Improving the safety of nasogastric feeding tube insertion

*Developing guidelines for the safe verification of feeding tube position - a decision analysis approach*

A Report for the NHS Patient Safety Research Portfolio

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Developing guidelines for the safe verification of feeding tube position

1. Background
   1.1 The morbidity and mortality of feeding tubes
   1.2 Current guidelines on checking procedure
   1.3 Summary

2. Objectives

3. Methods overview

4. Literature review
   4.1 Literature review methods
   4.2 Traditional bedside methods
      4.2.1 Auscultation
      4.2.2 Visual characteristics of feeding tube aspirates
      4.2.3 pH of feeding tube aspirates
         4.2.3.1 Accuracy of pH paper
         4.2.3.1 Influence of acid-inhibiting medication
      4.2.4 Other methods
   4.3 More recent methods
      4.3.1 Capnometry and colorimetry
      4.3.2 Magnetic devices
      4.3.4 Pilot studies
   4.4 Monitoring feeding tube placement
   4.5 Summary

5. Developing safety recommendations
   5.1 Defining the problem: who does the recommendation apply to?
      5.1.1 Defining patients at high risk for aspiration
   5.2 What kind of test do we need
   5.3 Oesophageal pH
   5.4 Gastric residual volumes
   5.5 Areas of controversy: Small bowel vs gastric feeding
   5.6 Feeding and medication history
5.7 Predicting the tube site using BBN
5.8 Summary
6. Bayesian belief networks
   6.1 Building the network: assumptions, data and structure
      6.1.1 Structure
      6.1.2 Definition of uncertain events
      6.1.3 Dependent relationships
      6.1.4 Parameters
      6.1.5 Prior probabilities
      6.1.6 Conditional probabilities
   6.2 Expert consultation
   6.3 Test selection
   6.4 Test assessment
   6.5 Sensitivity analyses
   6.6 Summary of key findings
7. Implications
   7.1 Tube site prediction in practice
   7.2 X-ray interpretation
   7.3 Comparison with existing guidelines
   7.4 Comparison with current practice
8. Validation against NRLS adverse event reports
   8.1 Methodology
      Database search
   8.2 Case selection and analysis
   8.3 Results
   8.4 Further analysis of pH results
   8.5 Further analysis of chest x-ray misinterpretation
      8.5.1 Assessment of safety guidelines
9. Overall discussion
10. Future research
11. Conclusion
12. Safety recommendations for blindly inserted nasogastric tubes

References
Appendix A Bayes’ theorem and effectiveness of tests
Appendix B Making decisions
Appendix C Test assessments
Appendix D Search Terms
Appendix E pH narratives and Chest X-ray narratives
Appendix F Scientific papers generated out of this project
## LIST OF TABLES

<table>
<thead>
<tr>
<th>Table</th>
<th>Description</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>Table 1</td>
<td>Selection criteria</td>
<td>22</td>
</tr>
<tr>
<td>Table 2</td>
<td>pH analysis of 1,500 samples</td>
<td>25</td>
</tr>
<tr>
<td>Table 3</td>
<td>The test, the findings and the conditional probabilities</td>
<td>42</td>
</tr>
<tr>
<td>Table 4</td>
<td>Likelihood ratios of the test findings</td>
<td>44</td>
</tr>
<tr>
<td>Table 5</td>
<td>Test selection based on diagnosticity of lung and oesophagus</td>
<td>45</td>
</tr>
<tr>
<td>Table 6</td>
<td>Positive findings of the tests</td>
<td>46</td>
</tr>
<tr>
<td>Table 7</td>
<td>Probability weights for computing the expected advantage of X-ray</td>
<td>48</td>
</tr>
<tr>
<td>Table 8</td>
<td>Probability weights for computing the expected advantage of pH ≤ 4</td>
<td>49</td>
</tr>
<tr>
<td>Table 9</td>
<td>Sensitivity analysis of tests</td>
<td>51</td>
</tr>
<tr>
<td>Table 10</td>
<td>Tube Site Predictions based on 50% tube placement error</td>
<td>53</td>
</tr>
<tr>
<td>Table 11</td>
<td>Outcomes of clinical guidelines</td>
<td>54</td>
</tr>
<tr>
<td>Table 12</td>
<td>Patient harm resulting from feeding tube misplacement NRLS</td>
<td>57</td>
</tr>
<tr>
<td>Table 13</td>
<td>Mode of failure to identify tube misplacement</td>
<td>57</td>
</tr>
</tbody>
</table>
# LIST OF FIGURES

<table>
<thead>
<tr>
<th>Figure</th>
<th>Description</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>The iterative process of model construction</td>
<td>21</td>
</tr>
<tr>
<td>2</td>
<td>Obtaining an aspirate from fine-bore feeding tubes</td>
<td>25</td>
</tr>
<tr>
<td>3</td>
<td>Risk factors for aspiration</td>
<td>32</td>
</tr>
<tr>
<td>4</td>
<td>The BBN for NG-tube checking procedures</td>
<td>39</td>
</tr>
<tr>
<td>5</td>
<td>Guideline scenarios and outcomes</td>
<td>54</td>
</tr>
<tr>
<td>6</td>
<td>pH distribution of gastric aspirates and fasting history</td>
<td>67</td>
</tr>
<tr>
<td>7</td>
<td>pH distribution of gastric aspirates &amp; respiratory samples</td>
<td>68</td>
</tr>
<tr>
<td>8</td>
<td>Lung sample pH readings pH meter</td>
<td>69</td>
</tr>
<tr>
<td>9</td>
<td>pH distribution for patients fasted at least 1 hour, no acid inhibitors</td>
<td>70</td>
</tr>
<tr>
<td>10</td>
<td>pH distribution of gastric aspirates &amp; respiratory samples - pH paper</td>
<td>71</td>
</tr>
<tr>
<td>11</td>
<td>Potential tube sites according to aspirate pH</td>
<td>72</td>
</tr>
<tr>
<td>12</td>
<td>Adverse event process mapping with proposed safety recommendations</td>
<td>73</td>
</tr>
</tbody>
</table>
## GLOSSARY OF TERMS

<table>
<thead>
<tr>
<th>Term</th>
<th>Definition</th>
</tr>
</thead>
<tbody>
<tr>
<td>Existing guideline</td>
<td>The current NPSA recommendation that a pH lower than 5.5 suggests stomach intubation and therefore safe feeding</td>
</tr>
<tr>
<td>Our recommendations</td>
<td>Our recommendation that aspirate pH test should be used for safe feeding but using a lower cut-off of 4.0 instead of the current cut-off of 5.5 to prevent feeding into the oesophagus (Page 65)</td>
</tr>
<tr>
<td>BBN</td>
<td>Bayesian Belief Network</td>
</tr>
<tr>
<td>NG tube</td>
<td>Nasogastric feeding tube</td>
</tr>
<tr>
<td>NPSA</td>
<td>National Patient Safety Agency</td>
</tr>
<tr>
<td>Auscultation</td>
<td>Listening with a stethoscope for characteristic sounds</td>
</tr>
<tr>
<td>Capnometric/colorimetric</td>
<td>Measurement of carbon dioxide (CO2)</td>
</tr>
<tr>
<td>Enteral feeding</td>
<td>The delivery of nutrition into the gastrointestinal tract</td>
</tr>
<tr>
<td>Magnetic guidance</td>
<td>The detection of electromagnetic material to indicate tube position</td>
</tr>
<tr>
<td>pH test</td>
<td>The acidity or alkalinity of tube aspirate fluid measured on a pH scale – using either pH meter or pH paper.</td>
</tr>
<tr>
<td>Visual characteristics</td>
<td>The appearance of tube aspirate to the naked eye</td>
</tr>
</tbody>
</table>
EXECUTIVE SUMMARY

Nasogastric tubes (NG-tubes) are in widespread use in the National Health Service (NHS) in the UK. Feeding through NG-tubes is popular because it can be used to meet medicational and nutritional needs of patients on a daily basis, and used in conjunction of small amounts of food intake. Misplacement of nasogastric feeding tubes into the respiratory tract can have serious consequences. For blind insertion, rates of respiratory placement between 1 – 3% are common; inadvertent tube placement in the oesophagus was observed in 19 of 100 blind nasogastric tube insertions (19%). There is a distinct lack of consensus as to the optimum method of checking feeding tube position. The NPSA guideline is based on pH assessment of tube aspirate, with a pH of 5.5 or below suggesting gastric position and a safe situation to start enteral tube feeding. The routine use of X-rays to verify tube position is not recommended. No single test can provide a definitive answer to tube location. Even X-rays, the gold standard, can be misinterpreted. The NPSA worked with the PSRP to commission further research to aid the development of an evidence-based safety guideline with the emphasis on starting tube feedings safely.

Decisions to commence feeding depend on the tube sites as well as on the benefits of feeding correctly in comparison to the costs of feeding incorrectly. The challenge lies not only in uncertainties inherent in each individual test (including x-ray), but also in the need to combine not just one but many signs, symptoms and other data. Expert opinions are important because the literature rarely contains all the necessary information and also because clinicians will be the practitioner of the recommendations.

In view of all these, this research applied a multi-modality approach to inform the development of the safety guideline, encompassing a systematic literature review, construction of a Bayesian belief network (BBN) model, decision analysis, coordinating a steering group panel of experts for feedback and guidance and comparing the recommendations against current practice and historical adverse event data. Only those tests that can be used at the bed-side were considered and their capacity, both when used in isolation and in combination, in differentiating among four tube sites: lung, oesophagus, stomach and intestine, was examined. The systematic review demonstrates the following:

- **Traditional bedside methods:** observing for respiratory signs or symptoms such as coughing, dyspnoea, or cyanosis does not provide evidence of tube misplacement into the airway.
- **Auscultation:** the auscultation method has been discredited largely due to numerous case reports of tube misplacement in which this method falsely indicated correct gastric position, including reports in the recent literature.
• **Visual characteristics of feeding tube aspirates**: an observational study by Metheny et al was limited – the aspirate appearance method includes the variation of possible aspirate features, considerable overlap between tube sites and the highly subjective nature of the assessment.

• **pH of feeding tube aspirate**: The collective studies performed by Metheny et al represent the most impressive body of research looking at aspirate pH measurement and prediction of feeding tube position. The research group collected prospective data with a standard well-designed study protocol from 6 acute care hospitals, and their cumulative data have been reported in 5 separate publications over a 12-year period.

• **Accuracy of pH paper**: there are mixed reports of the accuracy of pH indicator papers in common clinical usage. Some authors have questioned the validity of using pH paper for accurate measurement of gastric pH, particularly in the critical pH range of 4 – 6.

• **Influence of acid-inhibiting medication**: acid-inhibiting medication will reduce the sensitivity of pH measurement for gastric placement, but will not alter the specificity or render the method unsafe with regard to feeding decisions.

• **Oesophageal pH**: There is a lack of data regarding any method to check tube position in the oesophagus. Studies on normal volunteers all use a pH cut-off of 4.0, based upon guidelines for the definition of gastro-oesophageal reflux. The collated data demonstrate that the median percentage time with oesophageal pH measured less than 4.0 is between 0.5 – 3.1% of recorded 24-hour periods in healthy individuals.

• **Feeding and medication history**: results do not support any benefit of fasting for longer than an hour prior to aspirating the feeding tube.

• **Capnometry and colorimetry**: this technique has been reported in 3 pilot studies and 3 prospective clinical studies using either capnography or colorimetry for CO₂ detection. Overall sensitivity is 95.8% and overall specificity 99.6%. However the technique does have significant limitations as it gives no information about tube placement within the gastrointestinal tract.

• **Magnetic devices**: this system demonstrated 100% agreement with X-ray for tubes placed in the stomach (n=4) with a sensitivity for small bowel placement of 79% (n=19). There is incomplete and inconsistent presentation of the data for this study, making worthwhile interpretation of the results difficult.

• **Gastric Residual Volumes (GRV)**: GRV are frequently used to monitor the safety and efficacy of tube feeds. The definition of a high gastric aspirate as an appropriate marker for the risk of aspiration is extremely variable in clinical practice.

• **Patients who have high risk for aspiration**: The recommendations for safe insertion of feeding tubes may have limited applicability to high-risk patients. Risk assessment for individual patients needs to be carried out to inform the appropriate site for enteral feeding.
We shared the findings with a group of tube-feeding experts. BBN models were used to demonstrate the dynamic relationship between tube site, test result, and interpretation of test results (pH only). Decision analysis method is used to select and identify the ‘best test’, by considering not only the predictions of the tube sites but also the consequences of the most likely feeding decisions in light of the knowledge of the predicted tube site. The main findings of decision analysis include:

- Improving the quality of initial tube insertions is vital to safe feeding
- The existing sensitivity and specificity data suggest that magnetic guidance is the single best test, followed by tube aspirate pH \( \leq 4.0 \)
- Tests such as auscultation, appearance, or capnography/colorimetry, when used on their own, do not provide evidence for initiating safe feeding

The low quality of published evidence on magnetic guidance renders the test unsuitable for use in a clinical guideline. We therefore recommend the pH test, and lower the cut-off for safe feeding from 5.5 to 4.0 to avoid feeding into the oesophagus. If the aspirate pH is 4.0 or lower, feeding can start safely. If the aspirate pH is 5.5 or higher, feeding should only start if a chest x-ray confirms stomach intubation. When the aspirate pH is in the range between 4 and 5.5, we recommend an assessment of the risk of feeding into the oesophagus. Feeding should only start if the risk is assessed as low, or if the risk is high but a chest x-ray confirms stomach intubation and therefore safe to feed. In light of the potential risks of x-ray misinterpretations, we emphasize the importance of obtaining a correct interpretation before feeding can start safely.

