum of five phases and three characteristic points (Fig. 1, middle): resting state (phase 1 of the impedance curve), facultative arrival of an air volume pre-

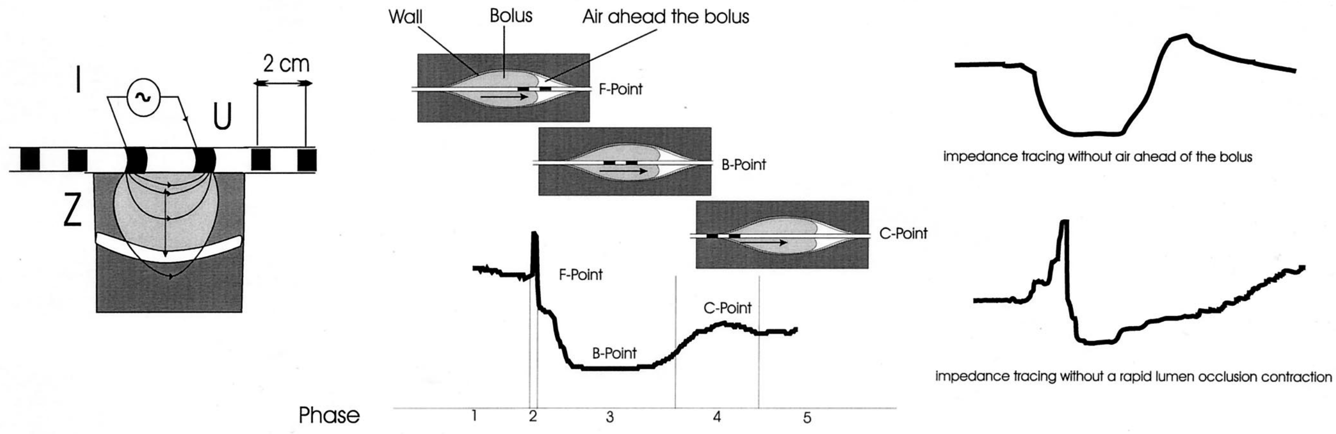

FIG. 1. *Left*: Principles of intraluminal impedancometry: the electrical impedance (Z) of a electric field between two electrodes is the ratio between applied voltage (U) and resulting current (I). *Middle*: Example of a typical impedance tracing related to a bolus passage over one measuring segment, showing a maximum of five phases and three points (F, B, and C). Phase 1 is the resting stage of the organ; phase 2 represents the arrival and the passage of an air volume ahead the bolus; phase 3 is associated with the arrival and the passage of a bolus; phase 4 is associated with the wall contraction with facultative lumen occlusion; and phase 5 is the transitory stage to the resting stage. The F-point shows the arrival of the bolus head at the corresponding segment, indicated by the return of the impedance amplitude to the baseline; the B-point characterizes the moment at which the maximal bolus volume is located within the corresponding segment, indicated by the lowest impedance value during the phase 3; the C-point is facultative and represents the moment of rapid lumen occlusion, caused by a contraction wave clearing the bolus tail, and indicated by the maximal impedance value during phases 3–5. This tracing type was predominantly observed. *Right*: Impedance tracings divergent to normal cases. Upper panel: air ahead of the bolus is missed, *e.g.*, in the duodenum. Lower panel: a rapid lumen occlusion is missed, *e.g.*, across the esophagogastric junction.

ceding a bolus (phase 2), arrival and passage of a bolus (phase 3), facultative rapid wall contraction associated with lumen occlusion (phase 4), and state transitory to resting stage (phase 5). During phase 1, a relatively high impedance can be expected, as the muscular wall with its low electrical conductivity is situated in proximity to the measuring electrodes. Phase 2 should be accompanied by a very high impedance caused by the air inclusion in front of the bolus. In contrast to phase 2, a bolus within the measuring segments results in a relatively low impedance in phase 3. This value decreases further with the increase of the bolus diameter in the measuring segments as a logarithmic function of the bolus thickness. In phase 4, in which the tube segment is constricted, all channels within this segment must yield a relatively high, and well as reproducible, impedance value. The impedance in phase 5 reflects the complex processes of wall relaxation, tube opening and soaking of saliva into the measuring segment. Impedance tracings related with a missing of air ahead of the bolus, as frequently seen in the duodenum, or a missing of a rapid lumen-occlusion contraction, as frequently seen across the esophagogastral junction are shown in Figure 1, right side.

The impedance tracing shows some characteristic measuring points (Fig. 1, middle): the F-point shows the arrival of the bolus head at the corresponding segment, indicated by a return of impedance amplitude to the baseline after increase caused by air passage; the B-point characterizes the moment at which the maximal bolus volume is located within the corresponding segment, indicated by the lowest impedance value during the phase 3; the C-point is facultative and represents the moment of rapid lumen occlusion, which is caused by a contraction wave clearing the bolus tail, and indicated by the maximal impedance value during phases 3–5 after the bolus passage.

VALIDATION STUDIES

To test the impedance procedure as an appropriate method for the recording of gastrointestinal motility in man, several validation studies in healthy volunteers were performed (24, 25).

In the first part, the correctness of the impedance approach is examined by concurrent impedancometry with 15 channels and cineradiography of a x-ray opaque bolus during its transit through the esophagus proceeding with 12.5 frames/s. The experiments consisted of 4 swallows of each 8 ml of a radiopaque suspension consisting of barium sulfate and water, with the subjects studied in a supine position. The x-ray image is focused to a frontal thorax area with a diameter of 17 cm and the camera is moved manually along with the bolus. Analysis of the recording tracings and frames showed that the physical interpretation of the impedance method corresponds well with the actual bolus transport. The entry, the transit, and the leaving of the bolus are clearly indicated by impedance changes in each measuring segment, as confirmed by cineradiography. The actual front and end of the bolus in the corresponding measuring segment as well as the momentary bolus length and the direction of its movement can be recognized from the impedance tracings. Compared with the impedance in the quiescence phase, the impedance increases in each measuring segment during the passage of an air bolus and decreases during the transit of an electrically highly conductive bolus.

The second experiments were focused on the comparison

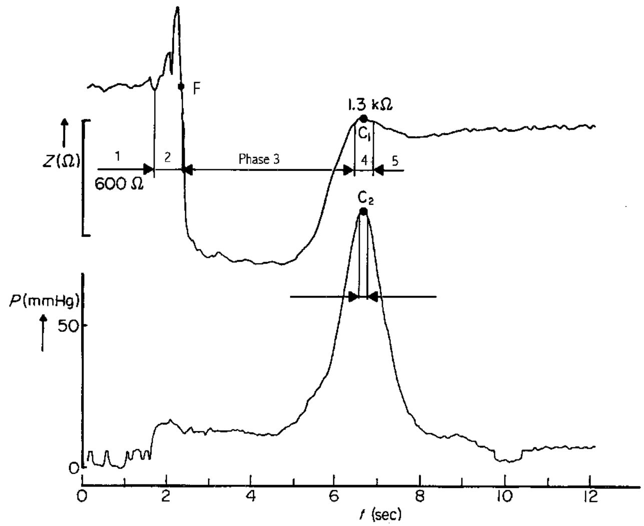

FIG. 2. Concurrent impedance measurement and manometry in the distal esophagus of a healthy volunteer using a catheter containing one impedance segment and one semiconductor pressure transducer in the center of the impedance segment. The intense impedance changes, caused by air in front of the bolus and bolus entry into the measuring segment, are evident, but they have no parallel in the pressure signal and, therefore, cannot be proven by it. The instant of the extreme values (points C1 and C2) in both courses indicating the constriction of the muscular tube segment coincide (adapted from Ref. 25).

