An Impedance-Manometry Based Method for Non-Radiological Detection of Pharyngeal Post-Swallow Residue

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Abbreviations:

AIM automated impedance manometry
SRI swallow risk index
UES upper esophageal sphincter
PAS penetration-aspiration scale
BRS bolus residue scale
Z impedance
Zn nadir impedance
iZn/Z integrated Zn/Z ratio
Abstract

INTRODUCTION: Post-swallow residue is indicative of impaired pharyngeal bolus clearance. The integrated nadir impedance to impedance ratio (iZn/Z) is a novel functional variable that can be derived using automated impedance manometry (AIM). In this study the post-swallow pharyngeal iZn/Z was evaluated as a potential correlate post-swallow residue and therefore predictor of ineffective swallowing.

METHODS: Optimal iZn/Z criteria were determined using a database of 50 randomly selected bolus swallows recorded with impedance, manometry and videofluoroscopy. The iZn/Z was derived for a region of interest (ROI), spanning the midpoint of the pharyngeal stripping wave to the UES proximal margin and from 0.25-1.25 sec after the peak of the pharyngeal stripping wave. Videofluoroscopy was scored by four experts using a six point bolus residue scale (BRS) score. Optimised criteria for iZn/Z were then applied to a much larger database of 225 swallows recorded scored for residue by one expert observer.

RESULTS: Amongst individual data-base swallows iZn/Z was significantly correlated with average expert BRS score (r = 0.748, p<0.0001). An iZn/Z of ≥500 was optimally predictive of swallows with residue defined by a BRS score of 4 or more. Within the larger cohort, iZn/Z was higher in dysphagia patient swallows compared to controls (2 [1, 4] vs. 1 [1, 3], p<0.005) and swallows with an iZn/Z ≥500 had higher bolus residue scores (4 [1, 6] vs. 2 [1, 4], p<0.001).

CONCLUSION: The AIM derived iZn/Z is an easily determined objective non-radiological marker of clinically relevant post swallow residue and therefore has potential diagnostic relevance as a predictor of ineffective swallowing.

(<250 words)

Key Words: deglutition and deglutition disorders, manometry, electric impedance, radiology, diagnosis, bolus residue
**Introduction**

Significant post-swallow residue is an indicator of interest when evaluating the dysphagic patient, and is indicative of impaired pharyngeal propulsion and/or increased resistance to flow at the upper esophageal sphincter (UES). Videofluoroscopy is the standard tool for evaluation of post-swallow residue, however fluoroscopy is not always readily available and there can be inherent difficulties in achieving good quality studies in patients with mobility and cognitive impediments. Such patients could potentially benefit from non-radiological methods of assessment (1).

Pharyngeal automated impedance manometry (AIM) analysis is a new non-radiological methodology which can be used to analyze the patterns of flow and pressure generated during bolus swallowing (2-4). AIM analysis has high intra-rater and inter-rater reproducibility (4) and derives pharyngeal pressure-flow variables which are objective markers of deglutitive function and, through derivation of the swallow risk index (SRI), can predict circumstances were swallows are so abnormal that they are likely to be ineffective and/or associated with aspiration risk (2-4). The SRI is however only an indirect predictor of residue (3) and a more direct measurement method is still needed.

To date the direct detection of bolus residue using intraluminal impedance recording has been problematic. Standard impedance analysis relates post-swallow impedance to pre-swallow baseline impedance. Failure of clearance is defined by a delay in recovery of the impedance to the level of a predetermined cut-off (usually 50% of baseline). This approach has been unsuccessful when applied to the pharynx due to large inter- and intra-patient differences in the pre-swallow impedance which can fluctuate considerably due to the secretions, intermittent mucosal contact, the presence of air and the presence of bolus residue from previous swallows (5-7).