Compared to the current guideline, the controversial area is for tube aspirate pH values of between 4.0 and 5.5. These values principally relate to the potential for tube feeding into the oesophagus. The consensus view is that delivery of enteral feeds into the oesophagus will increase the risk of pulmonary aspiration for all patients, and therefore oesophageal feeding should be avoided, which is better achieved by the lower pH cut-off. In addition, studies of pH measurement accuracy show an increased incidence of disagreement between pH paper and pH meter with pH paper values above 4.0, such that readings of pH 5.0 from pH paper were read by pH meter at higher than 6.0. This could indicate respiratory tube misplacement but be misinterpreted as gastric placement on pH paper testing alone, leading to potentially harmful feeding errors. Although feeding into the lungs is very unlikely with a pH cut-off of \( \leq 5.5 \) there is a clear potential for error that can be eliminated with a lower cut-off of pH \( \leq 4.0 \).
If we assume that every patient with a pH higher than 4 will be x-rayed, then compared to the current guideline using the pH cut-off of 5.5 (i.e. feed if pH is 5.5 or lower, x-ray if otherwise), our recommendation increases the unnecessary x-rays (i.e. x-rays for those patients with tube correctly placed in the stomach) from the existing 24.14% to 34.05% but lowers the feeding errors (feeding into the lung or oesophagus) from 9.38% to 0.62%.

The major drawback of applying a lower pH cut-off is an increase in the likelihood of unnecessary X-rays. However, the consensus view is that delivery of enteral feeds into the oesophagus will increase the risk of pulmonary aspiration for all patients, and therefore oesophageal feeding should be avoided. Therefore, we believe the consequences of tube feeding errors will be far worse than any delay in commencing tube feeds or the increased exposure to X-ray required for a plain chest radiograph.

Using a lower pH cut-off there is a cohort of patients with tube aspirate pH between 4.0 and 5.5 in whom X-rays will be requested. This same cohort will have tube feeding initiated without X-ray if the current NPSA alert guideline is applied. In terms of potential adverse outcomes, the safety of this cohort is enhanced with the lower pH cut-off: only the proportion of patients whose X-rays are misinterpreted or unable to be performed have the potential for catastrophic tube feeding errors as opposed to the entire cohort if the higher pH cut-off $\leq 5.5$ is relied upon.

We validated our recommendations against the National Reporting and Learning System (NRLS) database. A broad search was performed to include all potential reports of adverse events related to tube insertion or feeding. A total of 2368 adverse event reports were found using the predefined search terms. The event narratives were reviewed for each report retrieved and the majority were not related to enteral tube feeding. Reports with absent or insufficient narratives to describe the clinical scenario were also excluded. From the 2368 reports retrieved, only 75 narratives with documented feeding tube misplacement allowed for further analysis after excluding all the irrelevant reports including those with missing or insufficient narratives and all narratives not related to feeding tube insertion or enteral tube feeding. Further review of these narratives showed that there were 5 incidents of respiratory tube misplacement and documented feed aspiration into the lungs in which a pH cut-off of 5.5 was used to indicate safe feeding. Lowering the pH cut-off to 4.0 could have prevented these incidents.

**Limitations**

This research is limited by the scarcity of evidence and the unsatisfactory study quality that prevents tests with great potential (e.g. magnetic guidance) from being used. These cast doubt on the external validity of the research findings, which we are trying to provide a remedy by a clinical verification of the recommendations.
Conclusion

Despite shortage of literature, we combined available evidence using a multi-modality approach. This allowed us to formulate evidence-based recommendations (see Page 68) that includes clear exclusion criteria for the validity of the pH test for tube aspirates and also provides a stepwise approach to obtain the aspirate based upon best available data. The focus of our recommendations is on the safest outcome for patients requiring tube feeding. The crucial step of correct X-ray interpretation is integrated into the decision-making process. Importantly, while our recommendations will increase the number of X-rays required for tubes that are positioned in the stomach, this does not translate into more frequent feeding errors. No single bedside test is perfect for verification of tube position and there is a need for large prospective clinical studies to further evaluate emerging technologies as well as the reliability of existing pH indicators. This research has demonstrated that, based upon the best evidence available, the NPSA safety alert guidelines can be made safer.

OBJECTIVES AND ACHIEVEMENTS

The ultimate aim of the proposal is to develop recommended policies and evidence-based recommendations for correct placement of nasogastric tubes. We attained this by presenting a multi-modality approach that led to the development of an evidence-based safety recommendation (Page 49).

We proposed five specific objectives, which are:

1. **Provide a systematic review of different bedside tests for correct placement of NG-tubes.**
   This systematic review can be found in Page 14-20.

2. **Use decision analysis modelling to illustrate the advantages and disadvantages of various practices and to assist in the development of evidence based guidelines**
   We have applied decision conferencing to solicit data from experts and employed Bayesian belief networks to combine the expert judgments along with evidence extracted from the systematic review. Using decision analysis method, we also developed the procedure for screening and selecting the tests that were eligible for checking the position of NG-tubes. The whole process is presented from Page 27-39, as well as in Appendix B, and Appendix C.

3. **Construct and validate guidelines for best practice**
   We have developed the recommendations that can be converted to safety guidelines. The recommendations are presented as a flow chart (Page 65). The guideline is validated by cross-
checking NRLS adverse event report analysis. This analysis can be found in Page 43-45. We are also in the process of validating the recommendation clinically.

4. **Recommend possible prioritisation for the development and evaluation of new tests.**
   We propose that more research into magnetic guidance needs to be conducted. Literature review based decision analysis (Page 21, Page 32-36) found that magnetic guidance satisfied the following conditions which are important as the tests used for checking the NG tube positions. Firstly, the test needs to be non-ionising because of the potential harms done to the patients. Secondly, the patient needs to be conducted at the bed-side to avoid the potential danger imposed on the patient in the course of transportation. Thirdly, the test needs to have a fail-safe design because the current best-practise, i.e., using x-rays, suffers from potential misinterpretation.

5. **Conduct a feasibility study for a bedside test that does not involve ionising radiation.**
   We did not complete the feasibility study because of unexpected administration changes in QinetiQ led to the reassignment of the Melodi technology to another company that has different priorities. We have explored other collaborations and will pursue the proposed research.


DEVELOPING GUIDELINES FOR THE SAFE VERIFICATION OF FEEDING TUBE POSITION - A DECISION ANALYSIS APPROACH

1 Background

1.1 The morbidity and mortality of feeding tubes

Nasogastric tubes (NG-tubes) are in widespread use in the National Health Service (NHS) in the UK. The National Patient Safety Agency (NPSA) estimates that at least 1 million tubes are purchased every year in England and Wales[1]. Nasal insertion of small-bore feeding tubes has been widely practised since the early 1980s, and is associated with complications including pneumothorax, intrapulmonary feeding or “aspiration by proxy”, aspiration pneumonia, lung abscess, pleural effusion, empyema and oesophageal perforation.

Inadvertent tube placement in the oesophagus is more common: in a prospective assessment of 100 blind nasogastric tube insertions, Benya et al[2] observed oesophageal placement in 19 tubes (19%). Placement of the tube feeding port into the oesophagus or even in the stomach when small bowel feeding is recommended can increase the likelihood of tracheobronchial aspiration. Inserted tubes can coil in the pharynx or loop back up into the distal oesophagus from the stomach. It is difficult to estimate the prevalence of tube misplacement since cases are not frequently reported. Reported rates of tube misplacement on insertion and tube migration after correct initial placement vary in the literature between 1.3% and 50% in adults[3]. The variability in reported prevalence reflects the various definitions of tube misplacement and the different types of enteral tubes used in clinical scenarios. Tube placement into the respiratory tract is the most common error, and case reports are still appearing in the recent literature. For blind insertion, rates of respiratory placement between 1 – 3% are commonly reported [4].

Misplacement of nasogastric feeding tubes into the respiratory tract can have serious consequences. The incidence of adverse events depends on correct tube position and the patient population: Bankier et al [5] reported a major respiratory complication rate in 57% of Intensive Therapy Unit (ITU) patients with tube misplacement in the tracheobronchial tree. Patients with cuffed endotracheal or tracheostomy tubes are not protected from tube malpositioning in the airway. In a recent review of 4,190 patients with feeding tube insertions over a 3-year period, the rate of tracheobronchial placement was 2.1%. Of these patients, 28.7% had a tracheostomy tube and 39.1% had an endotracheal tube in place at the time of feeding tube insertion [6].
A retrospective study published by de Aguilar-Nascimento et al [7] reviewed all small-bore feeding tube placements over a 12-month period in a single-centre tertiary referral hospital. A total of 1822 nasal or oral small-bore feeding tubes were placed into 729 adult patients. Respiratory tract placements as documented by X-ray occurred with 27 feeding tubes in 23 patients (3.2% of patients). Four patients (0.5%) died as a direct consequence of tube misplacement[7]. Sorokin and Gottlieb[8] observed a tube misplacement rate of 2.4% (50/2079 tubes) using relevant chest radiograph reports to identify tube placements. In this series, 26 out of 50 patients with respiratory misplacement were mechanically ventilated. A recent prospective study of 740 fine-bore feeding tube insertions identified 14 patients (2%) with tracheobronchial tract placement, of whom 13 patients had a cuffed endotracheal tube in place. The overall rate of major complications with tube insertion was 0.7% with a mortality rate of 0.3%[9].

The National Patient Safety Agency was first contacted in April 2004 by H.M. Coroner for Yorkshire following his inquest into the death of a child in December 2002. The decision of the Coroner was that death arose as a consequence of a misplaced nasogastric feeding tube. Subsequently the NPSA became aware of 11 separate incidents of fatalities directly relating to misplacement of nasogastric tubes[1,10].

In response to this, safety alerts were published in February 2005 giving clear instructions on correct procedures for checking the position of feeding tubes[11][12]. However, since these alerts were made available, there have been 6 cases of death due to nasogastric tube misplacement reported directly to the NPSA up to November 2007, with a further 2 deaths identified via the Coroner or the media. These include 3 cases of malposition using inappropriate checking procedures and 3 cases of X-ray misinterpretation by clinical staff. Also reported to the NPSA were 6 documented incidents of aspiration-by-proxy causing serious morbidity but not death and 7 “near misses” that did not result in patient harm[13]. Recently, misplacement of an NG tube and lung feeding have been classified by the NHS as a ‘never event’, making the development of an evidence-based safety guideline ever more imperative.

1.2 Current guidelines on checking procedure for nasogastric tubes

There is a distinct lack of consensus opinion as to the optimum method of checking feeding tube position. The NPSA patient safety alerts recommended that certain procedures were not to be used to verify tube position. Unreliable methods identified include: observing bubbles at the end of the tube when placed underwater; interpreting the absence of respiratory distress as an indicator of correct positioning; testing the acidity or alkalinity of aspirated fluid using blue litmus paper; auscultation of air insufflated through the feeding tube (the ‘whoosh’ test); and using the appearance of feeding tube aspirate as an indicator of tube position. The NPSA guideline is based on pH assessment of tube aspirate, with a pH of 5.5 or below suggesting gastric position and a safe situation to start enteral tube
feeding. The use of routine X-rays to verify tube position is not recommended\(^2\). The use of a pH cut-off of 5.5 is supported elsewhere in the literature, although questions remain about its reliability, particularly in the intensive care unit, where routine use of continuous feed regimens and stress ulcer prophylaxis can alter gastric pH\(^{14}\)\(^{15}\).

A practice alert issued by the American Association of Critical Care Nurses (AACN) in 2005 again discredits the auscultatory method as unreliable, but also states that while observation and pH measurement of tube aspirate can be helpful, no one single bedside method has been shown to be reliable for continuous assessment of tube position\(^{16}\). The AACN recommend that an X-ray is obtained to demonstrate tube position every time a new tube is inserted prior to commencing tube feeds or administering medications. Radiographic confirmation of correct placement is advocated by some authors for all blindly inserted feeding tubes\(^{17}\) while others advise X-ray only if there is clinical doubt regarding proper position\(^{15}\)\(^{18}\) or difficulty in obtaining a tube aspirate\(^2\). There is some disagreement about the perceived merits of plain radiography as a gold standard, since X-rays can often be misinterpreted. Fluoroscopic contrast studies through the tube have been suggested as a more appropriate gold standard to ascertain tube position\(^{19}\).

Guidelines describing the use of the auscultation technique to indicate correct gastric placement still appear in the recent literature\(^{18}\)\(^{20}\). Aspirate appearance and pH measurement have been suggested as valuable methods for indicating correct placement after initial insertion\(^{14}\) and for monitoring tube position prior to each administration of enteral feed\(^{21}\).

More important than opinions expressed in published guidelines and journal articles is a measure of what is actually happening in current clinical practice. Changes in practice reflecting outcomes in published research may be slow to occur. Change is a difficult thing to accept, and certain nursing practices may be based upon tradition, rituals and outdated information. The confirmation of feeding tube placement may be one such area in which a theory-practice gap exists\(^{22}\).

In an effort to identify variations in the care of patients with nasogastric tubes, Schmieding et al\(^{23}\) conducted a mailed questionnaire survey of 350 registered staff nurses randomly selected from 11 acute care hospitals in Rhode Island, USA. They achieved an overall response rate of 43% (n=153). The methods selected by 55 respondents (16%) to check tube position after initial placement included auscultation in 39, aspiration in 34, X-ray in 14, pH in 1 and immersing the tube underwater in 3. Although many participants reported that they use more than one method, the most frequently used combination was auscultation and aspiration (n=22). The most popular single method employed by respondents was auscultation (n=12), followed by aspiration (n=7) and X-ray (n=5). Nurses in teaching hospitals were more likely to use X-ray to check initial placement than were nurses in community hospitals (29% vs. 9\%)\(^{23}\).
Roynette et al[24] recently reported a cross-sectional questionnaire survey of enteral feeding practices in 383 intensive care units from 20 European countries. A total of 373 respondents employed a variety of procedures to establish feeding tube position. The most popular method was auscultation of injected air in 84.7% (n=316) of intensive care units, with aspirate appearance used in 28.7% (n=107) and pH measurement in only 3.5% (n=13) of respondents. Chest radiograph was used in 32.7% (n=122), although a combination of more than one technique was applied in 43.2% (n=161) of participating units[24, 25].

In a smaller study published by Persenius et al[26], 44 out of 63 registered nurses in 3 intensive care units responded to a questionnaire about enteral nutrition, including methods to confirm tube placement. The technique of auscultating over the epigastrium while insufflating air through the tube was practised by 38 out of 44 respondents (86%), while chest radiograph was routinely ordered to check tube position by 32 nurses (73%)[26].