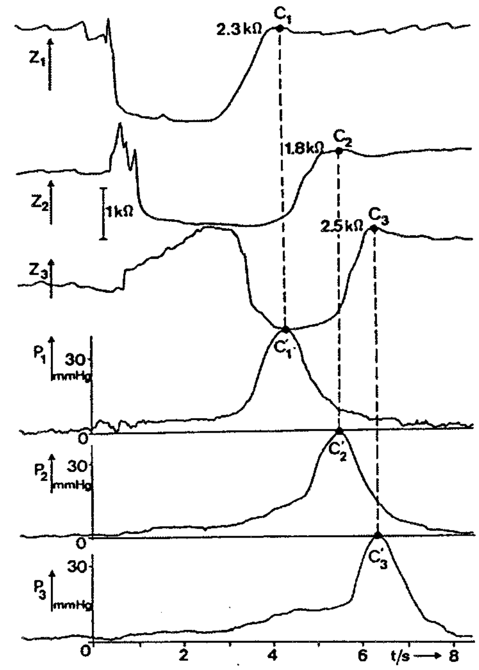

FIG. 3. Concurrent impedance measurement and manometry in the distal esophagus of a healthy volunteer using a catheter containing three impedance segments and three semiconductor pressure transducers in the center of the impedance segments showing similar propagation velocities of the contraction wave, as assessed by impedancometry and manometry (adapted from Ref. 25).

between the manometric and impedance tracings from simultaneous recordings of esophageal motility, using combined impedance pressure catheters.

In one experimental set-up, a catheter containing one semiconductor pressure transducer localized in the center of the impedance measuring segment was employed. Figure 2 shows the correlation between impedance Z and pressure P in the human esophagus during a swallow with 15 ml curd in detail. The validity of the predicted correlation between the impedance alteration and the peristaltic wave stages can be confirmed. During transit of a bolus the pressure increases gradually. The maximum of the pressure (point C2) results from the maximal contraction in a short segment around the pressure sensor. Relaxation of the muscles lets the pressure decrease again to the quiescence level. In contrast, during entry of the bolus into the measuring segment, the impedance value takes a low level. With the narrowing of the bolus in the second half of phase III, the impedance and pressure both increase. At the time instant C, the impedance measuring segment with a length of 2 cm is just becoming bolus-free because of the constriction of the tubular wall in this section. The instants of the extreme values (points C and C2) in both courses indicate that the lumen-occluding constrictions are coinciding. During the muscle relaxation the impedance diminishes only slightly, but the time course reflects the relaxation process indicated in the pressure channel. The intense impedance changes caused by the air in front of the bolus and the bolus entry into the measuring segment are evident, but they have no parallel in the pressure signal and, therefore, cannot be proved by it.

In another experimental set-up, three comparative impedance pressure spaced 5 cm apart were used for the acquisition of the motility in the esophagus. Swallowing of 15 ml of curd and the ensuing "dry" swallowing (saliva of an undefined volume) were performed and analyzed. During the swallowing of curd, the minimal impedance is slightly lower than in the "dry" deglutition, which indicates a greater bolus diameter with a curd bolus. During both deglutition processes the pressure maxima originated at the same time as the extrema in the comparative impedance channels, and the evaluated velocities of the contraction waves were very similar for the impedance-pressure pairs in each swallowing (Fig. 3). From the impedance courses the values of the bolus length were calculated. For all deglutitions of curd the mean bolus length was calculated showing an essential reduction of the mean bolus length during transit through the esophagus.

Comparative impedancometry and manometry has recently been performed in the small intestine using a combined catheter device comprising 11 impedance channels and four manometric channels (personal observations). The phase III of the Migrating-Motor-Complex showed the same features with regard to duration, propagation direction, and contraction frequency as recorded by impedancometry and manometry (Fig. 4).

CLINICAL STUDIES

Faß *et al*. (27) performed concurrent perfused manometry and multiple intraluminal impedancometry in 10 healthy

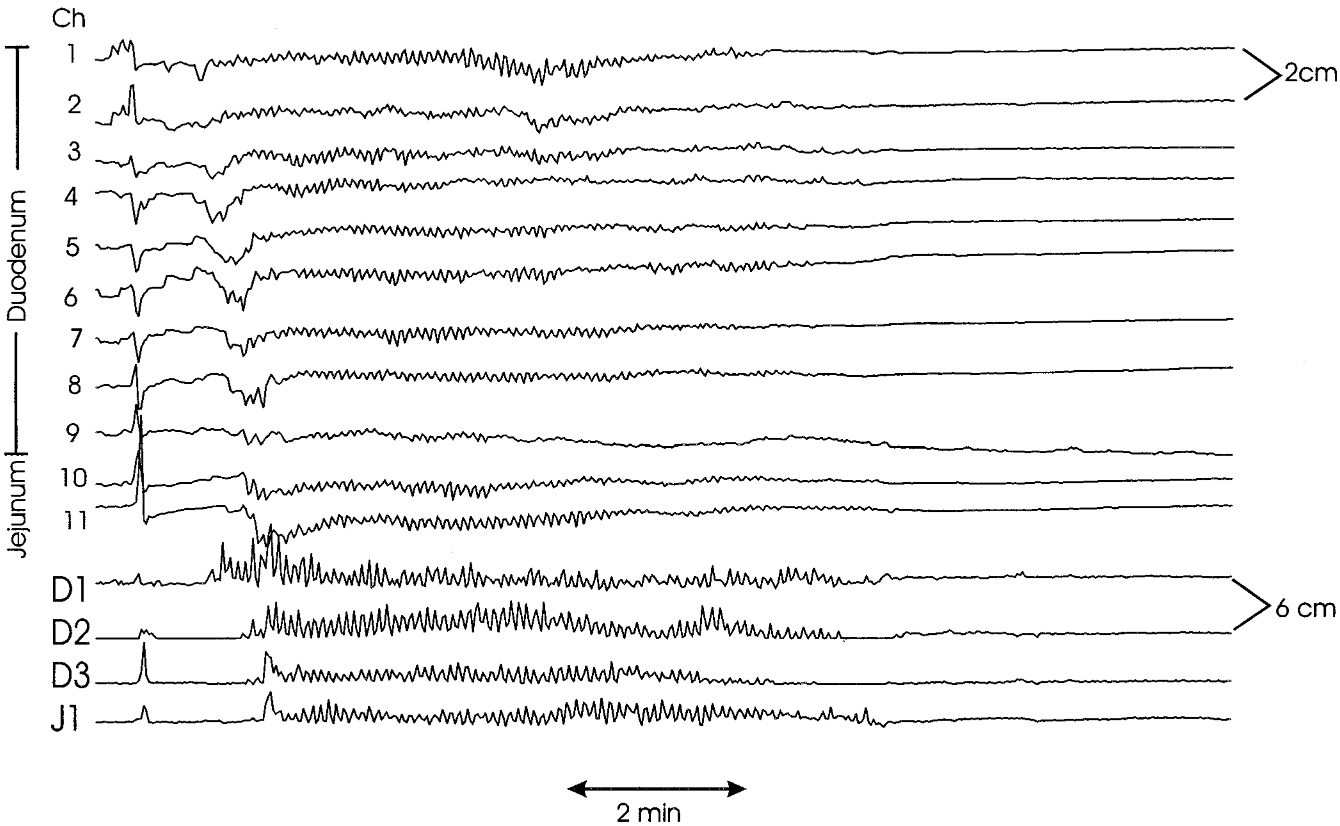

FIG. 4. Concurrent recording of impedance and pressure in the duodenum of a healthy subject using combine catheter consisting of 11 impedance segments and four semiconductor pressure transducers showing a Migration-Motor-Complex. The pressure transducers D1, D2, D3, J1 (three in the duodenum and one in the jejunum) are located between the impedance channels 1–2, 4–5, 7–8, and 10–11, respectively.