The nadir impedance recorded during bolus passage is a critical measure used by AIM analysis which identifies the centre of a swallowed bolus in both time and space. Unlike pre-swallow impedance, the nadir impedance during bolus passage can be easily and reliably determined. In this study we tested the hypothesis that, in patients with dysphagia, the integral of ratio of nadir
impedance to post-swallow impedance (\(iZ_n/Z\)) is elevated in relation to post-swallow residue on videofluoroscopy and therefore a potential non-radiological predictor of ineffective pharyngeal bolus clearance.
Methods

In order to determine if the iZn/Z for a swallow was predictive of post-swallow residue we first optimised this variable for incorporation into AIM analysis by using a database of 50 randomly selected bolus swallows recorded with videofluoroscopy, high resolution manometry and impedance that were double-scored for bolus residue by four experts (refer to Optimisation Study). This database has been previously used to evaluate the intra-, inter-observer reliability of AIM analysis variables (4).

Following optimisation, we examined the relationship between iZn/Z and post-swallow residue within a database swallows from our full cohort 48 patient and control studies performed to date which were single-scored for post-swallow residue by one expert analyst (refer to Cohort Study).

Optimisation Study

Optimisation of the methodology for detection of abnormal bolus residue was performed using a previously described test data-base (4) comprising 50 randomly selected bolus swallows of semisolid (n = 20, 10 from controls) and liquid (n = 30, 10 from controls) recorded in a sub-cohort of 18 dysphagia patients and 8 controls (refer to Cohort Study for specific details of the combined fluoroscopy, impedance and manometry measurement protocol). Fluoroscopy video files were compiled for sequential analysis by expert observers and AIM analysis was performed on the corresponding impedance-manometry text data files.

Fluoroscopy Analysis

In order to ensure that bolus residue was scored with a high degree of accuracy, fluoroscopy analysis was performed by four experienced observers who were considered to be experts in fluoroscopy routinely reviewing fluoroscopy images in a professional capacity (geriatrician, radiologist and two speech pathologists). The analysis was based upon review of computer video files (.mp4) of swallows. Video-loops were de-identified and edited such that only one bolus swallow was displayed per video-loop. Fluoroscopic images were repeat-scored for the presence or absence of post-swallow residue in the valleculae, piriform sinus and/or posterior pharyngeal wall.
and were assigned a bolus residue scale (BRS) score between 1 and 6 according to the number of
structures showing evidence of residue: No residue in any of these structures was assigned a BRS
score of 1. If residue was present, then additional scores were weighted towards the anatomical
regions in which residue posed an aspiration risk (+1 for valleculae, +2 for piriform sinus and +2
for posterior pharyngeal wall). Hence valleculae only = BRS 2, posterior pharyngeal wall or
piriform sinus only = BRS 3, valleculae and posterior pharyngeal wall or piriform sinus = BRS 4,
posterior pharyngeal wall and piriform sinus = BRS 5; all structures = BRS 6 (3).

Each observer performed repeat analyses. Expert consensus BRS score was determined for each
swallow based upon the most frequently assigned BRS score for that swallow (if two BRS scores
were equally the most frequently assigned then the average was taken). Based on studies performed
in our Centre, the 95th percentile for BRS score in asymptomatic subjects is 4. A BRS score of 4-6
was therefore considered abnormal for the purposes of this analysis and diagnostic criteria were
optimised for detection of BRS score within the range of 4-6.

AIM analysis

AIM analysis of impedance-manometry text data files was performed usingAIMplot, a purpose-
designed MATLAB-based analysis program developed to increase the applicability of the
methodology for routine use (4). To operate AIMplot the observer was required to define three
space-time landmarks from a standard pharyngeal pressure topography plot (also shown in Figure
1D).

These were:

- The time of onset of pharyngeal swallow; defined by the onset of upper esophageal sphincter
  (UES) relaxation often, but not always, associated with a proximal excursion of the UES
  high pressure zone.
- The position of the UES proximal margin immediately post pharyngeal swallow.
- The position of the velopharynx; defined as the pressure zone immediately above the
  propagated pharyngeal stripping wave.
Guided by definition of these landmarks, AIMplot then automatically derived values for pharyngeal pressure-flow variables and the Swallow Risk Index (SRI) (2-4) as well as values for $\frac{Z_n}{Z}$ (as per method described below). Note: pressure and impedance data were smoothed by a cubic interpolation method which doubled the temporal data and increased the amount of spatial data by a factor of 10 (pressure) and 20 (impedance), hence achieving a virtual increase from 1 pressure and 0.5 impedance values per 1 cm sampled every 5msec (20Hz) to 10 pressure and impedance values per cm sampled every 2.5msec (40Hz).