The safe insertion and verification of correct feeding tube position not only incorporates quantitative data from published studies but is also significantly influenced by expert judgment (see the section on Expert Consultation). The impact of expert judgment is not readily assessed by common research methods.

1.3 Summary
NG-tube misplacements are common and varied. Misplacements can occur in oesophagus and respiratory tract, among other places. Misplacements can lead to serious consequences including death. Methods for verification of tube sites vary between hospitals and countries. Commonly used ones include auscultation, appearance of aspirates, pH, chest x-rays. Despite possibilities of misinterpretations, X-rays remain the current gold standard for tube site verifications. NPSA guideline recommends the use of pH assessment of tube aspirates, with a pH of 5.5 or below suggesting gastric position and a safe situation to start enteral feeding.

2 Objectives
The primary aim of this project was to develop an evidence-based guideline for verifying nasogastric tube position in adult patients, with an emphasis on starting tube feedings safely. A secondary aim is to recommend an effective bedside checking procedure to decrease the number of X-rays requested and reduce patient exposure to ionising radiation.

A key issue of developing a safety guideline for NG tube feeding is to establish a process for ascertaining tube position that clinicians can apply easily and with confidence. This problem is characterised by two features: (1) uncertainty because no item of data or test is definitive (even X-rays, the gold-standard, can be misinterpreted), and (2) presenting not just one but many signs,
symptoms and other data. Decisions of whether or not feeding should be commenced can be affected by both features.
3 Methods overview

We employed a multi-modality approach to develop the guideline, encompassing a systematic literature review, construction of Bayesian belief networks (BBNs), decision conferencing, coordinating a steering group panel of experts for feedback and guidance and comparing the guidelines against current practice and historical adverse event data.

At the centre of this approach is a Bayesian belief network model that quantifies the uncertainties. The model relied on information retrieved from the literature review, as well as opinions of tube feeding experts during the NPSA steering group meetings. The process is iterative rather than linear, involving constant interactions between different components. For instance, after building an initial BBN model from evidence retrieved from the literature; we presented findings to the members of the steering group. Their feedback was incorporated into the model, complimented by further literature search and evidence review. The updated model with revised findings was presented in steering group meetings.

Figure 1 The iterative process of developing recommendations

In what follows, we describe each of the three components in turn, starting with the literature review.
4 Literature Review

4.1 Literature review methods

Online databases searched included PubMed, the Cochrane Library and Ovid SilverPlatter selecting British Nursing Index and Archive, EMBASE, All EBM Reviews, Ovid MEDLINE with In-Process and other non-indexed citations, and Journals at Ovid Full Text. The search strategy included a MeSH Terms search using “Enteral Nutrition” and “Intubation, gastrointestinal” and relevant subheadings, with the search restricted to major topic headings only. The following search term strategy was also used: “NG, nasogastric, gastric, enteral” AND “feeding, nutrition, tube, tubes” AND “correct position, checking procedures, correct placement, accurate location, location, positioning, placement”. Searches were limited to include only human studies with abstracts published in the English language, between the years 1980 and 2008. The Related articles function was used to broaden the search, and all abstracts, studies and citations scanned were reviewed. References of the articles obtained were also searched by hand.

Conference abstracts of the British Association for Parenteral and Enteral Nutrition (BAPEN), European Society of Parenteral and Enteral Nutrition (ESPEN), and the American Society of Parenteral and Enteral Nutrition (ASPEN) were hand searched for relevant studies.

Studies were assessed for quality using the STARD criteria [27] and selected on the basis of pre-defined criteria as detailed in Table 1.

Table 1 Selection criteria

<table>
<thead>
<tr>
<th>SELECTION CRITERIA</th>
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<tbody>
<tr>
<td>Clear use of a BEDSIDE test</td>
</tr>
<tr>
<td>Clear comparison to a reference standard</td>
</tr>
<tr>
<td>Nasogastric tubes ONLY</td>
</tr>
<tr>
<td>Prospective studies only</td>
</tr>
</tbody>
</table>

1 Despite misinterpretations, x-rays remain the most common ‘gold standard’ for verification of tube sites. We selected studies with clear demonstration of using a reference standard. For these studies, we assumed interpretations of x-rays were accurate. The subsequent Bayesian network model only used evidence retrieved from studies that met the inclusion criteria. Although BBNs have the capacity to model the impact of inaccurate x-rays, we felt this assessment would not be useful because the validity of the evidence in its entirely can be questioned in one way or another and tackling this would go far beyond the scope of this research. We however make it clear in the final recommendation that x-rays should best be interpreted by trained professionals.
4.2 Traditional bedside methods

4.2.1 Auscultation
The auscultation method has been discredited largely due to numerous case reports of tube misplacement in which this method falsely indicated correct gastric position, including reports in the recent literature[28],[29],[30],[31],[32],[33]. Metheny et al[34] conducted a study artificially recreating the auscultation method by making 115 tape recordings of air insufflated through feeding tubes known to be in the oesophagus, stomach or duodenum. Five selected clinicians were asked to predict the tube position after listening to the recordings that included 49 nasogastric tubes. The rate of stomach tubes correctly identified was 41.6%, with an average correct classification for each tape of 34.4%[34]. Unfortunately no respiratory tract recordings were available for comparison.

In a subsequent study comparing aspirate pH measurement and the auscultation method to an established gold standard, Neumann et al[35] found that out of 16 tubes confirmed to be outside the stomach on X-ray, 15 were incorrectly identified as being positioned in the stomach by the auscultation method. However the paper does not state where the confirmed radiographic tube positions were. In a comparative study Kearns and Donna [36] reported that the auscultation method incorrectly identified 6 out of 11 tubes that were misplaced above the diaphragm in 131 patients, a sensitivity of only 45%.

4.2.2 Visual characteristics of feeding tube aspirates
An observational study by Metheny et al[37] aimed to assess the ability of the tube aspirate appearance to distinguish between stomach and lung tube position. A convenience sample of 30 nurses were given selected photographs of aspirated fluid from the respiratory tract (n=6) and stomach (n=7) and asked to determine their site of origin. The participants correctly identified 48% of stomach aspirates, improving to 58% after being given a description of suggested visual characteristics of aspirates from the potential tube sites. Nurses accurately predicted 57% of respiratory aspirate photographs, yet this decreased to 46% after reviewing the list of aspirate criteria[37]. The principle limitations of the aspirate appearance method include the variation of possible aspirate features, considerable overlap between tube sites and the highly subjective nature of this assessment.

4.2.3 pH of feeding tube aspirate
Numerous studies have assessed the accuracy of measuring the aspirate pH in predicting feeding tube placement. Neumann et al[35] reported results from a prospective sample of 28 tube aspirations from 33 attempts, a success rate of 85%. Standard 8 French small-bore feeding tubes were used throughout the study, with pH measured by 1 – 11 pH paper and predictions of tube site compared to subsequent radiographic confirmation of tube position. All 33 patients were fasted for at least one hour prior to attempted aspiration. When compared to X-ray as the gold standard, 19 tubes with a pH equal to or
less than 4.0 had a reported sensitivity for placement of 100%, with a specificity of 88%. For 9 tubes with a pH>4.0, sensitivity for incorrect placement is quoted at 86.4% with a specificity of 50% and negative predictive value of only 37%[35]. Several problems arise when trying to interpret these results, particularly with the lack of raw data presented. It is not clear how the reported figures were derived. A sensitivity of 100% means all confirmed gastric tubes were correctly identified by a pH equal to or less than 4.0, but a specificity of 88% means that 12% of tubes were falsely identified as being in the stomach: the paper does not state in what position these tubes were on X-ray, and 12% of 19 tubes equals 2.28 tubes which does not make practical sense. Tube site predictions were made independently of pH values leading to confusing and inconsistent presentation of results. The study did not include a predefined pH cut-off value to indicate stomach position or otherwise, hence in 5 tubes with a pH>4.0 study observers wrongly predicted gastric placement, being more willing to rely on auscultation findings than on pH analysis.

The collective studies performed by Metheny et al.[38-42] represent the most impressive body of research looking at aspirate pH measurement and prediction of feeding tube position. The research group collected prospective data with a standard well-designed study protocol from 6 acute care hospitals, and their cumulative data have been reported in 5 separate publications over a 12-year period[38-42]. Standard inclusion criteria for sample collection were applied throughout the study, including no antacid medication within the previous 4 hours, no other medications within 1 hour, and patients fasting for at least one hour that was increased to at least 4 hours after the first 5 years of the study. For patients on continuous feeds (~75% of patients with NG tubes), formula delivery was interrupted for the minimum required time prior to tube aspirate sampling. X-ray confirmation of tube position was performed within 5 minutes of pH measurements to avoid potential tube migration. A standard procedure for aspirating feeding tubes was followed[43] (Figure 2) and this achieved a 93.8% success rate for NG tubes with multiple ports[39]. pH measurement using both Beckman pH10 portable pH meters and 1-11 Vivid pH paper was carried out on tube aspirates from the oesophagus, stomach, small bowel and respiratory tract, together with pH analysis of tracheobronchial secretions and pleural fluid. The correlation between pH paper and pH meter readings was 0.97 for over 1000 samples tested by both methods [41]. Relatively small differences were seen in the mean values of pH meter and pH paper measurements – less than the margin of error for pH paper accuracy. The most recent published data for Metheny’s group is displayed in Table 2[42].

The limitations of these studies include the assumption that samples of pleural fluid and tracheobronchial secretions will reflect aspirates of tubes placed into the respiratory tree. Due to a low number of misplaced respiratory tube aspirates being available (n=6) this approach was considered the best surrogate analysis. Similarly, tube aspirates from the oesophagus are underrepresented in this data set (n=9) and insufficient to provide meaningful results. For the cumulative results to be translated into the everyday practice, the same study conditions need to apply
to the clinical scenario, including the use of multiple-port tubes with ports limited to a narrow segment to facilitate aspiration of fluid from only one anatomical site. The high aspiration success rate of 94% for Metheny’s group contrasts with a reported success rate of 65% for single-port feeding tubes. Despite the fact that data were collected from 6 separate centres, the research findings are subject to the potential bias of only one principal investigator.

Potential confounding factors limiting the validity of the pH measurement technique include alteration of the gastric pH with increasing patient age, co-morbidities such as uncontrolled type II diabetes, duodenal reflux into the stomach and delayed gastric emptying.

Table 2 pH analysis of 1,500 samples [42]

<table>
<thead>
<tr>
<th>Confirmed tube site</th>
<th>Mean pH</th>
<th>Overall Mean pH</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Acid-inhibitors</td>
<td>No Acid-inhibitors</td>
</tr>
<tr>
<td>GASTRIC</td>
<td>4.34 ± 0.14</td>
<td>3.33 ± 0.10</td>
</tr>
<tr>
<td>n=680</td>
<td>n=445</td>
<td>n=235</td>
</tr>
<tr>
<td>INTESTINAL</td>
<td></td>
<td>7.14 ± 0.03</td>
</tr>
<tr>
<td>n=578</td>
<td></td>
<td></td>
</tr>
<tr>
<td>RESPIRATORY</td>
<td></td>
<td>7.64 ± 0.03</td>
</tr>
<tr>
<td>n= 280</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Figure 2 Obtaining an aspirate from fine-bore feeding tubes[43]

1. Use 50/60 ml syringe – gently insufflate 20ml air:
   clears lumen & moves away from bowel wall
2. Aspirate using the same syringe – air and fluid easier with large syringe
3. If no fluid, try a) Repeat Step 1
   b) Aspirate using 10 ml syringe
4. If still no fluid, try a) Wait 30 mins then repeat steps 1-3
   b) Move patient to supine position/ left lateral / right lateral
4.2.3.1 Accuracy of pH paper

There are mixed reports of the accuracy of pH indicator papers in common clinical usage. Some authors have questioned the validity of using pH paper for accurate measurement of gastric pH[44, 45], particularly in the critical pH range of 2 – 6[46]. Studies vary in their design, with comparisons of different types of pH paper to both hand-held pH meters and intra-gastric pH probes, and various measurements of clear buffered solutions and tube aspirates.

When using pH paper it is reportedly more difficult to differentiate between higher values (especially 6 and 7) and lower values. To maximise the accuracy of pH measurement, pH paper needs to cover the range from 0 – 14. The accuracy of 0 – 14 universal indicator pH paper across the range pH 3 – 6 is supported by a survey testing solutions of known pH with different commercially available pH strips[47]. Additional reports support the accuracy of Merck pH indicator paper for clear buffered solutions of a known pH and samples of gastric aspirate within the range pH 2 – 6[48, 49].

There are conflicting reports comparing pH paper to a calibrated hand-held pH meter. Layon et al[50] measured solutions of known pH in triplicate with both pH paper and a pH glass-electrode and found close correlation after linear regression analysis with a coefficient r² value of 0.98. Dobkin et al[45] however report a sensitivity for pH paper to measure pH<4 of only 67% compared to pH meter when actual gastric aspirate samples were compared[51]. A comparison of 85 gastric aspirate samples found significant disagreement between pH meter and pH paper values[44]. The largest reported study includes 985 gastric aspirate samples from 51 critically ill patients[46]. The overall concordance correlation coefficient was 0.896, with a 95% confidence interval between -0.412 and 1.45. There was an improved correlation between pH paper and pH meter readings with a pH<4.0: there were no patients with an aspirate pH paper reading <4.0 and 2 consecutive pH meter readings ≥4.0. The accuracy of the pH paper decreased with an increase in pH. Of all the samples with a pH paper reading of 5.0 there were 3 pH meter readings >6.0 and 1 pH meter value >7.0. This negative bias of pH paper readings at a cut-off higher than 4.0 has crucial implications for potential feeding errors. Given that a pH value >7.0 could indicate respiratory tube placement, relying on a pH paper reading between 5.0 and 5.5 may not be accurate enough to avoid inadvertent feeding into the lungs.