subjects and compared the results with those obtained from 10 patients with reflux esophagitis. In healthy subjects, a typical course of normal esophageal motility was obtained. The propagation velocity of the bolus was determined, which showed small variance, accounting for a maximum of ~8.4%. The bolus transit velocity was dependent on the viscosity of the bolus. Several pathological features have been obtained from patients with reflux esophagitis, including delayed bolus transport and impaired chyme clearance function at the distal parts of the esophagus, whereas the proximal parts showed normal motility patterns. The results confirm disturbed motor activity of the distal esophagus in patients with reflux esophagitis, probably secondary to mucosal inflammation.

Frieling *et al*. (28) consecutively performed simultaneous measurement of manometry and impedance in eight healthy subjects to compare motility and transport in the esophagus and to characterize the effect of bolus consistency on esophageal transit. Recordings were obtained in supine position by an conventional eight-lumen manometry tube, which was additionally equipped with 16 metal ring electrodes attached pairwise close to the perfusion orifices for the impedance measurements. Esophageal motility was induced by wet swallows of 5 ml of liquid formula diet and semisolid swallows of 5 ml of mashed potatoes. Esophageal wall contraction velocities as measured by manometry and by impedancometry were virtually identical for both wet and semisolid swallows. Bolus front velocity as measured only by impedancometry was significantly faster than contraction front velocities, and showed dependency on bolus viscosity. The results indicate that intraluminal electrical impedance measurement is a reliable technique to detect esophageal motility as well as to differentiate between transit of wet and semisolid bolus consistencies.

In several steps we applied the impedance technique to characterize the chyme transport in the esophagus and the duodenum of healthy subjects, as well as of selected patients with major gastrointestinal motor function disturbances (29–31). For these studies, a custom-made flexible polyvinyl catheter of 2.6 mm in outer diameter and 2.5 m in length, consisting of 17 electrodes 4 mm long, was applied. The electrodes were attached to the catheter and positioned 1.6 cm apart from each other. Bipolar impedance measurements were performed between adjacent electrodes, thus yielding 16 recording segments 2 cm long (between the midpoints of each electrode pair) over a total distance of 32 cm. This catheter device was selected to gather complete information about bolus transport over a long distance, which should cover the whole length of the esophagus and duodenum.

The dynamics of a bolus transport through the esophagus were studied in 10 healthy subjects using bolus with different viscosities, and subject studied at different body posi-

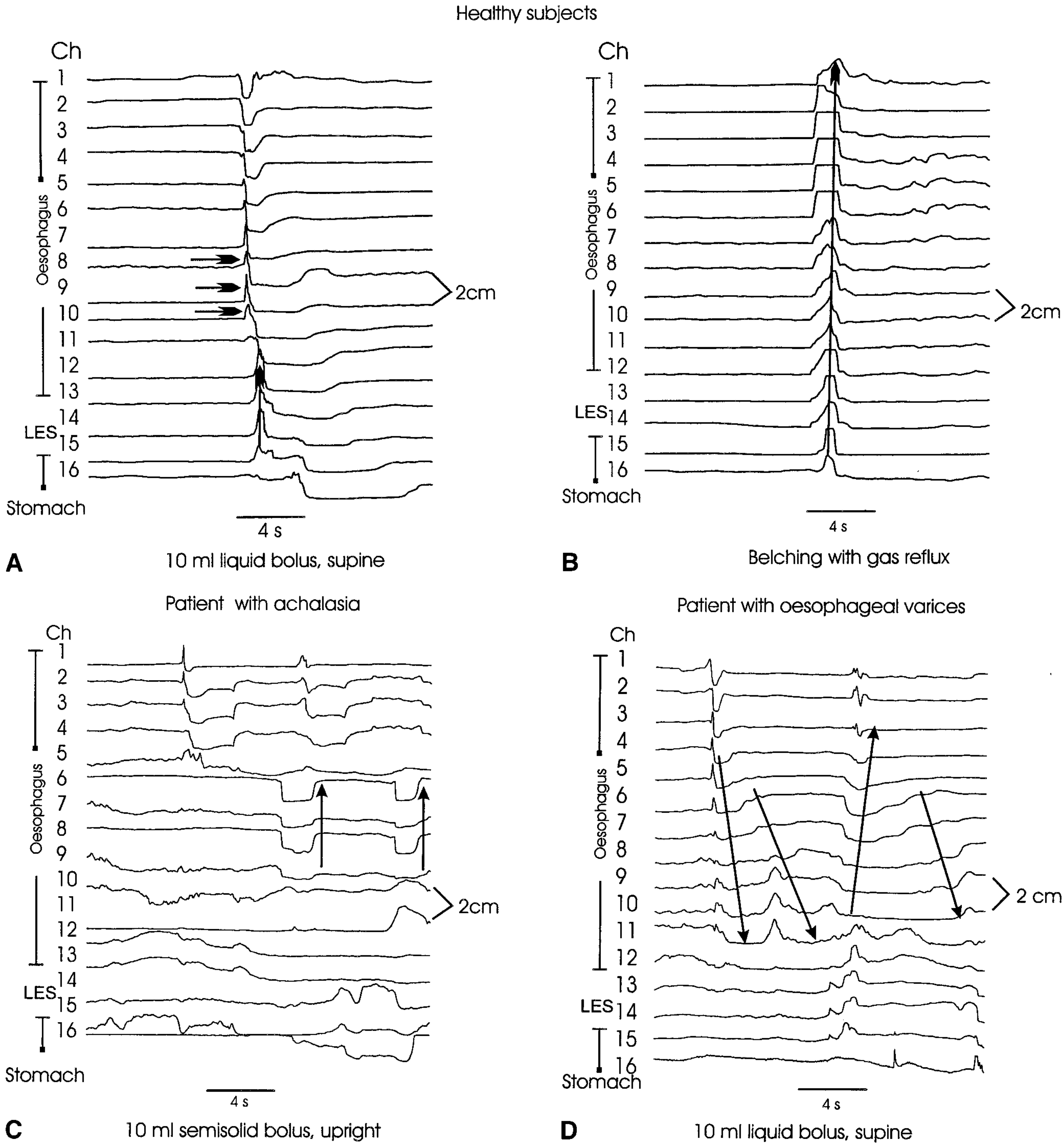

FIG. 5. Examples of swallow-induced impedance patterns in the human esophagus. *In healthy subjects*: (*A*) Transport of a liquid bolus at supine position. (The horizontal arrows indicate that air preceding the bolus head accumulates at the distal esophagus region. The vertical arrows indicate air reflux into the distal esophagus following deglutition.) (*B*) Impedance pattern related to gas reflux due to belching, showing simultaneously an abrupt, high level increase of impedance related to retrograde gas escape. *In patients with major disturbances of esophageal motor function*. (*C*) A patient with achalasia stage III. (The primary peristalsis pattern is missed. Chyme transport through the proximal channels were normal, whereas no regular chyme transport was seen in the esophagus. Arrows indicate air trapping within the proximal esophagus.) (*D*) A patient with esophageal varices. The chyme transport is disturbed at the distal esophagus due to mechanical dysfunction. Arrows indicate retrograde and anterograde chyme movement.