**Calculation of Integrated Zn/Z**

For each array of impedance values, nadir impedance (Zn) to impedance (Z) ratio (Zn/Z ratio) was calculated and then values of Zn/Z ratio residing within an optimal post-swallow region of interest (ROI) were numerically integrated in order to generate a single value reflecting the overall intensity of Zn/Z ratio within the ROI (hence the term *integrated Zn/Z*).

Figure 1 (A-C) illustrates the calculation of Zn/Z ratio at a single location along the pharyngeal contractile wave. To calculate the Zn/Z ratio over time, the raw value of Zn (Figure 1 B) was divided by all sampled values of Z (Figure 1 B). Hence when Z equals Zn the Zn/Z ratio is 1 and when Z is greater than Zn the Zn/Z ratio is less than 1. Being reciprocal to impedance, Zn/Z ratio increases during the passage of a bolus and decreases when the bolus is cleared (Figure 1 C).

We hypothesised that the optimal space-time coordinates of the post-swallow ROI should be defined as follows: Firstly, with respect to space, the ROI should be limited to the distal half of the region from velopharynx to upper esophageal sphincter proximal margin. This was in order to specifically identify residue within the area encompassing piriform sinus, valleculae and posterior pharyngeal wall (Figure 1 D). Secondly, with respect to time, the ROI should start sufficiently late of the pharyngeal contraction peak so as to not be influenced by pharyngeal compression of the catheter. In addition the ROI should end sufficiently early so as to not be influenced by subsequent clearing swallows. A separate iterative evaluation of a range of start-times and durations for the
post-swallow ROI was performed (data not shown) and this determined that a ROI start time of peak+0.25sec and ROI duration of 1sec would be optimal (Figure 1 E). To complete the analysis, the data array of Zn/Z ratios within the area of the ROI (comprising 40 samples/sec x 10 samples/cm mid pharyngeal length) was integrated (by cumulative trapezoidal numerical integration) to calculate the iZn/Z. Figure 2 shows example plots and iZn/Z calculations for swallows without and with bolus residue.

Statistical analysis

Intra-rater test/retest reproducibility and inter-rater reliability of the expert BRS score was assessed by calculation of intraclass correlation coefficient (ICC). For intra-rater reproducibility, data derived during the first and second analyses were correlated for each observer. For inter-rater reliability, data derived from the first analysis was correlated for each combination of observers. The correlation between the expert consensus BRS score and the magnitude of iZn/Z was determined using Pearson Correlation.

The degree of agreement between expert consensus BRS score and individual observer BRS score as well as different levels of iZn/Z was determined using Cohen’s kappa statistic ($\kappa$). The scale for $\kappa$ values is: 0.00 = no agreement, 0.00 – 0.2 = slight, 0.21-0.40 = fair 0.41-0.60 = moderate, 0.61-0.8 = substantial, 0.81-1.00 = almost perfect. Prognostic accuracy was also assessed through calculation of sensitivity and specificity.

Cohort Study

In this study the iZn/Z diagnostic criterion optimised for detection of residue within the range of BRS score 4-6 was tested amongst our full data-base of patient and control swallows. We analysed all possible swallows recorded during videofluoroscopic investigations performed in 40 adult dysphagic patients (24 males, mean age 46 yrs, age range 23-95 yrs) and 8 healthy adult controls (3 males, mean age 38 yrs, age range 24-47 yrs). All subjects were enrolled in study protocols that were approved by the Research Ethics Committee, University Hospitals Leuven, Belgium. In dysphagic patients, underlying diseases/conditions were identified through a review of medical
records. Eighteen patients had a neurological history (10 stroke and 2 Parkinson’s disease, 1 Huntington’s disease, 1 multiple sclerosis, 2 dementia, 1 spina bifida, and 1 post neurosurgery). Eight patients had underlying gastrointestinal disease (oesophageal motility disorders, GERD). Four patients had an oropharyngeal tumor. Six patients had pulmonary disease (COPD, lung abscess, pneumonia). The remaining four patients were post cervical surgery, Wegener disease, post septic shock and diabetic.