Studies comparing pH paper measurements to intra-gastric graphite antimony pH probes provide further evidence of pH paper accuracy in the clinical setting [52-56]. Levine et al[56] and Rastegarpanah et al[52] both report excellent correlation between gastric aspirate pH measurements determined with pH-sensitive litmus paper and those obtained using intra-gastric pH probes (r² = 0.94, p<0.01; 95% confidence interval of -0.155 to 0.176). There was no significant difference demonstrated between the two monitoring methods (chi-square= 0.5, p>0.48), and the kappa statistic (0.95, p<0.001) demonstrated excellent concordance.
To assess the clinical relevance of measurement methods for indicating feeding tube position, an outcome study is needed comparing patients whose gastric pH is measured with both pH paper and meter, and patients randomised to have feeding decisions based on “paper only” or “meter only” pH values. No such study was identified in the literature review.

4.2.3.2 Influence of acid-inhibiting medication

Acid-inhibiting medication will reduce the sensitivity of pH measurement for gastric placement[57], but will not alter the specificity or render the method unsafe with regard to feeding decisions. In addition, pH data are less reliable for checking tube position in patients having a continuous feed regimen. During a study to determine the effect of continuous tube feedings on pH readings[58], aspirate samples were taken immediately after the enteral feed was turned off, the lumen of the tube having been cleared of formula with injection of 30ml of air. The mean pH was 5.7 ± 0.1 with 21 out of 55 samples (38%) having a pH of at least 5.0[58]. In a subsequent study of pH measurements during continuous feeds, 578 out of 1,881 aspirates from 85 nasogastric tubes had a pH>6.0 (63%) with an overall mean pH for all gastric aspirates of 6.4.

Patients with an increased risk of respiratory tube placement include those with decreased level of consciousness, diminished cough and gag reflex and the presence of an endotracheal tube or recent tracheal extubation. For these patients, it is recommended that X-ray confirmation of initial tube placement always be obtained prior to commencing tube feeds.

In order to obtain comprehensive details of the pH studies, the raw dataset was obtained with the kind agreement of Professor Norma Metheny. Analysis of the collated data demonstrates an overall mean pH of 3.91 in 754 NG tube aspirates, with 74.3% of aspirates equal to or less than pH 5.5. For patients without acid inhibitors, 83.5% of aspirates were equal to or less than pH 5.5. A total of 279 pleural fluid or tracheobronchial samples had a mean pH of 7.81, with the lowest pH reading = 5.99.

4.2.4 Other methods

Observing for respiratory signs or symptoms such as coughing, dyspnoea, or cyanosis does not provide evidence of tube misplacement into the airway. This is especially true for patients with an impaired conscious level or diminished cough or gag reflex. The use of fine-bore tubes for feed delivery is increasingly accepted as standard, and these tubes can inadvertently be placed into tracheobronchial tract without causing any subjective or objective change in the clinical state of the patient.

Another unreliable method assumes that the appearance of air bubbles while immersing the tube underwater once the tube is advanced 20-25cm indicates respiratory placement. False-negative results will arise if the tube becomes blocked with tracheobronchial secretions thereby preventing air bubbles from appearing despite tube position in the airway. Also, certain fine-bore tubes may not permit air
exchange when a guide-wire is in place. False-positive results will result from accumulated air in the gastric fundus escaping via the feeding tube and causing bubbles to appear [28].

4.3 More recent methods

4.3.1 Capnometry and colorimetry

There is recent renewed interest in the detection of carbon dioxide (CO2) through enteral feeding tubes as an indicator of misplacement in the respiratory tree. This technique has been reported in 3 pilot studies[59-61] and 3 prospective clinical studies[62-64] using either capnography or colorimetry for CO2 detection. Colorimetric end-tidal CO2 devices use a sulfonephthalein-impregnated pH-sensitive filter paper that changes from purple to yellow in the presence of CO2. These demonstrate encouraging results in detecting respiratory tree placement when it occurs. Pooling the data from relevant studies includes tube insertions in 275 participants, with radiographically confirmed tracheal feeding tube placement in a total of 24 patients (excluding those deliberately inserted via endotracheal tubes). This gives an overall tube misplacement rate of 8.7%[46-51]. The remaining 251 tubes were either in the oesophagus or stomach on X-ray appearance. There was 1 false positive (colour change in oesophagus) and 1 false negative (no colour change in trachea) for colorimetric detection of CO2 predicting correct tube site[64]. Overall sensitivity is 95.8% and overall specificity 99.6%. However the technique does have significant limitations as it gives no information about tube placement within the gastrointestinal tract. Studies to date give conflicting results of CO2 detection with tubes coiled in the mouth or pharynx[59, 61, 63]. This method is not sufficient to determine when a tube is safe for administration of enteral nutrition because feed delivered into the oesophagus increases the risk of pulmonary aspiration.

4.3.2 Magnetic devices

Devices detecting ferrous magnets or electromagnetic fields generated within the tips of feeding tubes can display information about their anatomical location. Prototypes have recently been developed and evaluated in pilot studies on healthy volunteers[65-67] and also in a critical care setting[68]. These studies are of variable quality, with inconsistent comparison standards and somewhat selective design. Some of the devices are cumbersome and not appropriate for bedside use. Ackerman and Mick[69] report their experience with the Cortrak enteral access system, designed to guide feeding tube insertion into the small bowel. This system demonstrated 100% agreement with X-ray for tubes placed in the stomach (n=4) with a sensitivity for small bowel placement of 79% (n=19)[69]. The largest study reported to date was published by Kearns and Donna[36, 70]. The traditional feeding tube verification methods of auscultation, aspiration and pH measurement were compared to a bedside electromagnetic technique in a prospective, randomised, multi-centre trial. A total of 134 patients
were included, using X-ray as a gold standard for comparison. Respiratory tract misplacement occurred in 11 out of 134 feeding tubes (8%; 95% CI 3-13%). Electromagnetic detection correctly identified 8 of these 11 tubes as being positioned above the diaphragm. When “unable to determine” was interpreted as being out of position, all 11 tubes were correctly identified (sensitivity = 100%). The overall accuracy of the magnetic technique is reported as 76% compared to X-ray[36]. However, there is incomplete and inconsistent presentation of the data for this study, making worthwhile interpretation of the results difficult.

4.3.3 Pilot studies
Attempts have been made to distinguish respiratory tube placement from gastrointestinal tract placement based on the premise that gastric pressures should be positive, with a negative pressure on inhalation in the pulmonary system. Swiech et al[71] reported a study of 46 adult patients with a spring-gauge pressure manometer attached to inserted feeding tubes, to measure luminal pressures generated on inhalation and exhalation. All 44 gastric tubes correctly positioned on X-ray gave positive manometer readings on inhalation (mean 4.59cm, SD 3.77). The 2 tubes inadvertently placed in lung gave negative manometer readings (<0) on inhalation[71]. Major drawbacks of this study are the very limited sample size and inadequate blinding for data collection, as X-ray verification was undertaken prior to manometer readings. This method could be unreliable if the tube gets lodged in small airway, making pressure changes undetectable. Furthermore, no attempt is made to assess oesophageal or gastric tube position within the gastrointestinal system.

A different approach recently described by Rulli et al[72] involves inserting a flexible cable of 1.3mm diameter through the nasogastric feeding tube. The cable is connected to a cold light source. In 16 patients undergoing laparoscopic or open surgery, the stomach was fully transilluminated by the fibreoptic cable, with the position of the NG tube confirmed at the time of operation in all patients[72]. An obvious drawback to this study is that all participants were under general anaesthesia in an operating theatre environment; this method may not be applicable for the ITU or ward patient.

4.4 Monitoring feeding tube placement
The correct position of feeding tubes needs to be confirmed prior to each administration of enteral feed. Tube migration into the lower oesophagus increases the risk of pulmonary aspiration and possible subsequent pneumonia. It is recommended that tube position be checked at least 3-4 times daily. Once initial gastric tube placement has been confirmed (either by aspirate pH testing or X-ray) then subsequent methods can be tailored toward checking for tube migration.

A recent study was designed to determine the accuracy of four simple bedside assessments to predict tube position in either the stomach or small bowel of 201 critically ill patients receiving continuous feedings over 2-3 days[73]. Variables recorded during the study included the external length of
feeding tube and the volume, appearance and pH of the aspirate observed during residual volume measurements. Radiographic reports of tube location provided a standard for comparison. A mean increase of 14.32 ± 1.92cm of the external tube length was predictive of upward displacement in 24 out of 25 tubes that migrated. Use of dichotomised pH was less accurate, as 63% of gastric aspirates had a pH>6.0. Approximately 81% of tube site predictions were correctly classified when using a combination of external tube length, aspirate volume, and aspirate appearance for indicating tube position[73]. Observing for an increase in the measured external tube length with a cut-off of 12cm should alert clinicians to the possibility of upward tube displacement and may provide a valuable assessment of tube position only after confirmation of initial tube insertion into the stomach.

4.5 Summary
Despite widespread use of nasogastric tubes in clinical practice, there is little research on the accuracy of bedside checking procedures for verification of feeding tube position. This review shows that traditional methods such as observing for clinical signs of respiratory distress, auscultation while insufflating air and observing the colour of fluid aspirated from the tube are no longer recommended. There is evidence to support the use of pH paper with a cut off <5.5 to exclude lung placement, although with several confounding factors in pH measurement of tube aspirate. Magnetic detection is promising but reported studies are limited by inconsistent standards and small sample size, and further well-designed prospective studies are needed to evaluate the technology. Carbon dioxide detection techniques are useful for excluding respiratory tract placement but cannot provide valuable information about tubes coiled in the pharynx or oesophagus.
Developing safety recommendations

5.1 Defining the problem: who does the guideline apply to?

5.1.1 Defining Patients at High Risk for Aspiration

Pathogenesis of aspiration pneumonia is multi-factorial. It depends on the frequency of aspiration, the pH and bacterial content of the aspirate, and associated host defences in various clinical situations. Microaspiration may be a natural phenomenon, occurring in an estimated 45% of normal individuals during sleep[74], but certain patient groups have an increased risk of developing pneumonia. Impaired swallowing due to decreased level of consciousness, sedative drugs, or the presence of an endotracheal or nasogastric tube will predispose to aspiration. A decreased cough reflex, altered oesophageal motility and altered upper or lower oesophageal sphincter tone impairs patient defence against gastro-oesophageal reflux. The presence of a nasogastric tube can interfere with the function of upper and lower oesophageal sphincters. Delayed gastric emptying for any reason increases the risk of reflux and the potential for aspiration. Gastroparesis is associated with certain drugs (especially opioid analgesia), electrolyte imbalance and sepsis[75]. Patients nursed in a supine position are predisposed to gastroesophageal reflux.

Gastroesophageal reflux is recognized as the initial event leading to aspiration of highly acidic gastric contents that may result in acute lung injury. The resulting impaired bacterial clearance predisposes to secondary infection. Although controversial, gastric reflux and abnormal colonisation of the oropharynx with subsequent aspiration to the lower airways could both play a part in the pathogenesis of nosocomial pneumonia[76, 77]. Abnormal colonisation of the stomach is promoted by the use of systemic or local acid-inhibitor therapy and enteral formulas used with continuous feeding regimens that reduce the gastric pH and facilitate opportunistic bacterial growth.

Reported frequency of aspiration depends upon the following variables: the definition of aspiration; the method of diagnosis including tagged feeds, pepsin analysis, glucose strips or blue dye; feeding tube position in the gastrointestinal tract; type of feeding tube; bolus vs continuous feeds; biased patient selection. The reported prevalence of pulmonary aspiration ranges from under 2% to 95%, with an incidence of 0 – 21% in mechanically ventilated patients with a nasogastric tube[78].

McClave et al[79] recently published a prospective study in 40 critically ill patients receiving enteral nutrition via nasogastric or percutaneous endoscopic gastrostomy. Microscopic yellow beads were added to the tube feeding and detected by fluorometry in tracheobronchial secretions. At least 1 aspiration event was experienced by 75% patients (30 out of 40). The mean percentage of samples containing yellow beads was 22.1% (range 0 – 94%)[79].
Figure 3: Risk factors for aspiration [80, 81]

<table>
<thead>
<tr>
<th>Major Risk Factors for Aspiration</th>
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<tr>
<td>• Documented previous episode of aspiration</td>
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<tr>
<td>• Decreased level of consciousness – GCS &lt;9</td>
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<tr>
<td>• Persistently high gastric residual volumes &gt;400ml</td>
</tr>
<tr>
<td>• Vomiting</td>
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<tr>
<td>• Prolonged supine positioning</td>
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<tr>
<td>• Neuromuscular disease or structural abnormalities of the aerodigestive tract</td>
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</table>

<table>
<thead>
<tr>
<th>Additional risk factors</th>
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<tbody>
<tr>
<td>• Presence of endotracheal tube</td>
</tr>
<tr>
<td>• Presence of a nasoenteric tube</td>
</tr>
<tr>
<td>• Documented GERD</td>
</tr>
<tr>
<td>• Intermittent or bolus feeding</td>
</tr>
<tr>
<td>• Abdominal/thoracic surgery or trauma – slowed GI motility part of stress response</td>
</tr>
<tr>
<td>• Delayed gastric emptying – diabetes, hyperglycaemia, sepsis, drugs, electrolyte imbalance</td>
</tr>
<tr>
<td>• Poor oral care – decayed teeth or plaque = potential reservoir for microbes</td>
</tr>
<tr>
<td>• Age – reduced swallowing and airway clearing ability</td>
</tr>
<tr>
<td>• Inadequate registered nurse staffing level</td>
</tr>
<tr>
<td>• Large-bore feeding tube</td>
</tr>
<tr>
<td>• Malpositioned feeding tube</td>
</tr>
<tr>
<td>• Transport</td>
</tr>
</tbody>
</table>

Metheny et al[80] undertook pepsin analysis of tracheobronchial secretions in 360 mechanically ventilated adult patients over 4 days, and found that 31.3% of 5857 specimens tested positive for pepsin. There was at least 1 aspiration event in 88.9% of patients (n=320), the vast majority of which were clinically silent. Patients with more than 25% of pepsin-positive secretions, dubbed “frequent aspirators”, had a greater risk of pneumonia than those with fewer positive secretions. The mean percentage of pepsin positive secretions was 42.4 ± 25.1% for patients with pneumonia and 21.1 ± 18.2% for those without. Independent risk factors for aspiration included a mean backrest elevation of less than 40° (p = 0.20), a Glasgow Coma Score of less than 9 (p = 0.021), one or more episodes of vomiting (p = 0.01), and a diagnosis of gastroesophageal reflux disease (p = 0.033). Although the patients were not randomised to receive either gastric or post-pyloric enteral feeds, gastric feedings were observed more often in the high-aspiration group of patients (p = 0.009). Logistic regression analysis demonstrated a strong relationship between aspiration frequency and pneumonia, with patient...
sedation and the use of paralytic drugs also associated with an increased risk of pneumonia[80]. The commonly accepted risk factors for aspiration are summarised in Figure 3.