tions (29). Transit of different parts of a bolus (bolus head, body, and tail) was analyzed close to the anatomical segments (pharynx, proximal, middle, and distal third of the esophagus). In all subjects, a highly characteristic pattern of bolus transport was seen (Fig. 5*A*). Air was observed to be swallowed together with a bolus and propelled ahead of bolus. Belching with gas reflux also featured typical impedance pattern (Fig. 5*B*). Bolus head propelled significantly

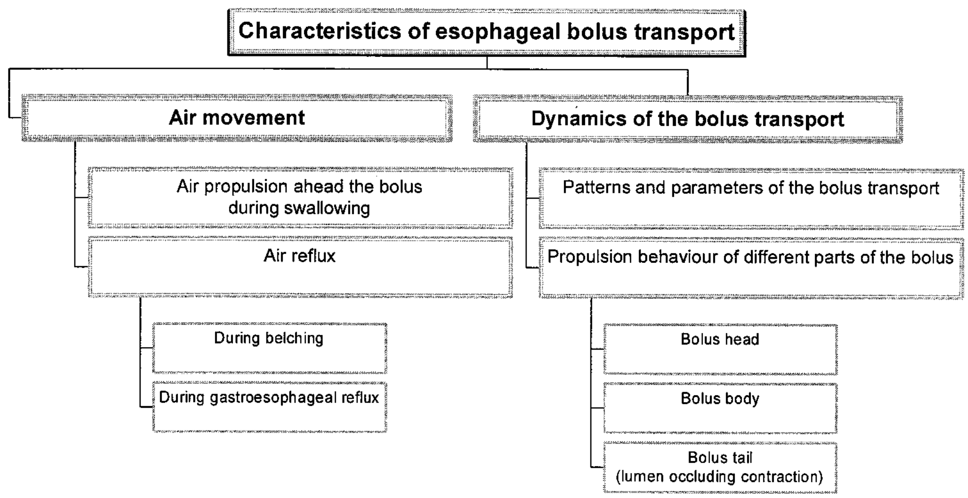

FIG. 6. Characteristics of esophageal bolus transport. Transit of air can be demonstrated. Patterns and parameters of a bolus transport can be obtained. The different parts of the bolus can be separately studied.

faster than bolus body and bolus tail. Bolus propulsion featured significant regional differences: pharyngeal propulsion is significantly faster than esophageal propulsion, and within the esophagus the propulsion velocity gradually decreased. Bolus transport was significantly affected by bolus characteristics and testing conditions: transit time and propagation velocity of a bolus were accelerated in upright position and decelerated with increased bolus viscosity. Thus, the dynamics of a bolus transport has completely been evaluated in details, and the complexity of a bolus transport from the pharynx into the stomach has been demonstrated. There are preliminary experiences of the impedance technique applying to study esophageal bolus transport in patients with dysphagia and major motor function disturbances of the esophagus (personal observations). Patients with achalasia and esophageal varices featured different pathological bolus transport patterns. These patterns significantly differed from those found in healthy subjects, and showed features corresponding to the underlying motor disturbances (Fig. 5*C* and 5*D*). The current results show that the spatial and temporal resolution of a bolus transport can be faithfully recorded by the impedance technique (Fig. 6).

Consecutively, the following studies were performed to study the reliability of the technique in the small intestine (30, 31). First, patterns and parameters of chyme transport in the duodenum of 14 healthy subjects (six during fasting and eight after a test meal) were studied during fasting and after administration of a standard test meal (30). All main characteristic features of the interdigestive state were obtained including length of MMC cycles, duration of different phases of the MMC cycle, duration and migration velocity of phase III activity fronts, and frequency of contractions during phase III activities. Several patterns of chyme transport, termed a Bolus-Transport-Event (BTE), were identified. This term was inaugurated to illustrate an impedance pattern correlated with the transport of a bolus. Four distinct patterns of BTEs were defined according to site of onset/spread direction, spread distance, and number of components (Fig. 7). They were short distance propulsive, simple long distance propulsive, retrograde, and complex long dis-

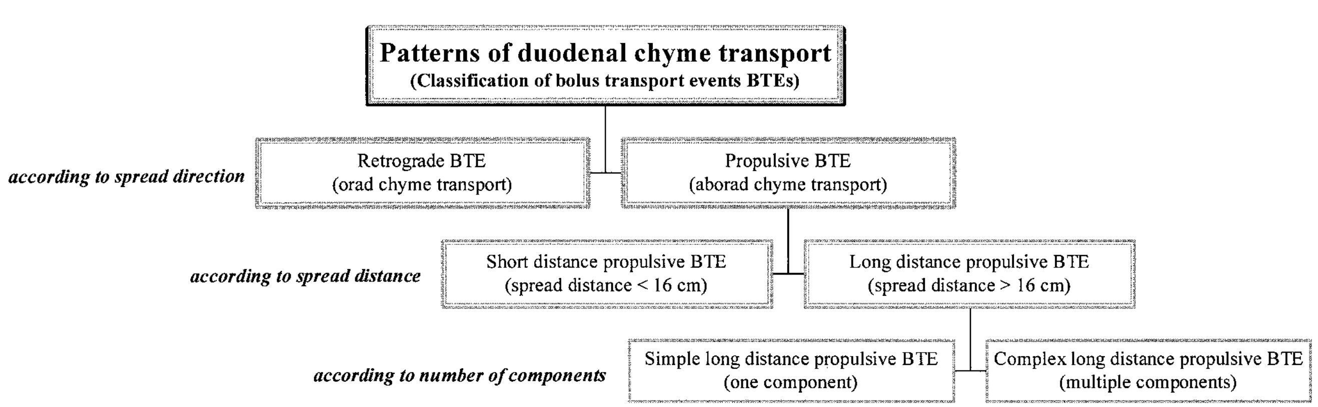

FIG. 7. Classification of chyme transport patterns in the human duodenum showing different patterns related to the complex function of the small intestine. The contractile patterns can be classified as propulsive, retropulsive, or segmenting.