Measurement Protocol

Studies were performed in the Radiology Department, University Hospitals Leuven with a 3.2mm diameter solid state manometric and impedance catheter incorporating 25 1cm-spaced pressure sensors and 12 adjoining impedance segments, each of 2 cm (Unisensor USA Inc, Portsmouth, NH). Subjects were intubated after topical anaesthesia (lignocaine spray) and the catheter was positioned with sensors straddling the entire pharyngo-esophageal segment (velo-pharynx to proximal esophagus). Pressure and impedance data were acquired at 20Hz (Solar GI acquisition system, MMS, The Netherlands) with the subject sitting upright. Most subjects were tested with at least 5 boluses in the lateral view; liquid (x3), semi-solid (x1) and solid boluses (x1). A standard liquid contrast material (Micropaque™) was given as liquid bolus and used with thickener (Thick & Easy™) for semisolid boluses. A low osmotic hydrosoluble iodium compound (Ultravist™) was used when aspiration was suspected. The viscosity of the administered boluses was determined by a Rheomat 115 Viscometer. The Bingham viscosity of the liquid Barium (Micropaque™) was 0.22PA s, 4.50 PA s for the semisolid bolus and 15.7 PA s for solids. All controls were given boluses of 10ml volume while patients were given either 5ml or 10ml volumes as determined on clinical grounds by the attending specialist. Solid boluses consisted of a 4cm² piece of bread soaked in the appropriate radiological marker. All bolus stock contained 1% NaCl to enhance conductivity.

Fluoroscopy Analysis

Video-loops of the fluoroscopic images of swallows acquired at 25 frames/sec were reviewed once by a single expert (speech pathologist) who had already participated in the video analysis.
component of the Optimisation Study. The expert analyst scored video-loops for bolus residue using the BRS score as previously described and aspiration using the validated 8-point penetration-aspiration scale (PAS) score (8). The PAS score assessed the depth to which material passes in the airway and by whether or not material entering the airway is expelled during the swallow sequence (Score 1 = no aspiration, 2-5 = penetration, 6-8 = aspiration). The expert analyst was blind to all impedance-manometry results but was not blinded to patient details and, having participated in the acquisition phase of the study, was aware of clinical histories. As determined by the expert analyst, swallows with poor image quality were not included for analysis.

**AIM Analysis**

Pharyngeal AIM analysis of impedance-manometry text data files was performed using AIMplot to derive values for swallow risk index (SRI) and iZn/Z as previously described. AIM-based aspiration risk was defined for individual swallows by an SRI $\geq 20$ (optimal criteria for single liquid swallows (2)).

**Statistical analysis**

The primary analysis compared fluoroscopically measured bolus residue with iZn/Z for individual swallows grouped according to patient/control and criteria of iZn/Z above/below the optimal cut off. Swallow data were compared using Mann-Whitney Rank Sum Test or Kruskal-Wallis One Way Analysis of Variance on Ranks and Pairwise Multiple Comparison Procedures (Dunn's Method). Correlation was assessed using Pearson correlation.
Results

Optimisation Study

The intra-rater reproducibility of expert BRS scores ranged from ICC 0.895-1.000 (average 0.972) and inter-rater reproducibility ranged from ICC 0.716-0.880 (average 0.780). 25, 19, 14 and 9 swallows had consensus BRS scores of ≥2, ≥3, ≥4 and ≥5. The kappa agreement of individual experts determining abnormal residue (BRS score≥4) with the consensus BRS score showing the equivalent ranged from $\kappa$0.63-0.90 (average 0.77) with a sensitivity of 0.61-1.00 (average 0.79) and specificity of 0.95-1.00 (average 0.98).