5.2 What kind of test do we need?

A key evaluation of any diagnostic tool is the sensitivity and specificity of the test. The sensitivity of a screening test is the proportion of the screened population that has the disease with a positive test, and high sensitivity means a low number of false negatives. The specificity of a test is the proportion of the screened population that is disease free that test negative; a high specificity means a low number of false positives. For serious or untreatable conditions, a high specificity is preferred to avoid making a false positive diagnosis. Similarly, if we want a test to tell us whether or not a nasogastric tube is in the stomach, it is less important to identify every tube correctly in the stomach (true positives) than it is to identify every tube not in the stomach (true negatives) to avoid calamitous feeding errors. Hence we need a high specificity to avoid false positives. Conversely, for tube insertion in the lung, if we have a test to diagnose lung position it is crucial to correctly identify every tube placed in the lung to avoid using the tube. So we need a high sensitivity for lung placement. This is compounded by the relatively low prevalence of tube misplacement in the respiratory tree needing a high sensitivity to identify when it does occur.

5.3 Oesophageal pH

Enteral feed delivery through a feeding tube placed in the lower oesophagus is a recognised risk for aspiration. From the available evidence it is apparent that nasogastric tube misplacement in the oesophagus is more common than respiratory tract misplacement, although the consequences may not be so immediately serious. For a safety guideline on checking procedures prior to tube feeding it is vital to incorporate the potential harm of tube placement in the oesophagus. There is a lack of data regarding any method to check tube position in the oesophagus. The pH studies from Metheny’s group include a very limited number of oesophageal tube aspirate samples. However, there is a wealth of literature on 24-hour pH monitoring available in studies looking at gastroesophageal reflux disease. While this patient cohort represents a select group, there are also studies of oesophageal pH monitoring in healthy individuals with valuable data[82-87]. Studies on normal volunteers all use a pH cut-off of 4.0, based upon guidelines for the definition of gastroesophageal reflux[88]. The collated data demonstrate that the median percentage time with oesophageal pH measured less than 4.0 is between 0.5 – 3.1% of recorded 24-hour periods in healthy individuals. This suggests that using a pH cut-off of less than 4.0 as an indicator for gastric placement will significantly reduce the incidence of tube misplacement into the oesophagus.
5.4 **Gastric Residual Volumes**

Gastric residual volumes (GRV) are frequently used to monitor the safety and efficacy of tube feeds. The definition of a high gastric aspirate as an appropriate marker for the risk of aspiration is extremely variable in clinical practice. There is no consensus opinion regarding the acceptable volume of gastric residual for tube feed monitoring[79]. There are no data to suggest that high gastric aspirates predict aspiration or that aspiration does not occur with low aspirates[89]. Nevertheless, published guidelines from the British Society of Gastroenterology[90] and the American Society for Parenteral and Enteral Nutrition[91] recommend that for the critically ill, feeding should be withheld if 2 consecutive GRV of more than 200 ml are measured, and the individual feeding policy reviewed. Residuals should be checked every 4-5 hours when starting feeds, until a plateau of less than 50ml is achieved. More recent reports suggest that increasing the GRV threshold from 200 ml to 400 ml does not incur an increased risk of aspiration[79]. The measured GRV has a poor reported sensitivity for detecting aspiration over a wide range of GRV values. Although a particular GRV threshold may not be a valid indicator of aspiration risk, patients with persistently high GRV may still benefit from jejunal tube feeding.

5.5 **Areas of controversy: Small Bowel vs Gastric feeding**

The benefits of enteral nutrition over parenteral nutrition for patients with a functioning gastrointestinal tract are well-established. Enteral nutrition maintains mucosal integrity and mucosal immunity, reducing infectious complications in critically ill patients. Patients with increased risk of aspiration, significant gastroesophageal reflux, gastroparesis, gastric outlet obstruction, previous gastric surgery or planned early enteral feeding after major abdominal surgery may be best suited to post-pyloric feeding. Whether gastric or post-pyloric positioning is the best site for nutritional support is the subject of ongoing debate. Studies comparing the effects of tube position on pulmonary aspiration are difficult to interpret, limited by small sample size, equivocal definitions of aspiration and uncertain methods for determining tube location.

A meta-analysis published by Marik and Zaloga[92] found no influence of gastric versus small bowel feeding on overall mortality, ITU stay, caloric intake or incidence of pneumonia for critically ill patients. Early gastric feeding was recommended for most patients with pro-motility agents for patients with high gastric residuals. Post-pyloric feeding is recommended in patients at a high risk of aspiration and those who are intolerant of gastric feeding. Heyland et al[93] prefer the small bowel route based on a perceived reduction in aspiration pneumonia. Various clinical guidelines state that there is no significant difference in the efficacy of jejunal versus gastric feeding in critically ill patients[94, 95]. The gastric route is usually technically simpler and in most circumstances achieves equivalent nutrient delivery with similar risks. Ideally, safe feeding into the stomach requires intact gag and cough reflexes and adequate gastric emptying. Stomach feeding enables a more
physiological regimen and permits the use of hypertonic feeds at higher feeding rates. Small bowel feeding by contrast requires a continuous infusion due to the loss of gastric reservoir. Post-pyloric feeds may have a detrimental effect, as the release of cholecystokinin from the small bowel in response to enteral feed can inhibit gastric emptying and increase gastric secretions[90]. The resulting increase in gastric pH may promote bacterial overgrowth.

Advancing a feeding tube tip beyond the pylorus is not easy, with a variety of techniques reporting success rates between 15 – 92%, and jejunal intubation is even more difficult, typically being achieved in ≈20% of cases[96].

Ho et al[97] performed a meta-analysis including a total of 11 randomised studies and 637 ITU patients. The reported rate of pneumonia development was less with jejunal feeding in three studies, but no significant difference was found between the two feeding methods with respect to mortality or length of stay. Overall the analysis failed to demonstrate any clinical benefit to feeding beyond the pylorus.

5.6 Feeding and medication history

Sample collection needs to be carried out with the same standard protocol as applied during data collection in the pH studies. Although the latter part of the data were collected after fasting for at least four hours, this length of time has implications for delaying enteral nutrition delivery to the detriment of clinical goals. On analysis of the pooled data, there was as expected a significantly higher average pH meter reading (mean = 4.89) in the group of 77 patients fasting less than an hour when compared to 113 patients fasting for one hour or longer (mean= 3.31, p<0.0001 2-tailed t-test). The pH distributions are displayed in Figure 3. However there was no significant difference between 18 patients fasting for exactly an hour (mean= 3.03) and the group of 95 fasting longer (mean= 3.36, p=0.584 2-tailed t-test). Although these subgroups are limited by their sample size, these results do not support any benefit of fasting for longer than an hour prior to aspirating the feeding tube.

5.7 Predicting the tube site using BBN

The information from the literature review was used to construct a BBN model that can be used to predict the diagnostic capabilities of any combination of the tests. We shared the findings of the model with a group of tube-feeding experts, who assessed the structure and predictions of the model as well as consequences of feeding errors. The first round of literature review identified six tests that can potentially serve as alternatives to x-rays, which are pH, bilirubin, auscultation, appearance, capnography/colorimetry and magnetic guidance. After expert consultation, the decision was made to exclude bilirubin as a bed-side available test while to include oesophagus as a potential tube site, and in so doing, the total number of possible tube sites increased to four, i.e. stomach, oesophagus, lung and intestine. This triggered a second round of literature review, in which we searched for evidence
of any test among the five tests () that can be diagnostic of oesophageal intubation. As a result of this search, we revise the model, and in particular the level of pH, to include a new cut-off of pH ≤4.

Even with the help of BBN modelling, the process of selecting the ‘best’ test is still complex because of a large number of possible tests and the need to assess the consequences of feeding errors along with the uncertainties (as achieved by BBN modelling). Firstly, given the five candidate tests, the best test can be one single test or a combination of several tests. There is no limit as to how many tests the composite test should include except for the maximum possible number of five. This gives rise to as many as 31 possible tests\(^2\), even without considering the four different cut-offs we might use for the pH (e.g. 4, 5, 5.5, 6), which can quadruple the size of the tests. Secondly, with the exception of correctly interpreted x-rays, all tests provide only partial (imperfect) information as to where a blindly inserted tube might be. Choosing one test over another therefore entails a trade off between not feeding certain fraction of patients with the tube correctly placed in the stomach and feeding into the wrong sites for certain proportion of patients. In the latter case, we have to differentiate between three different types of feeding error (feeding into the lung, oesophagus and intestine) that have divergent consequences.

To handle these complexities in the construction, selection and assessments of the tests, we employ methods of decision analysis [98]. The basic idea is to make decisions such that the expected value of a decision is maximized, which is the sum of the outcome values weighted by the probabilities of these outcomes. Following this logic, Test A is preferred to Test B if the decisions made under the findings of Test A yield a higher expected value than do the decisions made under the findings of Test B. We make final recommendations based on this logic. The technical details of this approach are contained in the three appendices, Appendix A, B and C. Appendix A illustrates the logic underlying the BBN model which predicts the diagnostic validity of combinations of multiple tests; Appendix B shows how to choose between feeding and no feeding, given a finding; Appendix C illustrates how to assess tests based on assumptions of prior distributions of tube locations upon initial insertion and outcome values of feeding versus no feeding. Finally, we performed sensitivity analyses to examine the range of validity of the final recommendations.

5.8 Summary

Patients suffering from high risk of aspirations need a test that can rule out chances of tube misplacement. Tests that can minimise tube misplacement are highly sensitive to the tube sites other than the stomach. Oesophagus pH is most likely beyond 4. Gastric residual volumes have no definite relationship with safe feeding. Complexity in test selection, compounded by multi-layered

\(^2\) There are a total number of 5 single tests, 10 composite tests using either two or three tests, 5 composite tests using four tests and 1 composite test using all five tests.
uncertainties necessitates the use of decision analysis methods, notably, Bayesian belief networks, for the development of safety recommendations.
6 Bayesian Belief Networks

Bayesian belief networks [99-101], also known as Bayesian networks, belief networks and probabilistic causal networks, are tools of decision analysis used for handling uncertainties. Uncertainties are expressed in the form of probabilities. A BBN contains nodes, connected by arcs; nodes indicate uncertain quantities or events; arcs pointing out from a child node while into a parent node indicate the dependence of the child on the parent, with missing arcs indicating conditional independence. BBNs accomplish a graphical and intuitive representation of uncertainties, rendering the reasoning process inherent in the decision making available for communication and analysis.

BBNs function by the addition and multiplication laws of probability, including Bayes’ theorem [102] in doing so, which prescribes the revision of opinions in light of new information (Appendix A). This ensures the predictions of BBNs are mathematically sound. BBNs have the capacity for handling complex problems with many layers of uncertainty and can make predictions based on cumulative evidence. Most notable of all is their capacity for incorporating expert opinions along with hard data, in the form of quantitative information such as prior and conditional probabilities, as well as qualitative information such as the independent relationships between uncertain events. Expert opinions are particularly valuable when the ‘evidence’ retrieved from the literature is incomplete or simply inapplicable to a particular problem setting. Although computations involving Bayes’ theorem can be quite complex, computer software has been developed that alleviates the burden to a user.3

6.1 Building the network: assumptions, data and structure

To specify any Bayesian network, we need to provide information regarding its structure and its parameters.

6.1.1 Structure

The structure of a model refers to the definition of the uncertain events, their levels, or a set of mutually exclusive and collective exhaustive states, and the way in which the uncertain events depend on each other, i.e. whether an arc is present and the direction of an arc. All modelled uncertain events and their levels can be seen in the final BBN we used to make predictions (Figure 4).

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3 We used Netica® (www.norsys.com) to construct all the networks for this investigation.
6.1.2 Definition of uncertain events

We use one node, i.e. ‘tube_site’ to represent tube sites; it has four different levels, which in this case are simply the four hypotheses we have, namely stomach, intestine, lung and oesophagus.

We model five tests that may potentially serve as alternatives to X-ray. These are: pH, capnography/colorimetry, magnetic guidance, auscultation, and appearance. The levels of each test are essentially the findings that can provide diagnostic information of the hypothesized tube sites. For instance, for magnetic guidance, the findings is either ‘above diaphragm’ or ‘below’, which indicate a high probability of a lung intubation or otherwise.

The case of pH test is worth noting. First, pH depends not only on tube sites but also on patients’ status of receiving feeding and medication, which appear in the model as ‘feeding’ and ‘acid_inhibitors’, each with binary states (‘on’ or ‘off’ and ‘yes’ or ‘no’). Second, pH can be measured by pH meter or pH paper. Metheny’s database (see literature review) provides evidence for a less than perfect correlation between these two measurements. This calls into question the accuracy of pH testing. We include in the model both ‘pH_meter’ and ‘pH_paper (Baxter)’ with identical levels, i.e. cut-offs, i.e. 4, 5, 5.5 and 6. It is important to note that at the stage of test assessments, we use information of pH meter rather than that of pH paper. This is done for two reasons. Firstly, the same procedure of test assessments is applicable to both. Secondly, accuracy of pH varies with the particular make of pH paper; and this issue is not unique to pH. Even X-rays, the current gold standard of checking tube placements, are known to suffer from misinterpretations as well. Modelling pH meter and pH paper (Baxter) allow us to gain insights in the impact of lack of accuracy. At the final stage of this investigation, we employ sensitivity analyses to examine how sensitive the final
recommendations are towards data; accuracy issues are one source of data variation and assumptions about probability distribution is another (see below).

6.1.3 Dependent relationships
The dependencies among the uncertain events determine whether an arc exists between the events and the direction of this arc. If A depends on B rather than the other way around, an arc points out from A while into B and the conditional probabilities that describe the strength of this dependence is accordingly defined.