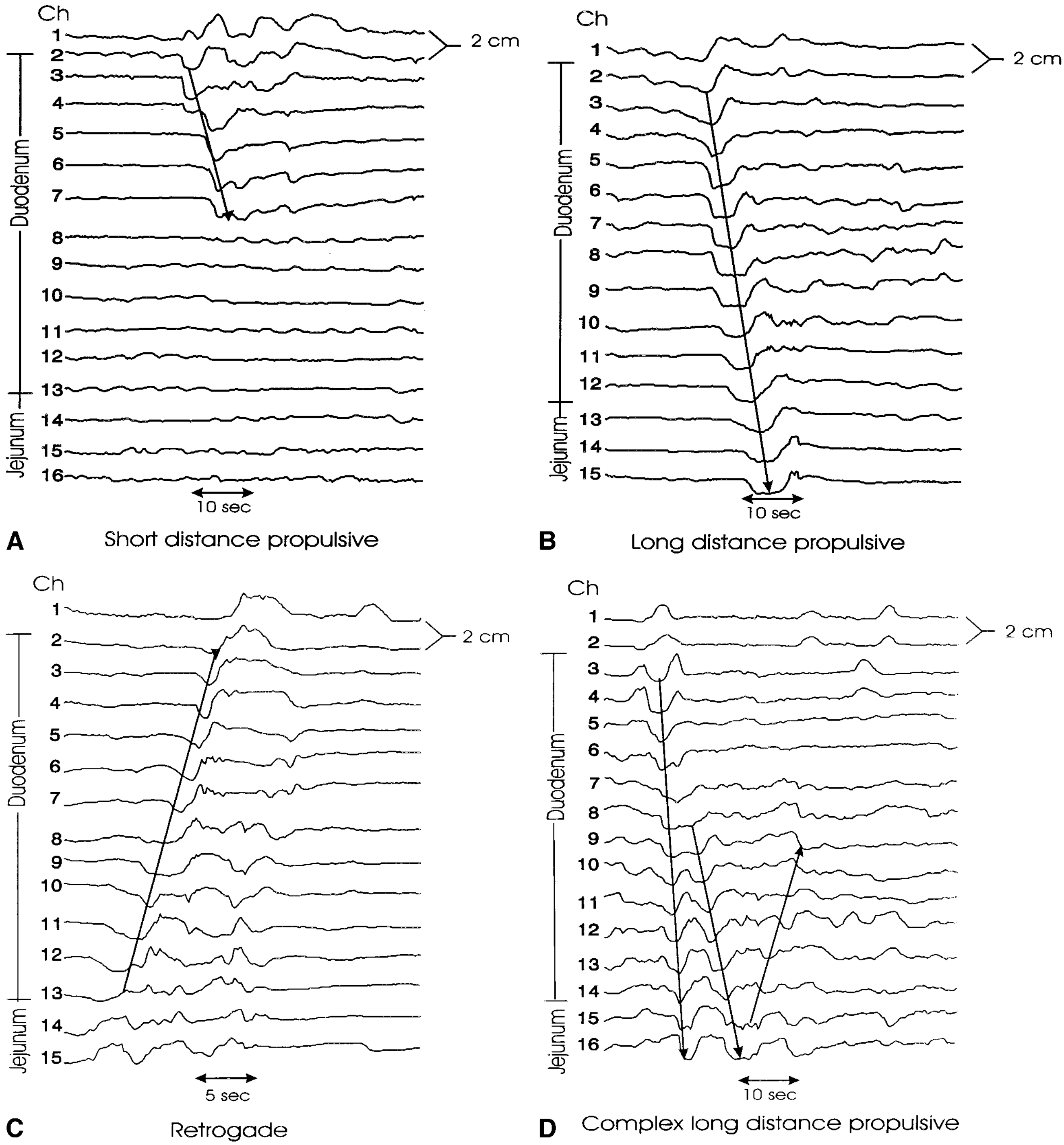

FIG. 8. Examples of impedance patterns in human duodenum, during phase II of the MMC-Cycle and after a test meal. The numbers and positions of the measuring segments in duodenum or jejunum are shown at the left margin. (*A*) A short distance (left) and a long distance (right) propulsive BTE originating from the proximal duodenum. (*B*) A short distance propulsive BTE starting from the proximal duodenum (left), and a retrograde BTE starting from proximal jejunum (right). (*C*) A complex long distance propulsive BTE featuring two propulsive components with various propagation velocities during bolus propulsion to the proximal jejunum. (*D*) A complex long distance propulsive BTE featuring a propulsive and a retrograde component at the mid-duodenum during bolus propulsion to the proximal jejunum. (Short distance = propulsion distance $<$16 cm; long distance = propulsion distance $>$16 cm; simple = one component; complex = multiple components).

tance propulsive BTEs (Fig. 8*A–D*). The first three patterns were seen during both the fasting and postprandial states, whereas the last pattern was recorded only postprandially. We have also defined two parameters of chyme transport, including the number of BTEs (transport activities) and distribution of BTEs (transport organization), which may reflect the postprandial gastric and duodenal functions (Fig. 9). Based on these parameters, the phase II of the MMC-

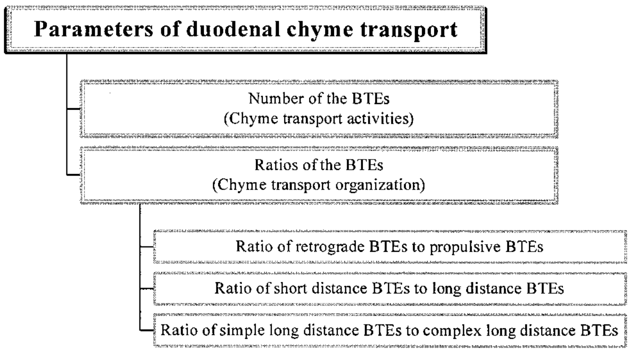

FIG. 9. Parameters of chyme transport in human duodenum. Based on the calculation of these parameters it was shown that the chyme transport activities and the chyme transport organization were significantly different between the interdigestive and the postprandial state, as well as between healthy subjects and patients with diabetic gastroparesis syndrome.

cycles and the postprandial state have been characterized showing that the interdigestive state differed significantly from the postprandial state concerning peristaltic activities and chyme flow patterns. In these studies, we also observed that the majority of postprandial BTEs were long distance propulsive, indicating that a major proportion of gastric contents is continuously transported into the jejunum during the postprandial state. The results show that patterns and parameters of human duodenal chyme transport, both during fasting and after a meal, can be characterized.

In the following investigations, the impedance technique was applied for investigation of pathological duodenal chyme transport (31). Postprandial duodenal chyme transport patterns and parameters were analyzed in ten patients with long standing insulin-dependent diabetes mellitus and clinical signs of gastroparesis and were compared with results obtained from 10 healthy subjects. Significant differences on numbers and contributions of the BTEs were found in the diabetics as compared with the healthy subjects. Diabetic patients featured a significantly lower number of propulsive BTEs than control subjects, indicating a reduced number of bolus passages across the gastroduodenal junction, which is consistent with reduced gastric emptying frequency and gastroparesis. In addition, significant higher ratios of retrograde BTEs to propulsive BTEs and complex long distance BTEs to simple long distance propulsive BTEs were found in diabetic patients as compared with control subjects. These data implicate disturbed propulsive chyme transport through the duodenum, and consecutively delayed chyme transport through the duodenum. However, similar propulsion velocities of propulsive BTEs were found in both groups, indicating that the duodenum of diabetic patients is not paretic. Thus, the term "duodenal chyme transport disorganisation" was preferred to describe the findings. The results demonstrate abnormal postprandial duodenal chyme transport in the diabetic patients as a part of the upper gut dysmotility, and extend information about postprandial duodenal motor function related to the diabetic gastroparesis syndrome.