The magnitude of $iZn/Z$ measured for individual swallows correlated with the expert average BRS score (Figure 3A). $iZn/Z$ cut-off levels from 0-1000 were evaluated against abnormal residue determined by expert consensus, this showed that an $iZn/Z$ cut-off levels of 300 and 500 were most optimal for detecting residues of BRS 2-3 or more ($\kappa$ 0.54 moderate; sens 0.79, spec 0.78) and BRS 4 or more ($\kappa$ 0.63 substantial; sens 0.64, spec 0.94) respectively (Figure 3B). The level of agreement between AIM $iZn/Z \geq 500$ vs. consensus BRS scores in the abnormal range of 4-6 was within the inter-rater range of the expert observers scoring fluoroscopy (Figure 3C).

Cohort Study

Integrated Zn/Z and Bolus Residue

A total of 225 bolus swallows were sequentially analysed comprising 40 control swallows (24 liquid, 16 semisolid) and 185 patient swallows (111 liquid, 42 semisolid and 32 solid). There were no significant differences between semi-solid and solid swallows in terms of BRS score and therefore these data were combined. Patient swallows had significantly higher BRS scores and higher integrated $iZn/Z$s than control swallows (Table 1). Higher subject average BRS score correlated with higher subject average $iZn/Z$ (all swallows $r = 0.581$, $p<0.0001$; liquid swallows $r = 0.512$, $p<0.0005$; semisolid/solid swallows $r=0.528$, $p<0.0005$). Swallows with an $iZn/Z \geq 500$ had significantly higher BRS scores (Table 2). The sensitivity/specificity of $iZn/Z$ cut-off level of 300
for detecting BRS 2+ was 0.77/0.76 and BRS 3+ was 0.85/0.61 and iZn/Z cut-off level of 500 for detecting BRS 4+ was 0.45/0.84 and BRS 5+ was 0.67/0.80.

**AIM Criteria and Aspiration of Liquids**

Penetration (PAS score 2-5) was observed for 38 swallows (25 liquid) and aspiration (PAS score 6-8) for 28 swallows (24 liquid). Swallows with an iZn/Z $\geq$ 500 had significantly higher PAS scores and a higher swallow risk index, this was particularly evident for liquid swallows (Table 2). PAS scores were highest overall for liquid swallows identified using AIM-based criteria as being both a residue risk (iZn/Z $\geq$ 500) and an aspiration risk (SRI$\geq$20 for individual swallows (2)) (Figure 4).
Discussion

In this study a novel AIM variable, $iZn/Z$, was optimised for the direct detection of post-swallow bolus residue using a sub-database of expertly multi-scored swallows. The optimised bolus residue detection criteria were then tested amongst our full database of swallows scored for residue and aspiration by a single expert. The $iZn/Z$ was elevated in proportion to higher bolus residue scores and optimised residue detection criteria appeared accurate. For detection of clinically significant post-swallow residue, an $iZn/Z \geq 500$ agreed with consensus scoring of residue to a level that was within the range of the inter-rater agreements seen for experts scoring fluoroscopy. When applied to the full cohort, swallows with $iZn/Z \geq 500$ were associated with poor deglutitive function as evidenced by higher BRS score, higher PAS score and higher SRI. These findings suggest that this novel objective approach has the potential to non-radiologically identify ineffective swallowing with post-swallow residue.

Our previous attempts to optimise criteria for the direct detection of bolus residue using intraluminal impedance employed the standard approach of expressing impedance drop relative to baseline (5-7). We discovered however, large differences in the optimal criteria determined for controls and patients as well as large inter-patient differences related to pathology (7).