For this investigation, we assume that all tests depend on tube sites. The tests are *conditionally independent*, meaning that given perfect information of the parent node, i.e. ‘tube_site’, the knowledge of one investigation does not impact the knowledge of another investigation. This allows us to model all the tests as separate child nodes of ‘tube_site’. In other words, there are no arcs that connect between the tests. Unique for pH meter, it depends on feeding and medication, in addition to tube sites; and pH paper is modelled as a child node of pH meter.

6.1.4 Parameters
The parameters of a BBN consist of two kinds of quantitative information, i.e. prior and conditional probabilities. Conditional probabilities describe the strength of the dependencies between the nodes; prior probabilities describe one’s beliefs about an uncertain event before any information becomes available. While prior distributions are applicable to root nodes only, i.e. nodes without a parent, conditional probabilities are specific to arcs.

6.1.5 Prior probabilities
In this investigation, the prior distribution of ‘tube sites’ is particular important as it contains information of one’s belief about the prevalence of feeding errors, that is, in the form of the probabilities that a tube might be inserted into oesophagus, lung or intestine. Literature review identifies a wide range of probabilities that feeding errors can occur (see Literature Review). By changing the prior probabilities, BBNs allow us the freedom of testing impact of different levels of feeding errors. For example, the current BBN model (Figure 4) assumes a feeding error of 50% - the tube is assumed to have a 50% chance of being inserted into the stomach, 20% chance of the lung or the oesophagus and 10% chance of the intestine.

6.1.6 Conditional probabilities
Conditional probabilities describe the extent to which uncertain events depend on their parent nodes. The conditional probabilities between a test and tube sites describe the diagnostic validity of the test; in the case of pH, the conditional probabilities describe the diagnostic validity of pH meter *conditional on* all the four different combinations of the states of receiving acid inhibitors and feeding.
Two things are worth noting. First, when more than one set of applicable conditional probabilities are reported, we combine them by summing up the probabilities weighted by the respective sample sizes. To give an example, suppose one study reports that among a total number of 100 patients with the tubes confirmed in the stomach, 60% of them have a pH less than 5.5 while another study finds that this probability to be 70% for 150 patients; the combined conditional probability of pH less than 5.5 given stomach is therefore 66% = (100*60% + 150*70%)/(100+150). Second, when the conditional probabilities are incomplete, we assume a ‘flat distribution’ across all findings as there is no reason to assume otherwise. These are the conditional probabilities in italics in Table 4. For instance, in the case of auscultation, data are missing when the tube is assumed to be in the lung. Flat distribution means the model assumes that the loudest sound is equally likely to be heard in epigastrium, LUQ (left upper quadrant) and RUQ (right upper quadrant), i.e. the three levels of the node ‘auscultation’.

In the case of pH, we have no data showing the distribution of oesophagus pH above 4 – all we know is the ratio of pH below 4 versus above 4 (about 5:95). We have assumed that pH has an equal chance of being in any of the following categories defined by the four cut-offs, i.e. between 4 and 5, between 5 and 5.5, between 5.5 and 6, and 6 and above.

In addition to these, unique for pH, instead of retrieving and combining conditional probabilities from the literature, we obtained a large data set from the author who has done the majority of the work in this field (Professor Metheny). The reason is that researchers reported different cut-offs and even the same researcher used different cut-offs in different papers. To combine data, we need to make additional assumptions about the distribution of pH at the cost of a decreased accuracy of predictions based on pH. By contrast, Metheny’s database is of a high-quality – they are clinically obtained and contain continuous pH meter readings and pH paper (Baxter) readings when the tube is in the lung, stomach and intestine from over 1700 patients along with detailed information of whether the patients were receiving acid inhibitors as well as the duration since last feeding prior to aspirations.

Table 3 presents the conditional probabilities. These can be either cumulative (what is the probability of pH ≤5.5) or categorical (what is the probability of pH between 5 and 5.5). We have chosen to present cumulative probabilities only in the case of pH. This is done because only one cut-off will be chosen in the end, and cumulative conditional probabilities provide the inputs we need for the assessment of the test.
| Test/Findings (levels) | Probability (test_finding|tube site) | | | |
|-----------------------|--------------------------------------|--------------------------------------|--------------------------------------|--------------------------------------|
|                       | lung                                 | stomach                              | oesophagus                           | intestine                            |
| pH                   |                                      |                                      |                                      |                                      |
| ≤4                   | 0.00                                 | 54.60%                               | 5.00%                                | 6.26%                                |
| ≤5                   | 0.00                                 | 67.80%                               | 30.00%                               | 10.13%                               |
| ≤5.5                 | 0.00                                 | 75.23%                               | 55.00%                               | 11.80%                               |
| <6                   | 0.36%                                | 84.51%                               | 80.00%                               | 14.38%                               |
| ≥6                   | 99.60%                               | 15.50%                               | 20.00%                               | 85.60%                               |
| Auscultation         |                                      |                                      |                                      |                                      |
| Epigastrium          |                                      |                                      |                                      |                                      |
|                      | 33.30%                               | 29.20%                               | 62.00%                               | 73.60%                               |
| LUQ*                 | 33.30%                               | 41.60%                               | 19.00%                               | 22.40%                               |
| RUQ*                 | 33.30%                               | 29.20%                               | 19.00%                               | 4.00%                                |
| Appearance           |                                      |                                      |                                      |                                      |
| lung                 | 46.10%                               | 21.20%                               | 33.30%                               | 20.00%                               |
| stomach              | 26.90%                               | 57.60%                               | 33.30%                               | 20.00%                               |
| intestine             | 26.90%                               | 21.20%                               | 33.30%                               | 60.00%                               |
| Capnography          |                                      |                                      |                                      |                                      |
| CO2 present          | 89.30%                               | 0.40%                                | 0.40%                                | 0.40%                                |
| CO2 absent           | 10.70%                               | 99.60%                               | 99.60%                               | 99.60%                               |
| Magnetic guidance    |                                      |                                      |                                      |                                      |
| Below diaphragm      | 0.00                                 | 75.00%                               | 0.00                                 | 75.00%                               |
| Above diaphragm      | 100.00%                              | 25.00%                               | 100%                                 | 25.00%                               |

#: probability distribution of pH is cumulative up till pH<6. *LUQ: left upper quadrant; RUQ: right upper quadrant; Probabilities in italics are computed based on the assumption of a flat distribution (equal chance of happening across all findings)
6.2 Expert consultation

In our investigation, experts in nasogastric tube-feeding made unique contributions by helping to define the goals of this investigation, determine the hypothesized tube sites, assess the practicality of each test and the consequences of feeding errors and by appraising the proposed safety recommendations.

One difficulty in utilizing expert judgments lies in knowledge solicitation. Cognitive biases are prevalent [103]. A structured process is needed to obtain unbiased opinions. We accomplish this by hosting decision workshops facilitated by one of the investigators (LP) who is an expert in decision theory and group process. During these workshops, experts provided feedback in terms of the tests and the tube sites under investigation; they also checked the dependencies between the tube sites and the tests.

The BBN model proved instrumental to the solicitation of expert judgments. Its graphical representation conveyed the essence of our approach – each test as an independent child node of ‘tube site’; the initial probability distribution of tube sites was the prior distribution, reflecting our status of knowledge before knowing any test finding; the sensitivity and specificity of each test were contained in conditional probability matrices (Table 3; Appendix A); once a finding entered into the model, the probability distribution of the tube sites changed in the direction consistent with the finding.

This understanding allowed experts to provide critical opinions, including the overall structure of the model and the number of findings included in each test. Most important of all, experts reached the consensus about the hypothesized tube sites, which were stomach, intestine, lung and oesophagus. They also defined the goal of this investigation as to, in the order of importance, rule out lung, rule out oesophagus and rule in stomach. Feeding into the intestine was considered as posing no foreseeable threats to patient safety. Additionally, it is also unlikely that a blindly-inserted tube will end up in the intestine. These insights were instrumental to the subsequent selection and assessments of the tests.

In addition, experts assessed the potential that the tests could be used at the bedside, which is an important inclusion criterion. Bilirubin is reported as being available for bedside use under research conditions in American studies, but the experts considered it not available in the UK for the foreseeable future. Hence bilirubin testing was excluded from the model.

6.3 Test selection

As discussed in Appendix A, the first step of test selection is accomplished by examining the capacity of a test for differentiating among different tube sites. This capacity is captured by likelihood ratios, or ratios of conditional probabilities. When there are more than two possible tube sites, the key is to define a sequence of binary hypotheses. Based on expert opinions, we select tests according to their
capacity for, in the order of importance, (1) discriminating between lung and not lung, denoted as ¬lung, (2) between oesophagus and stomach, and (3) between stomach and intestine. This allows us to define likelihood ratio, \( LR_1 \), \( LR_2 \) and \( LR_3 \), as in:

\[
LR_1 = \frac{P(\text{finding} \neg \text{lung})}{P(\text{finding} \text{lung})}, \quad LR_2 = \frac{P(\text{finding} \text{stomach})}{P(\text{finding} \text{oesophagus})}, \quad LR_3 = \frac{P(\text{finding} \text{stomach})}{P(\text{finding} \text{intestinal})}
\]

Table 4 presents the likelihood ratios computed based on the conditional probabilities in Table 3.

### Table 4  
**Likelihood ratios of the test findings**

<table>
<thead>
<tr>
<th>Test/Finding</th>
<th>( LR_1 )</th>
<th>( LR_2 )</th>
<th>( LR_3 )</th>
</tr>
</thead>
<tbody>
<tr>
<td>pH</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>≤4</td>
<td>Infinite</td>
<td>10.92</td>
<td>8.72</td>
</tr>
<tr>
<td>≤5</td>
<td>Infinite</td>
<td>2.26</td>
<td>6.69</td>
</tr>
<tr>
<td>≤5.5</td>
<td>Infinite</td>
<td>1.37</td>
<td>6.38</td>
</tr>
<tr>
<td>&lt;6</td>
<td>207.22</td>
<td>1.06</td>
<td>5.88</td>
</tr>
<tr>
<td>≥6</td>
<td>0.26</td>
<td>1.29</td>
<td>0.18</td>
</tr>
<tr>
<td>Auscultation</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Epigastrium</td>
<td>1.29</td>
<td>0.47</td>
<td>0.40</td>
</tr>
<tr>
<td>LUQ</td>
<td>1.01</td>
<td>2.19</td>
<td>1.86</td>
</tr>
<tr>
<td>RUQ</td>
<td>0.71</td>
<td>1.54</td>
<td>7.30</td>
</tr>
<tr>
<td>Appearance</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>lung</td>
<td>0.52</td>
<td>0.64</td>
<td>1.06</td>
</tr>
<tr>
<td>stomach</td>
<td>1.74</td>
<td>1.73</td>
<td>2.88</td>
</tr>
<tr>
<td>intestine</td>
<td>1.08</td>
<td>0.64</td>
<td>0.35</td>
</tr>
<tr>
<td>Capnography</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>CO2 present</td>
<td>0.00</td>
<td>1.00</td>
<td>1.00</td>
</tr>
<tr>
<td>CO2 absent</td>
<td>9.31</td>
<td>1.00</td>
<td>1.00</td>
</tr>
<tr>
<td>Magnetic guidance</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>below diaphragm</td>
<td>Infinite</td>
<td>Infinite</td>
<td>1.00</td>
</tr>
<tr>
<td>above diaphragm</td>
<td>0.44</td>
<td>0.25</td>
<td>1.00</td>
</tr>
</tbody>
</table>
To see what likelihood ratios indicate, suppose the initial odds of a tube in the stomach versus oesophagus is 4/1, meaning the tube is four times as likely (or three times more likely) to be located in the stomach as in the oesophagus. Upon observing a finding with an $LR_2$ of 10, the odds increase to 10 times of the original one (40/1) in the direction favouring the stomach. The larger the likelihood ratio, the more likely the tube site hypothesized in its nominator relative to the tube site hypothesized in the denominator. Findings with ‘infinite’ likelihoods confirm the nominator hypothesis and rule out the denominator hypothesis, whereas findings with a likelihood ratio of 0 confirm the denominator hypothesis with certainty. Findings with a likelihood ratio of 1 are useless. Based on our definition, an ideal test used to commence feeding safety should have infinite $LR_1$ to rule out lung intubation, infinite $LR_2$ to rule out oesophagus intubation and infinite $LR_3$ to confirm stomach intubation. Correctly interpreted x-rays would be one such test. However, a quick look at Table 4 reveals that neither of the five tests can achieve this on their own. Table 5 presents tests based on their diagnostic power to rule out lung and oesophagus.

Table 5  Test selection based on diagnosticity of lung and oesophagus.

<table>
<thead>
<tr>
<th>Tests diagnostic of lung $(LR_1)$</th>
<th>Tests diagnostic of oesophagus $(LR_2)$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Magnetic guidance (rule out)</td>
<td>Magnetic guidance (rule out)</td>
</tr>
<tr>
<td>pH (rule out)</td>
<td>pH</td>
</tr>
<tr>
<td>Capnography (rule in)</td>
<td>Auscultation</td>
</tr>
<tr>
<td></td>
<td>Appearance</td>
</tr>
</tbody>
</table>

Table 5 shows that based on existing data, magnetic guidance can be used to rule out both lung and oesophagus, despite that it is non-diagnostic of intestine $(LR_3=1)$. This has two implications. First, magnetic guidance has the potential to be the single best test other than X-ray for recommending safe feeding; second, magnetic guidance should be used alone rather than in combination with any other test. The table also shows that tube aspirate pH testing is the best test among the rest: a pH with any cut-off lower than 5.5 can rule out lung for certain while one lower than 4 reduces the chance of oesophagus by 10 folds $(LR_2=10.92)$. The lack of certainty in terms of oesophageal placement means we can look for a composite test that includes pH and other tests that are diagnostic of oesophagus, such as auscultation and aspirate appearance$^4$. This method also reveals that auscultation and

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$^4$The discussion here is based on likelihood ratios computed from conditional probabilities contained in Table 3. It is important to note that the quality of the data varies among the tests, as discussed in the literature review. For
appearance are not diagnostic of lung by themselves, and should never be used on their own for either confirming or disconfirming lung intubation.