Because the impedance technique is a reliable means of detecting chyme transport and determining its transport direction, it was simultaneously applied with pH-metry for characterizing patterns and parameters of gastroesophageal reflux (GER) (32, 33). Seventeen infants with clinical symptoms of GER disease such as recurrent apnea, aspiration pneumonia, wheezing, and failure to thrive were studied during two feeding periods. A unique pattern in the impedance measurement, correlated with a GER (as determined with pH metry), was observed. The impedance values decreased in all channels reached by the refluxate, and the change in impedance values began in the distal channel and proceeded to more proximal channels, indicating a retrograde flow of gastric contents (Fig. (10*A*, 10*B*). These impedance patterns were observed in 95 of all pH-metry–detected GER and in 490 other episodes not detected by pH-metry; 38 of them were acid (pH $<$4) but were not considered acid episodes by pH-metry because of their short duration ($<$15 s). None of them fitted the criteria of an alkaline GER (pH $>$7). Analysis of impedance data showed that $>$75% of all GER ascended to the most proximal impedance channel (the pharyngeal space). The results demonstrated that the impedance technique was especially useful for the detection of nonacid GER episodes, which are not detectable by pH-metry. The height reached by the refluxate in the esophagus can be determined. This method seems to provide important, additional information to pH-metry as a pH-independent technique. Sifrim *et al*. have recently applied this technique to characterize the patterns of gas and liquid reflux during transient lower esophageal sphincter relaxation in healthy subjects and patients with reflux disease (34). They found that the impedance technique is a sensitive nonradiological technique to monitor esophageal flow of gas and liquid. Mixed reflux (liquid and gas) seems to be more common than liquid or gas reflux alone.

DISCUSSION

Significant advances in the study of dysmotility disorders could be made toward understanding and predicting bolus movement within the gastrointestinal lumen together with the peristaltic activity. Multiple intraluminal impedancometry is a recently developed procedure for assessment of peristalsis and related bolus transport. Recent results indicate several important complementary aspects of this technique to manometry as the commonly applied technique.

The impedance responses to the bolus movement in the esophagus and small intestine are similar in essential details. From the impedance tracings, it is possible to distinguish between resting states, bolus transit, and wall contraction. The whole organ can simultaneously be investigated, and the beginning of a peristaltic wave, as well as its propagation direction can be deducted. The entry of a bolus can be clearly distinguished from air volume in front of it. Reliable data of the propagation velocities of the peristaltic waves were obtained (25, 27, 28). From each impedance tracing a

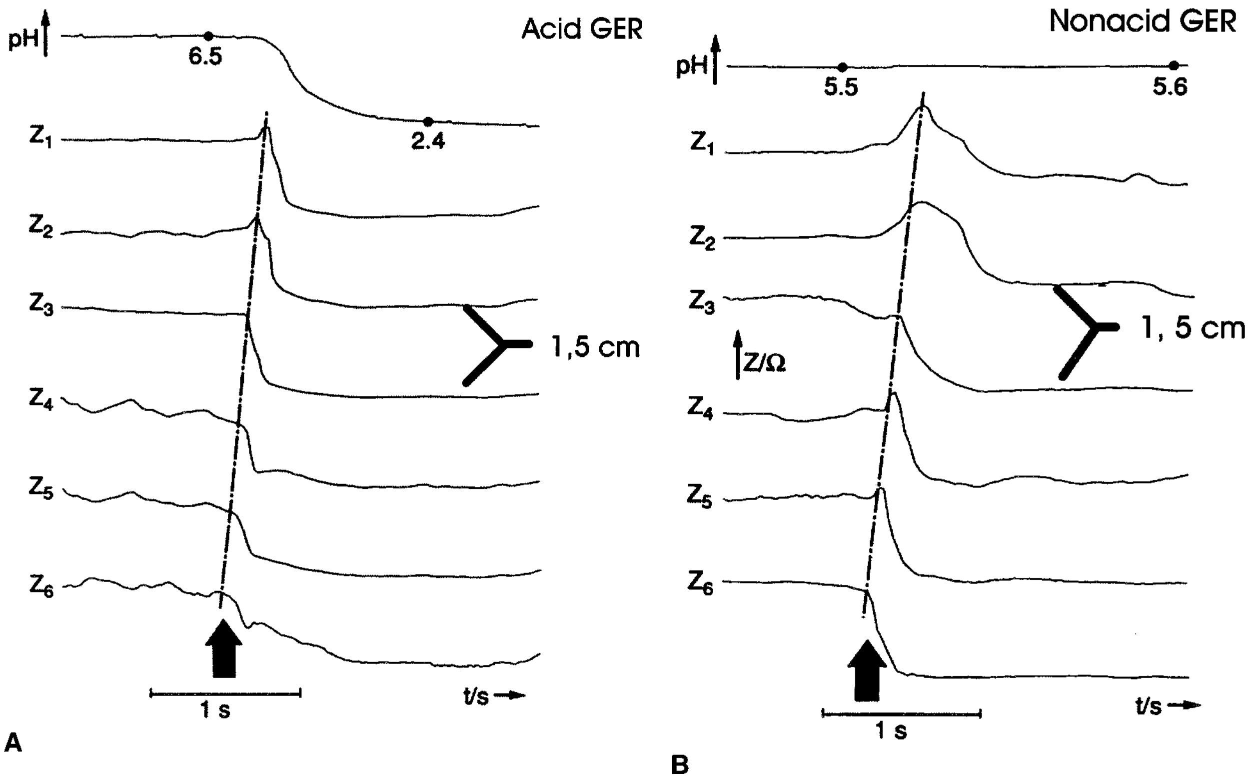

FIG. 10. Concurrent impedancometry and pH-metry in the esophagus of an infant showing typical impedance patterns related to gastrooesophageal reflux (GER). (*A*) Acid GER. (*B*) Nonacid GER. The pH-electrode is located in the middle of the fifth impedance measuring segment and about 3 cm above the gastroesophageal junction (adapted from Ref. 32).

number of characteristic points can be derived; and from them, different parts of a bolus (head, body, and tail) can be defined and their propagation velocities determined. It was possible to differentiate between transit of bolus with different consistencies (27–29). These parameters cannot usually be evaluated by manometry.

With a 16-channel impedance catheter, the peristaltic activity from a 32-cm-long portion of the esophagus and the small intestine was reliable acquired simultaneously and without a gap, thus providing new qualitative and quantitative data about peristaltic patterns and chyme transports in these organs (29–31). The spatial and temporal resolution of a bolus transport has been accurately recorded. Interesting details of transport and mixing were obtained, adding new aspects of the physiology of chyme transport in these organs.

In the esophagus, a unique chyme transport pattern found in all healthy subjects studied was concordant with its basic physiological function as a conduit organ through the chest providing a coordinated transport of swallowed material into the stomach (35). The most striking findings were that the dynamics of a bolus transport through the esophagus was shown to be very complex, and a bolus transit was significantly dependent on the experimental conditions including bolus characteristics, bolus volume, and body position as expected from its complex neurofunctional anatomy with different anatomic segments and innervation pathways (34–36). These results underline the necessary having an investigative technique that can simultaneously obtain data from the whole organ.