Our new approach was more successful than past attempts and this was due to number of factors: Firstly, the nadir impedance provided a more reliable reference for standardisation. Hence by using the reciprocal of the measured impedance relative to the nadir impedance (i.e. $Zn/Z$) we removed the need to estimate pre-swallow impedance baseline and the inaccuracies inherent in doing so. Secondly, we measured $Zn/Z$ ratio within a specific region of interest of the distal pharynx defined by rigid space-time criteria. This allowed the assessment of residue to be made in a way that was least likely to be affected by either the primary pharyngeal contraction or secondary contractions related to clearing swallows. Thirdly, $Zn/Z$ ratio data within the ROI were integrated over space and time to produce a single value of $iZn/Z$ which defined the presence of post-swallow residue. Finally, the calculation of $iZn/Z$ was made automated and objective through seamless
incorporation into an existing AIM analysis platform based upon three easily recognised landmarks, namely swallow onset time, velopharynx position and UES margin position. We have previously shown that the calculation of AIM variables guided by user definition of these landmarks has high intra- and inter-rater reliability in the hands of users with varying expertise (4). Although not specifically tested in this study, it is nevertheless very likely that calculation of iZn/Z will also prove highly reliable.

Many swallows in both patients and controls were observed to be ineffective and failed to completely clear the bolus. Residue was scored greater for patients than controls as was the iZn/Z significantly higher in patient swallows. The iZn/Z was optimised against video swallows that were repeat scored for bolus residue by four experts in videofluoroscopy. This indicated that an iZn/Z of 300 was optimal for detection of BRS scores of 2-3 or more and 500 was optimal for detection of abnormal BRS scores of 4 or more.

The optimised iZn/Z criteria were further evaluated in the cohort study. Within this larger database, iZn/Z criteria of 300 appeared to detect BRS of 2 or more with equivalent sensitivity/specificity to that determined by the optimisation study. The sensitivity of iZn/Z criteria of 500 for detecting BRS of 4 or more was however lower than that determined in the optimisation study (sens 0.45 vs. 0.64) and cut off criteria of 500 were markedly better for detecting BRS 5 or more (sens 0.67). It is important to recognise however that the analysis of fluoroscopy in the cohort study was of a far less rigorous standard than that for which optimal criteria were defined. As shown in the optimisation study, the inter-rater sensitivity for detecting BRS 4 or more ranges widely (sens 0.61-1.0). As the cohort study database only included swallows that were single-scored by one observer, the gold standard in this case was far less reliable (compared to double scoring by four observers). Indeed we considered the fluoroscopy scoring in to cohort study too unreliable to be able to confidently re-define our optimal iZn/Z cut off criteria for detection of residue. Nevertheless, having optimised iZn/Z criteria for detection of BRS scores of 4 or more, it was encouraging that BRS scores were significantly higher for cohort swallows with an iZn/Z of ≥500 and the median BRS score of cohort
study swallows with an iZn/Z $\geq 500$ was indeed BRS 4. Finally, the subject average values for iZn/Z correlated with the average BRS scores with a high level of statistical confidence.

The value of AIM analysis is that it takes into account several different objective measures of function in order to non-radiologically ascertain a global assessment of pharyngeal function/dysfunction using the swallow risk index. By quantifying the degree of dysfunction, aspiration risk can be predicted. Evidence that iZn/Z is a direct marker of presence of post-swallow residue makes this an important additional parameter that can be used to enhance the diagnostic accuracy of AIM-based assessments of swallowing. As clearly demonstrated with aspiration of liquid swallows, a positive SRI in combination with a positive iZn/Z provides very strong objective evidence of deglutitive aspiration risk. These data add further weight to our published pilot data in predominantly neurological patients (2) and we are very encouraged by the fact that our original observations with regard to the SRI being a robust predictor of aspiration risk, are still supported having now doubled the number of patients and introduced heterogeneity into the cohort as presented in the current study. In practice, having established pharyngeal effectiveness and aspiration risk, one could then turn to other individual AIM functional variables to identify pathophysiological causes. This potentially allows for a specific diagnosis of varying mechanical dysfunctions. From such analyses, it may be possible to devise well-targeted therapeutic interventions and, in turn, track the effectiveness of such interventions.