Capnography/colorimetry is an interesting case. With a zero $LR_1$, the presence of CO2 can confirm lung but the absence of CO2 cannot rule out lung as a potential tube site. As with auscultation or appearance, capnography/colorimetry should not be used to provide evidence for commencing safe feeding. For the purpose of investigation, neither should the test be used in combination with pH because tests non-diagnostic of oesophagus ($LR_2=1$) add no value to the single pH test.

To demonstrate the ability of the Bayesian model to cope with different information, we can consider the available checking procedures to verify feeding tube position. Despite more than 31 possible tests (single and composite), our actual choice is limited to magnetic guidance alone, pH test alone, or pH used in combination with auscultation and/or appearance. The possible cut-off values of pH are 4, 5, and 5.5, because these are the only three that have the potential of ruling out lung. This analysis therefore identifies a total number of 13 tests ($=1+3+3\times2+3$) to be assessed (Table 6).

<table>
<thead>
<tr>
<th>Test</th>
<th>Positive findings</th>
</tr>
</thead>
<tbody>
<tr>
<td>Magnetic guidance</td>
<td>Below diaphragm</td>
</tr>
<tr>
<td>pH</td>
<td>Below cut-offs: 4, 5, or 5.5</td>
</tr>
<tr>
<td>Auscultation</td>
<td>LUQ or RUQ</td>
</tr>
<tr>
<td>Appearance</td>
<td>Stomach</td>
</tr>
</tbody>
</table>

### 6.4 Test assessment

Appendix C presents the methodology of assessing the tests. The logic is this: since X-ray is considered as the gold-standard of checking tube placements, decisions made using (corrected interpreted) X-ray must yield the highest expected value among all the tests, single or composite. So how good a test is can be measured by the amount of difference in the expected value of the decisions made under X-ray and the one made under the findings of the test. For instance, Test A is better than

---

instance, the studies on magnetic guidance suffer from inconsistent comparison standards, selective design and small sample size. Similarly, reliability of auscultation and aspirate appearance tests compromise their contribution to a composite test.
Test B if the difference is smaller for Test A than for Test B. We call this difference the *expected advantage of X-rays*.

For safety reasons, the default decision before learning the finding of a test should be *no feeding*. It follows that a test is only useful if its findings can ultimately lead to the decision of feeding. So the first step towards assessing the value of a test is to identify such findings, which we refer to as *positive findings*. This is easily done as such findings must produce likelihood ratios $LR_1$ and $LR_2$ that exceed 1, the larger the likelihood ratio, the more the chance of stomach increases as a result of obtaining the positive finding:

Appendix C shows that the *expected advantage of X-rays* can be further decomposed into the *expected benefit* given each of the four tube sites, denoted as $EB(tube\ site)$.

\[
EB(stomach)[1 - P(finding|stomach)] + EB(lung)P(finding|lung) + \\
EB(oesophagus)P(finding|oesophagus) + EB(intestine)P(finding|intestine)
\]  
\hspace{1cm} \text{(Eq.10.2)}

So the expected advantage of x-rays is simply the expected benefit of a correct decision given a tube site ($EB(tube\ site)$) weighted by the posterior probability that the tube site is false. $EB(tube\ site)$ is itself a function of the prior probability of a tube site and the difference between the outcome values of a correct decision and an incorrect decision (e.g. given stomach, feeding is correct and no-feeding is incorrect; see Appendix C). Both prior probabilities and the difference between the outcome values are fixed for each patient. Therefore $EB(tube\ site)$ is constant. This leaves the posterior probability of a tube site given a positive finding the only factor that determines the expected advantage of x-rays. Table 7 presents these posterior probabilities as the decision weights of $EB(tube\ site)$.
Table 7  Probability weights for computing the expected advantage of X-ray

<table>
<thead>
<tr>
<th>Positive findings</th>
<th>EB (stomach)</th>
<th>EB (oesophagus)</th>
<th>EB (intestine)</th>
<th>EB (lung)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Magnetic guidance (below diaphragm)</td>
<td>25%</td>
<td>0%</td>
<td>75%</td>
<td>0%</td>
</tr>
<tr>
<td>pH ≤4</td>
<td>45%</td>
<td>5.00%</td>
<td>6.26%</td>
<td>0%</td>
</tr>
<tr>
<td>pH ≤5</td>
<td>32%</td>
<td>30.00%</td>
<td>10.13%</td>
<td>0%</td>
</tr>
<tr>
<td>pH ≤5.5</td>
<td>25%</td>
<td>55.00%</td>
<td>11.80%</td>
<td>0%</td>
</tr>
<tr>
<td>pH ≤4&amp;Auscultation (LUQ or RUQ)</td>
<td>61%</td>
<td>1.90%</td>
<td>1.65%</td>
<td>0%</td>
</tr>
<tr>
<td>pH ≤4&amp;Appearance (Stomach)</td>
<td>69%</td>
<td>1.67%</td>
<td>1.25%</td>
<td>0%</td>
</tr>
<tr>
<td>pH ≤5&amp;Auscultation</td>
<td>52%</td>
<td>11.40%</td>
<td>2.67%</td>
<td>0%</td>
</tr>
<tr>
<td>pH ≤5&amp;Appearance</td>
<td>61%</td>
<td>9.99%</td>
<td>2.03%</td>
<td>0%</td>
</tr>
<tr>
<td>pH ≤5.5&amp;Auscultation</td>
<td>47%</td>
<td>20.90%</td>
<td>3.11%</td>
<td>0%</td>
</tr>
<tr>
<td>pH ≤5.5&amp;Appearance&amp;Appearance</td>
<td>57%</td>
<td>18.32%</td>
<td>2.36%</td>
<td>0%</td>
</tr>
<tr>
<td>pH ≤4&amp;Auscultation&amp;Appearance</td>
<td>78%</td>
<td>0.63%</td>
<td>0.33%</td>
<td>0%</td>
</tr>
<tr>
<td>pH ≤5&amp;Auscultation&amp;Appearance</td>
<td>72%</td>
<td>3.80%</td>
<td>0.53%</td>
<td>0%</td>
</tr>
<tr>
<td>pH ≤5.5&amp;Auscultation&amp;Appearance&amp;Appearance</td>
<td>69%</td>
<td>6.96%</td>
<td>0.62%</td>
<td>0%</td>
</tr>
</tbody>
</table>

These probabilities are essentially the fractions of patients that are subjected to an incorrect decision given the three tube sites. The smaller they are, the better a test is. For instance, the best test for oesophagus is magnetic guidance, which recommends feeding to 0% of the patients with tubes placed in the oesophagus. Since we are trying to select the best option from these 13 single and composite tests, we can convert the expected advantage of x-rays to the expected advantage of pH ≤4. This is easily done. The expected advantage of pH ≤4 over pH ≤5, for instance, is simply the difference between the expected advantages of X-rays over the latter and that of the former, as captured in the difference in the probability weights (Table 8).
A positive (negative) percentage measures the extent to which a test is worse (better) than pH ≤4 given the column tube site. For instance, in terms of stomach, pH ≤4 is worse than magnetic guidance because it reduces the percentage of correct feeding in the stomach by 20.4%. As can be seen, no tests have all percentages that are all positive for the three tube sites, indicating that pH ≤4 is not strictly better than these tests. Nevertheless, under reasonable assumptions, we can rule out some tests that will be worse than the test pH ≤4.

Table 8  Probability weights for computing the expected advantage of pH ≤4.

<table>
<thead>
<tr>
<th></th>
<th>EB (stomach)</th>
<th>EB (oesophagus)</th>
<th>EB (intestine)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Magnetic guidance (below diaphragm)</td>
<td>-20.40%</td>
<td>-5.00%</td>
<td>68.74%</td>
</tr>
<tr>
<td>pH ≤5</td>
<td>-13.20%</td>
<td>25.00%</td>
<td>3.87%</td>
</tr>
<tr>
<td>pH ≤5.5</td>
<td>-20.63%</td>
<td>50.00%</td>
<td>5.54%</td>
</tr>
<tr>
<td>pH ≤4&amp;Auscultation (LUQ or RUQ)</td>
<td>15.94%</td>
<td>-3.10%</td>
<td>-4.61%</td>
</tr>
<tr>
<td>pH ≤4&amp;Appearance (stomach)</td>
<td>23.15%</td>
<td>-3.33%</td>
<td>-5.01%</td>
</tr>
<tr>
<td>pH ≤5&amp;Auscultation</td>
<td>6.60%</td>
<td>6.40%</td>
<td>-3.59%</td>
</tr>
<tr>
<td>pH ≤5&amp;Appearance</td>
<td>15.55%</td>
<td>4.99%</td>
<td>-4.23%</td>
</tr>
<tr>
<td>pH ≤5.5&amp;Auscultation</td>
<td>1.34%</td>
<td>15.90%</td>
<td>-3.15%</td>
</tr>
<tr>
<td>pH ≤5.5&amp;Appearance</td>
<td>11.270%</td>
<td>13.32%</td>
<td>-3.90%</td>
</tr>
<tr>
<td>pH ≤4&amp;Auscultation&amp;Appearance</td>
<td>32.33%</td>
<td>-4.37%</td>
<td>-5.93%</td>
</tr>
<tr>
<td>pH ≤5&amp;Auscultation&amp;Appearance</td>
<td>26.95%</td>
<td>-1.20%</td>
<td>-5.73%</td>
</tr>
<tr>
<td>pH ≤5.5&amp;Auscultation&amp;Appearance</td>
<td>23.92%</td>
<td>1.96%</td>
<td>-5.64%</td>
</tr>
</tbody>
</table>

One assumption is that about the outcome values. As discussed in Appendix B, we may assume that a correct decision in oesophagus is more valuable than a correct decision in stomach, which is more valuable than a correct decision in intestine. That is, \( NF_E \cdot F_E > F_S \cdot NF_S > NF_I \cdot F_I \). It is also reasonable to assume that the prior probability of stomach is at least twice that of intestine, or \( P_S > 2P_I \). Therefore, \( P_S(F_S - NF_S) > 2P_I(NF_I - F_I) \), or \( EB(stomach) > 2EB(intestine) \). It follows that if a test has positive probability weight for \( EB(stomach) \) as well as \( EB(oesophagus) \), and the probability weight for
**EB(stomach)** is at least twice that of **EB(intestine)**, then on balance, this test must be worse than the pH test of using 4 as the cutoff. This method allows us to exclude a total number of five tests from the subsequent analyses, which are the two composite tests using pH ≤5 or pH ≤5.5 combined with auscultation or appearance, and the composite test pH ≤5.5& Auscultation & Appearance. The rest of the tests are better than pH ≤4 in some aspects but worse than it in some other aspects. Which test is the best depends on decision makers’ judgments of outcome values and conditional probabilities of potential tube sites.

### 6.5 Sensitivity analyses

As shown in Table 8, the relative advantage of these tests is a function of the probability weightings and the three expected benefits, **EB(stomach)**, **EB(oesophagus)** and **EB(intestine)**, or the expected benefits of the correct decision in the stomach, oesophagus and intestine. To simplify the analysis, we first convert the three terms to be a function of **EB(stomach)**, by assuming probability odds favouring oesophagus and intestine, i.e. $P_{E}/P_{S} = \Omega_{E}$ and $P_{I}/P_{S} = \Omega_{I}$ as well as benefit ratios between non-stomach and stomach, i.e. $(NF_{E} - F_{E})/(F_{S} - NF_{S}) = \Phi_{E}$, $(NF_{I} - F_{I})/(F_{S} - NF_{S}) = \Phi_{I}$. In so doing, we obtain $EB(oesophagus) = EB(stomach)\Omega_{E}\Phi_{E}$ and $EB(intestine) = EB(stomach)\Omega_{I}\Phi_{I}$. For instance, the relative advantage of pH ≤4 over pH ≤5 can be now expressed as:

$$EB(stomach)(-13.2\% + 25.0\%\Omega_{E}\Phi_{E} + 3.87\%\Omega_{I}\Phi_{I}).$$

A positive (negative) valence of the expression indicates that pH ≤4 is the better (worse) test between the two tests given the tube sites. The overall preference, as embodied in the valence of this expression, depends only on the terms in the bracket. This allows us to examine the impact of different combinations of prior odds ($\Omega_{E}$ and $\Omega_{I}$) and benefit ratios ($\Phi_{E}$ and $\Phi_{I}$).

As an example, assume that the chance of correct placements is 50%, which means that 50% of the time a tube is inserted correctly into the stomach ($P_{S}=50\%$); the chances of oesophagus, lung and intestine are assumed to be 25%, 20% and 5%, respectively. This gives $\Omega_{E}=25%/50\%=0.5$ and $\Omega_{I}=5%/50\%=0.1$. We assume $\Phi_{I}$ to be 0.5, meaning that a correct decision given intestine is only half as valuable as a correct decision given stomach. Based on these and the probabilities in Table 8, we compute the expected advantage of pH ≤4 as a function of **EB(stomach)** under different $\Phi_{E}$. The values are shown in Table 9.
Table 9  Sensitivity analysis of tests (when $\Omega_E=0.5$, $\Omega_I=0.1$ and $\Phi_I=0.5$)

<table>
<thead>
<tr>
<th></th>
<th>$\Phi_E$</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>2</td>
</tr>
<tr>
<td>Magnetic guidance</td>
<td>-0.22</td>
</tr>
<tr>
<td>pH $\leq$5</td>
<td>0.12</td>
</tr>
<tr>
<td>pH $\leq$5.5</td>
<td>0.30</td>
</tr>
<tr>
<td>pH $\leq$4&amp;Auscultuation</td>
<td>0.13</td>
</tr>
<tr>
<td>pH $\leq$4&amp;Appearance</td>
<td>0.20</td>
</tr>
<tr>
<td>pH $\leq$4&amp;Auscultaiton&amp;Appearance</td>
<td>0.28</td>
</tr>
<tr>
<td>pH $\leq$5&amp;Auscultaiton&amp;Appearance</td>
<td>0.25</td>
</tr>
</tbody>
</table>

Several things are worth noting. First, under all the assumed values of $\Phi_E$, which ranges from 2 to 30, magnetic guidance is always better than pH $\leq$4, whereas pH $\leq$4 is always better than pH $\leq$5 and pH $\leq$5.5. Second, the advantage of pH $\leq$4 over pH $\leq$4&Auscultaiton&Appearance is always more negative than the one over pH $\leq$5&Auscultaiton&Appearance, suggesting that the composite test consisting of the lower cutoff is better than the one containing the higher cutoff. This means the best test is either magnetic guidance or the pH test with the cutoff of 4, when the latter is either used on its own or in combination with auscultation and/or appearance. The composite test becomes preferred when $\Phi_E$ increases.