In the small bowel, the impedance technique records all main characteristics of the interdigestive state as already known from manometry, demonstrating great intra- and interindividual variations (14, 38). Moreover, on the basis of several previously characterized impedance tracings, small intestinal contractile patterns have been classified as segmenting, propulsive, or retropulsive functions. One important finding was the characterization of chyme transport during fasting and after a meal, based on the qualitative and quantitative analysis of the chyme transport patterns found. Fundamental functional differences concerning chyme flow patterns and peristaltic activities between these nutritional states were found, similar to those previously reported (38). Another important finding was concerning the functional role of the duodenum (40). As several chyme transport patterns were found here, the motor function of the duodenum seems to be more complex than that of the esophagus. The majority of the transport patterns were found to be long distance propulsive over 16 cm, showing that gastric contents are continuously transported into the jejunum and indicating that the duodenum is able to generate aboral forces as previously shown (41). In addition, we found duodenal chyme transport disorganization to be a part of the diabetic gastroparesis syndrome, which may result in delayed duodenal chyme transport and impaired duodenal chyme clearance. This finding adds credence to the concept

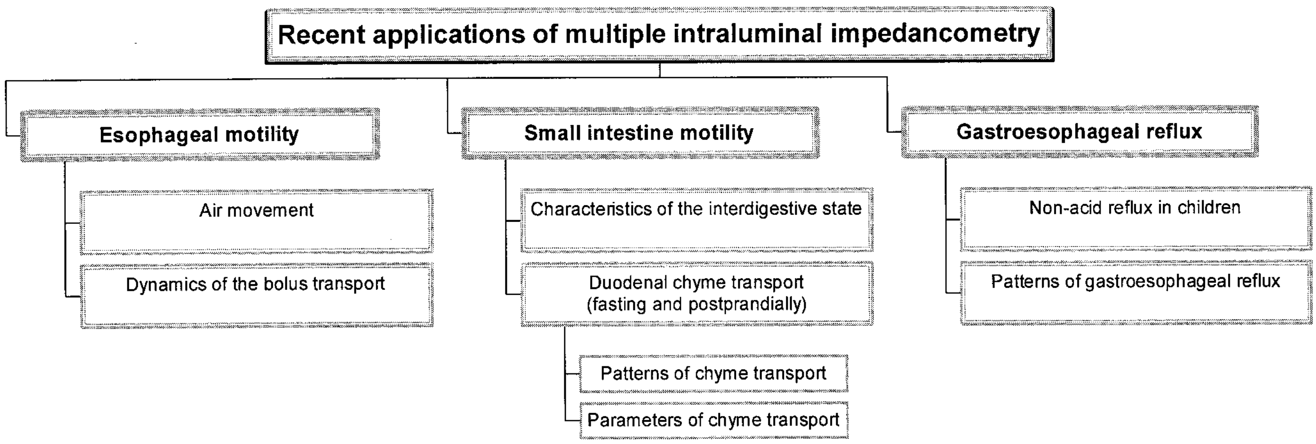

FIG. 11. Recent applications of the impedance technique in the esophagus and the small intestine.

of the role of the small intestine as a cofactor modulating gastric emptying (42–45).

However, the impedance technique also has some limitations. The contraction amplitude, as an important parameter in predicting organ function, cannot be determined. Because the results of the current studies indicate a great dependency of the data obtained under the experimental conditions, a standardization of the experimental set-ups (including equipment used and study protocols, as well as the analysis algorithm) is essential to effectively compare the results of further studies. The visual-manual analysis of the events studied is still time-consuming, requiring refinement of analysis algorithms, in particular, for semiautomatic detection and calculation of the parameters studied. The application of the multichannel impedance procedure at the current form in a larger hollow, nonperistaltic region such as the body and fundus regions of the stomach that have storage function is limited by the great-cross section diameter and the occurrence of great air volume, which disturbs the impedance recording. Experiences with this technique in the colon are still lacking.

Thus, recent results indicate that the main impact of the impedance technique is its capability to characterize esophageal and intestinal chyme transport (Fig. 11), thus providing interesting insight into mechanisms related to luminal chyme transport. This technology seems to be an interesting and innovative tool for basic research on gastrointestinal motility. Concurrent impedancometry and manometry will provide fundamental data on the relationships among peristaltic activity, intraluminal pressure, and resulting bolus movement.

Up-to-date data concerning the clinical significance of this technique are still lacking and, therefore, further studies are required. In the esophagus, this technique should be used for characterization of esophageal transport abnormalities in patients with nonobstructive dysphagia with manometric findings of nonspecific motility disorders (1, 7, 8). The more important applications are to study antropyloroduodenal mechanisms related to delayed gastric emptying, as well as to characterize abnormal small intestinal motility and associated disturbed chyme transport. Thus, further studies should be focused in patients with idiopathic gastroparesis, dysmotility-like nonulcer dyspepsia, and irritable bowel disease (46–49). An important approach is the development of an ambulatory measurement system for receiving in-depth recording and analysis of the peristaltic activities (49–51). The role of the impedance technique as a pH-independent technique concerning reflux evaluation is promising and deserves further attention.

We can conclude that the multichannel impedance procedure is as an innovative integrative approach for assessment of peristalsis and chyme transport that is developing into an interesting and important investigation tool complementary to manometry for evaluation of esophageal and small intestinal motility. However, because of limited experiences at this time, this technique should still be reserved for research applications before it can be widely used in clinical practice.

ACKNOWLEDGMENTS

Support in part by a grant of the University of Aachen (87/96-S).

Reprint requests and correspondence: Dr.med H. N. Nguyen, Medizinische Klinik III, Universitätsklinikum der RWTH-Aachen, Pauwelstr. 30, 52074 Aachen, Germany.

REFERENCES

1. Castell DO, Richter JE, Dalton C. Esophageal motility testing. Amsterdam: Elsevier, 1987.
2. Kahrilas PJ, Clouse RE, Hogan WI. American Gastroenterological Association technical review on the clinical use of esophageal manometry. Gastroenterology 1994;107:1865–84.
3. Vantrappen G, Clouse RE, Corazziari E, et al. Standardisation of oesophageal manometry: An outline of required measurements and technical standards. Gastroenterol Int 1989;2:150–4.
4. Diamant NE. Physiology of esophageal motor function. Gastroenterol Clin North Am 1989;18:179–94.
5. Wingate DL. Small bowel manometry. Am J Gastroenterol 1995;90: 536–9.