In conclusion, we present novel findings in support of iZn/Z as a useful diagnostic AIM variable predictive of post-swallow residue in dysphagia patients. These findings provide further evidence that AIM analysis can non-radiologically analyse pharyngeal swallowing and derive meaningful diagnostic information that may assist in the management of patients with pharyngeal dysphagia.
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Competing Interests:

Dr Omari is a technology consultant to Sandhill Scientific Inc. All other authors have no competing interests.
References


### Table 1. Bolus Residue Score and iZn/Z for control vs. patient swallows.

Data expressed as median [IQR]. *Significantly different to controls using Mann-Whitney Rank Sum Test. **p<0.005, ***p<0.001.

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Table 2. Bolus Residue Score and Swallow Risk Index for swallows with iZn/Z <500 vs. ≥500.

Median [IQR] data for 170 swallows with iZn/Z <500 (90 liquid) compared to 55 swallows with iZn/Z ≥500 (44 liquid). *Significantly different to <500 using Mann-Whitney Rank Sum Test. *p<0.05, **p<0.01, ***p<0.001.
**Figure 1. Calculation of integrated iZn/Z.**

A-C. Individual channel recordings at 1cm proximal to the UES high pressure zone from 0.5sec before to 2.5sec after swallow onset of a normal swallow, without post swallow residue.

A. Pressure (P) only showing the timing of pharyngeal contraction peak.

B. Pressure and impedance (Z) showing the timing of nadir impedance (Zn).

C. Pressure and impedance nadir to impedance ratio (Zn/Z ratio). Note the rise in Zn/Z ratio associated with bolus flow pre-swallow and the drop in Zn/Z ratio post-swallow.

D. A Clouse colour pressure topography plot showing the anatomical location of AIM analysis user identified space-time landmarks (○). The mid-point between velopharynx and proximal margin of the UES high pressure zone was used to define the optimal position of the ROI in space.

E. A combined pressure and Zn/Z ratio plot showing the optimal position of the ROI in space and time (defined as 0.25sec after the pharyngeal contraction peak). Pressure iso-contours are shown as lines. Purple shading indicates areas of high Zn/Z ratio reflecting bolus presence. To calculate the iZn/Z, all Zn/Z ratio data of within the perimeter of the ROI was numerically integrated.
FIGURE 1
Figure 2. Example swallows without and with bolus residue.

Clouse colour pressure topography plots (left) and pressure-$Zn/Z$ ratio plots (right) as described for Figure 1 D and E. Plots indicate the position of the ROI used for calculation of the $iZn/Z$ and show values determined for the variable. Examples are consecutive 10ml semi-solid boluses recorded in a 41 year old female control subject.

10ml semisolid swallow without bolus residue (Consensus BRS 1)

10ml semisolid swallow with bolus residue (Consensus BRS 4)
Figure 3. Optimisation of iZn/Z for detection of bolus residue.

A. Correlation of iZn/Z with the expert average BRS score determined for data-base swallows.

B. Kappa agreement of iZn/Z and presence/absence of residue based on BRS scores. Note: iZn/Z of $\geq 500$ was optimally predictive for abnormal BRS scores of 4 or more.

C. Predictive value of iZn/Z $\geq 500$ for detection of abnormal bolus residue. Data for swallows with/without consensus BRS score 2+ to 6 are shown. The shaded region shows the range of Kappa agreement determined for individual experts when compared to consensus. Note iZn/Z criteria of $\geq 500$ were optimised to BRS score 4 or more and are within the limits of the expert range.
**Figure 4.** Median penetration aspiration scale scores for individual liquid swallows grouped according to AIM criteria for residue (iZn/Z ≥500) and aspiration (swallow risk index ≥20). The graph plots inter-quartile ranges (box) and 95th percentiles (error bars). Values for Kruskal-Wallis One Way Analysis of Variance on Ranks are shown when significant. *NO/NO significantly different to YES/YES (p<0.05) using pairwise multiple comparison procedures (Dunn's Method).