6. Parkman HP, Harris AD, Krevxsky B, et al. Gastroduodenal motility and dysmotility: An update on techniques available for evaluation. Am J Gastroenterol 1995;90:869–92.
7. Ott DJ, Richter JE, Chen YM, et al. Esophageal radiography and manometry: Correlation in 172 patients with dysphagia. Am J Roentgenol 1987;149:307–11.
8. Hewson EG, Ott DJ, Dalton C, et al. Manometry and radiology: Complementary studies in the assessment of esophageal motility disorders. Gastroenterology 1990;98:626–32.
9. Massey BT, Dodds WJ, Hogan WJ, et al. Abnormal esophageal motility. An analysis of concurrent radiographic and manometric findings. Gastroenterology 1991;101:344–54.
10. Brasseur JG, Dodds WJ. Interpretation of luminal manometric measurements in terms of swallowing mechanics. Dysphagia 1991;6:100–19.
11. Kahrilas PJ, Dodds WJ, Hogan WJ. Effect of peristaltic dysfunction on esophageal volume clearance. Gastroenterology 1988;94:73–80.
12. Ren J, Massey BT, Dodds WJ, et al. Determinants of intrabolus pressure during esophageal peristaltic bolus transport. Am J Physiol 1993;264:G407–13.
13. Li M, Brasseur JG, Dodds WJ. Analyses of normal and abnormal esophageal transport using computer simulations. Am J Physiol 1994; 226:G525–43.
14. Sarna SK. Cyclic motor activity: Migrating motor complex. Gastroenterology 1985;89:894–913.
15. Camilleri M. Study of human gastroduodenojejunal motility. Applied physiology in clinical practice. Dig Dis Sci 1993;38:785–96.
16. Quigley EMM. Intestinal manometry-technical advances and clinical limitations. Dig Dis Sci 1992;37:10–3.
17. Pouderoux P, Ergun GA, Lin S, et al. Esophageal bolus transit imaged by ultrafast computerized tomography. Gastroenterology 1996;110:1422–8.
18. Miller LS, Liu JB, Colizzo FP, et al. Correlation of high-frequency ultrasonography and manometry in the study of esophageal motility. Gastroenterology 1995;109:832–7.
19. Evans DF, Lamont G, Stehling MK, et al. Prolonged monitoring of the upper gastrointestinal tract using echo planar magnetic resonance imaging. Gut 1993;34:848–52.
20. Silny J. Intraluminal multiple electric impedance procedure for measurement of gastrointestinal motility. Neurogastroenterol Motil 1991; 3:151–62.
21. Sutton JA. Impedance. In: Kumar D, Gustavsson S, eds. An illustrated guide to gastrointestinal motility. London: Wiley & Sons, 1988:113–8.
22. Fisher MA, Hendrix TR, Hunt JN, et al. Relation between volume swallowed and velocity of the bolus ejected from the pharynx into the esophagus. Gastroenterology 1978;74:1238–40.
23. Gregersen H, Stodkilde Jorgensen H, et al. The four-electrode impedance technique: A method for investigation of compliance in luminal organs. Clin Phys Physiol Meas 1988;9(suppl):61–4.
24. Gregersen H, Knudsen L, Eika B, et al. A time-dependent study of passive wall properties and collagen content in rabbits with esophageal varices. Dig Dis Sci 1991;36:1050–6.
25. Silny J, Knigge KP, Fass J, et al. Verification of the intraluminal multiple electrical impedance measurement for the recording of gastrointestinal motility. Neurogastroenterol Motil 1993;5:107–22.
26. Heindrichs UW. Funktionelle Untersuchung der Ösophagusmotilität mittels einer multiplen Impedanzmessung. Doctorat Thesis. Medicine faculty. University of Technology RWTH-Aachen, 1994.
27. Fass J, Silny J, Braun J, et al. Measuring oesophageal motility with a new intraluminal impedance device. First clinical results in reflux patients. Scand J Gastroenterol 1994;29:693–702.
28. Frieling T, Hermann S, Kuhlbusch R, et al. Comparison between intraluminal multiple electric impedance measurement and manometry in the human oesophagus. Neurogastroenterol Motil 1996;8:45–50.
29. Nguyen HN, Silny J, Albers D, et al. Dynamics of oesophageal bolus transport in healthy subjects studied using multiple intraluminal impedancometry. Am J Physiol 1997;273:G958–64.
30. Nguyen HN, Silny J, Wüller S, et al. Chyme transport patterns in human duodenum determined by multiple intraluminal impedancometry. Am J Physiol 1995;268:G700–8.
31. Nguyen HN, Silny J, Wüller S, et al. Abnormal postprandial duodenal chyme transport in patients with long-standing type 1 diabetes mellitus. Gut 1997;41:624–31.
32. Skopnik H, Silny J, Heiber O, et al. Gastrooesophageal reflux in infants: Evaluation of a new intraluminal technique. J Pediatr Gastroenterol Nutr 1996;23:591–8.
33. Skopnik H, Silny J, Schenke S, et al. Gastrooesophageal reflux and respiration. Status of intraluminal impedance measurement. J Pediatr Gastroenterol Nutr 1996;22:416A.
34. Sifrim D, Holloway RH, Silny J, et al. Patterns of gas and liquid reflux in patients with gastroesophageal reflux disease. Gastroenterology 1998;114(suppl):G1185, 289A.
35. Weinstock LB, Clouse RE. Esophageal physiology: Normal and abnormal motor function. Am J Gastroenterol 1987;82:399–405.
36. Diamant NE. Physiology of esophageal motor function. Gastroenterol Clin North Am 1989;18:179–94.
37. Clouse RE, Staiano A. Topography of normal and high-amplitude esophageal peristalsis. Am J Physiol 265;1993:G1098–107.
38. Kellow JE, Borody TJ, Phillips SF. Human interdigestive motility: Variation in patterns from oesophagus to colon. Gastroenterology 1986;91:386–95.
39. Kerlin P, Zinsmeister A, Phillips SF. Relationship of motility to flow of contents in the human small intestine. Gastroenterology 1982;82:701–6.
40. Camilleri M. The duodenum: A conduit or a pump? Editorial commentary. Gut 1997;41:714.
41. Ahluwalia NK, Thompson DG, Barlow J, et al. Human small intestinal contractions and aboral traction forces during fasting and after feeding. Gut 1994;35:625–30.
42. Camilleri M, Malagelada JR. Abnormal intestinal motility in diabetics with the gastroparesis syndrome. Eur J Clin Invest 1984;14:420–7.
43. Fraser R, Horowitz M, Maddox A, et al. Organization of antral, pyloric and duodenal motility in patients with gastroparesis. Neurogastroenterol Motil 1993;5:167–75.
44. Camilleri M, Brown ML, Malagelada JR. Relationship between impaired gastric emptying and abnormal gastrointestinal motility. Gastroenterology 1986;91:94–9.
45. Rao ASC, Lu R, Schulze-Delrieu K. Duodenum as an immediate brake to gastric outflow: A videofluoroscopic and manometric assessment. Gastroenterology 1996;110:740–7.
46. Kerlin P. Postprandial antral hypomotility in patients with idiopathic nausea and vomiting. Gut 1989;30:54–9.
47. Stanghellini V, Ghidini C, Ricci Maccarini M, et al. Fasting and postprandial gastrointestinal motility in ulcer and non-ulcer dyspepsia. Gut 1992;33:184–90.
48. Kellow JE, Phillips SF. Altered small bowel motility in irritable bowel syndrome is correlated with symptoms. Gastroenterology 1987;92:1885–93.
49. Kellow JE, Gill RC, Wingate DL. Prolonged ambulatory recordings of small bowel motility demonstrate abnormalities in the irritable bowel syndrome. Gastroenterology 1990;98:1208–18.
50. Quigley EMM, Pierre H, Deprez PH, et al. Ambulatory intestinal manometry. A consensus report on its clinical role. Dig Dis Sci 1997;42:2395–400.
51. Stein HJ, Demeester TR. Indications, technique, and clinical use of ambulatory 24-hour esophageal motility monitoring in a surgical practice. Ann Surg 1993;217:128–37.