6.6 Summary of key findings

- Improving the quality of initial tube insertions is an important aspect in tube-feeding

- The existing sensitivity and specificity data suggest that magnetic guidance is the single best test, followed by pH $\leq$4. Auscultation, appearance, and capnography/colorimetry should not be used on their own

- Published evidence of magnetic guidance testing and aspirate appearance is insufficient to recommend its use in a clinical guideline

- The composite tests using pH $\leq$4 in combination of auscultation and/or appearance is only better than the single test pH$\leq$4 when the tube has a high chance of being located in the oesophagus relative to the stomach ($\Omega_E$), or when the benefit of a correct decision given
oesophagus is higher relative to the benefit of a correct decision given stomach ($\Phi_E$). The less optimistic the conditions, such as a larger placement error ($\Omega_E$) or a more severe consequence of feeding into the oesophagus ($\Phi_E$), the more one should consider using pH combined with first auscultation and then appearance (refer to Table 8 for details).
7 Implications

7.1 Tube site prediction in practice

Table 10 displays the predicted tube sites based on the Bayesian model and pH measurements with pH paper. The specificity increases with a pH cut-off of 4.0 at the expense of reduced sensitivity. This is the safest option for the clinical problem faced, as a low number of false positives will reduce the risk of feeding in the wrong tube site. The distribution of pH readings from gastric tube aspirates under various conditions and respiratory samples is displayed in Figure 5.

<table>
<thead>
<tr>
<th></th>
<th>Using pH ( \leq 4 )</th>
<th>Using pH 5.5</th>
</tr>
</thead>
<tbody>
<tr>
<td>IF pH &lt; 4</td>
<td>95.6% stomach</td>
<td>IF pH &lt; 5.5</td>
</tr>
<tr>
<td>2.73% oesophagus</td>
<td></td>
<td>19.3% oesophagus</td>
</tr>
<tr>
<td>1.71% intestine</td>
<td></td>
<td>2.35% intestine</td>
</tr>
</tbody>
</table>

There are two key aims of safety guidelines for feeding tube insertion. The principal aim is to minimise the incidence of feeding errors. Another consideration is to avoid exposure to unnecessary X-rays. We can consider 3 clinical guideline scenarios: the first using a pH cut-off > 5.5 before requiring X-ray confirmation, the second using a lower pH cut-off > 4.0 and the third employing X-ray confirmation of tube position for all newly-inserted nasogastric tubes.

A key aspect of using the BBN model is the incorporation of prior probabilities. Referring to reported incidence of nasogastric tube misplacement provides the conditional probability of the inserted tube being in a particular position. In this way we can assume that stomach placement will occur in 75% of tube insertions, oesophageal placement in 20% of insertions and respiratory placement in 5% of cases. The main outcomes of interest are feeding errors and unnecessary X-rays. Applying the 3 guideline scenarios to patients with the same assumed prior probabilities has a dramatic effect on outcomes. This is displayed in Table 11 and Figure 5. There is a clear reduction in the likelihood of feeding errors when the pH cut-off is lowered from 5.5 to 4.0 (9.38% vs 0.62%). The trade-off is a comparatively minor increase in unnecessary X-rays with the same manoeuvre (24.2% vs 34.2%). In terms of improving the safety of the guideline, it would seem that using a tube aspirate pH of \( \leq 4.0 \) to indicate gastric tube position is required prior to commencing enteral feeding.
Table 11  Outcomes of clinical guidelines

<table>
<thead>
<tr>
<th></th>
<th>Placement errors</th>
<th>Unnecessary X-ray</th>
</tr>
</thead>
<tbody>
<tr>
<td>pH ≤5.5 feed; X-ray everyone with pH&gt;5.5</td>
<td>9.38%</td>
<td>24.15%</td>
</tr>
<tr>
<td>pH ≤4 feed; X-ray everyone with pH&gt;4</td>
<td>0.62%</td>
<td>34.05%</td>
</tr>
<tr>
<td>X-ray everyone</td>
<td>0</td>
<td>75%</td>
</tr>
</tbody>
</table>

Figure 5: Guideline scenarios and outcomes

1. Based on a prior probability of stomach placement in 75%, oesophageal placement in 20%, respiratory placement in 5%

7.2 X-ray interpretation

A crucial step in ensuring correct decisions about commencing tube feeding is the correct interpretation of radiograph films. As mentioned above, recent adverse events were as a direct result of X-ray misinterpretation[13]. A simple recommendation is to ensure that the purpose of ordering an X-ray, i.e. for confirmation of nasogastric feeding tube placement is made explicit on the request form. This will direct the duty radiographer to obtain the required view that includes the tip of the feeding tube. Recent reports of receiver-operator characteristics in chest and emergency radiograph interpretation demonstrate superior performance of senior radiologists as compared to trainee radiologists and non-radiology physicians[108-110]. Local policies and practices regarding X-ray
reporting will vary, yet a potentially important safety net would be to have every X-ray requested for confirmation of tube position reported in writing by a senior radiologist.

### 7.3 Comparison with existing guidelines

Guidelines on nutrition support for adults issued by the National Institute for Clinical Excellence[95] recommend that the position of NG tubes be verified on initial placement and before each use. Routine X-rays are not advised, but it is suggested that local policies be developed for high risk groups including intensive care units or for when an aspirate is not obtained. British Society of Gastroenterology (BSG)[90] guidance for enteral feeding suggests tube aspirate pH measurement needs to be less than 5.0 prior to every use, but advises that the pH test is valueless if the patient is on acid suppression.

The consensus view is that fine-bore tubes of 5 – 8Fr diameter should be standard for delivering enteral nutrition[90, 95]. Comparative studies have shown no difference in the microaspiration rate of gastric juice with the use of various feeding tube sizes[78, 104, 105]. The use of fine-bore tubes is not justified for the sole purpose of preventing aspiration and nosocomial pneumonia, but remains the default choice for improved patient comfort and a minimal risk of developing sinusitis, pharyngitis or erosive complications[106].

Canadian clinical practice guidelines published in 2003[107] note that no randomised trials exist that directly demonstrate an improvement in clinical outcomes for critically ill patients with a particular feeding protocol. The guidelines recommend consideration of post-pyloric feeding for patients that are on continuous intravenous sedation or paralytic agents, patients needing to be nursed flat, and patients with persistently high GRV or those who otherwise demonstrate digestive intolerance of feeds delivered into the stomach. Simple measures often advocated to prevent aspiration include elevating the head of the bed to at least 30 degrees, keeping the patient propped up for 30mins after feeding, and maintaining adequate airway management with careful vigilance of tube feed delivery and patient tolerance[91].

### 7.4 Comparison with current practice

Our recommendation is to use a pH cutoff of equal to or less than 4.0 to incorporate the possibility of oesophageal misplacement. Previous advice from the NPSA employs a pH cutoff of 5.5[12]. Using the collated data of the pH studies, if all 705 gastric aspirates are included for pH measurement with Baxter paper, a pH reading ≤4.0 has a sensitivity of 54.6% and a specificity of 100% for gastric placement. Using the NPSA cutoff for the same data, a pH reading ≤5.5 has a sensitivity of 75.2% but the specificity is reduced to 97.3%. This is without taking into account the possibility of oesophageal placement. Looking at the total of 280 respiratory tract samples, a pH reading >4.0 has a sensitivity of 100%, and a specificity of 32%. A pH reading >5.5 has a 97% sensitivity and 40.8%
specificity for respiratory tube placement. The sensitivity of a pH paper reading ≤4.0 for diagnosing stomach placement improves to 70.2% when samples taken from patients on acid-inhibitor therapy are excluded (n= 235). In 629 gastric tube aspirates taken from patients fasted for at least one hour, the sensitivity increases to 61.4%.

If the possibility of tube placement into the oesophagus is taken into account, aspirate pH of the oesophagus can be assumed to be <4.0 on less than 5% of occasions. A pH reading of ≤5.5 has a sensitivity of 75.2% but a poor specificity of 57.5% for gastric placement, whereas lowering the pH cut-off to ≤4.0 improves the specificity to 97.5% at the expense of a reduced sensitivity of 54.6%.

As compared to AACN guidance that advocates routine X-rays for every new tube insertion[16], this guideline will reduce the requirement for radiographic confirmation in 57.2% of all patients and in 70.2% of patients without acid-inhibitors. This represents a significant reduction in exposure to ionising radiation and procedural cost.

8 Validation against NRLS Adverse Event Reports

8.1 Methodology

Database search
Inclusion criteria for the search were all cases with evidence of nasogastric tube misplacement at any site outside the stomach entered into the National Reporting and Learning System (NRLS) database from the date of inception in October 2003 to 28th February 2009. Exclusion criteria were all paediatric cases as the safety guideline was applicable only to adults. The search terms used are detailed in Appendix D.

8.2 Case selection and Analysis
The narratives from the initial NRLS dataset were further examined to identify cases of nasogastric tube misplacement in any site outside the stomach. Two independent reviewers classified the adverse event reports according to whether or not current NPSA safety alert guidelines were followed prior to enteral feed being commenced. This was only possible for those reports that included sufficient information in the narratives. For reports that described tube feed or medication being administered via incorrectly placed nasogastric tubes, the reason for this was identified and classified.

The classification of the failure to correctly identify a misplaced tube originated from process mapping based on the existing and proposed safety guidelines.

8.3 Results
The number of incidents found from the NRLS database using the predefined search terms was a total of 2368 adverse event reports. Further examination of these reports yielded a total of 104 cases with
documented feeding tube misplacement. We excluded all the irrelevant reports including those with missing or insufficient narratives and all narratives not related to feeding tube insertion or enteral tube feeding. The outcomes of tube misplacement in terms of patient harm are summarised in Table 12.

Table 12 Patient harm associated with feeding tube misplacement (NRLS database)

<table>
<thead>
<tr>
<th>Effect on patient</th>
<th>No. of cases</th>
</tr>
</thead>
<tbody>
<tr>
<td>Death</td>
<td>6</td>
</tr>
<tr>
<td>Severe harm</td>
<td>15</td>
</tr>
<tr>
<td>Moderate harm</td>
<td>23</td>
</tr>
<tr>
<td>Low harm</td>
<td>17</td>
</tr>
<tr>
<td>No harm</td>
<td>43</td>
</tr>
</tbody>
</table>

In 29 reports there was too little information to support further analysis of the checking procedure employed to identify tube misplacement. Of the 75 narratives which allowed for further analysis, 11 reports described the wrong location of NG tube being discovered prior to feed or medication administration. These 11 cases included 5 incidents of tube misplacement identified by a tube aspirate pH > 5.5 followed by chest radiography and 6 incidents identified by chest radiography alone. For the remaining 64 cases in which the correct test was not used to locate the nasogastric tube or the results were incorrect, analysis of the reasons for failing to identify tube placement prior to tube use was performed and the results detailed in Table 13.

Table 13 Mode of failure to identify tube misplacement

<table>
<thead>
<tr>
<th>Type of failure</th>
<th>No. of cases</th>
</tr>
</thead>
<tbody>
<tr>
<td>pH test correctly carried out but invalid (pH &lt;5.5 but tube not in stomach)</td>
<td>10</td>
</tr>
<tr>
<td>pH test wrongly interpreted (thought OK if pH = 6)</td>
<td>1</td>
</tr>
<tr>
<td>Aspiration used as checking procedure; unclear whether pH tested</td>
<td>5</td>
</tr>
<tr>
<td>Bubble or Whoosh test used as only checking procedure</td>
<td>2</td>
</tr>
<tr>
<td>CXR incorrectly interpreted</td>
<td>25</td>
</tr>
<tr>
<td>Correct test indicated tube in stomach but tube moved prior to starting feed</td>
<td>4</td>
</tr>
<tr>
<td>No action taken to assess tube placement</td>
<td>12</td>
</tr>
<tr>
<td>CXR done but not checked prior to feeding</td>
<td>2</td>
</tr>
<tr>
<td>Other (misinterpretation of CXR report) (CT scan misreported)(direct vision and no further checks)</td>
<td>3</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td><strong>64</strong></td>
</tr>
</tbody>
</table>
8.4 Further analysis of pH results

Of those narratives in which a tube aspirate pH was documented, the test failed to identify a misplaced tube in 10 adverse event reports. Of these cases a tube aspirate pH of between 4.0 and 5.5 was recorded in 9 incidents. These included 6 tubes that were subsequently documented to be misplaced in the lung, 2 tubes coiled in the oropharynx and 1 tube position described as “very little” being inserted into the patient. There was one incident when the tube aspirate pH was 1.5 and the tube demonstrated to be inserted to only 26cm although the anatomical tube position was not verified.

Incidents in which the documented tube aspirate was between 4.0 – 5.5 with tube misplacement confirmed in the lung included one case in which the tube was aspirated after flushing the tube with sterile water, contrary to NPSA alert guidelines. A report with a tube aspirate pH of 5.5 commented that the tube may have been aspirated after aspiration of gastric contents into the lung. There was one case in which the tube aspirate tested with pH paper gave an uncertain result of either 5.5 or 6.0 and the individual interpreted the result as pH 5.5 and therefore safe to commence feeding according to NPSA alert guidelines. Unfortunately this led to a large volume of feed being aspirated into the lung and subsequent death of the patient.

8.5 Further analysis of Chest X-ray (CXR) misinterpretation

There were a total of 25 documented incidents of X-ray misinterpretation leading to adverse event reports associated with tube misplacement (Table 13). Chest radiographs were misinterpreted by the junior House Officer in 4 cases and the Senior House Officer in 6 cases, while it was not clear what level of doctor misread the radiograph in 14 cases. The chest radiograph from the wrong date was reviewed in 2 cases of tube misplacement.

Process mapping of the feeding errors with the proposed safety guidelines is displayed in Figure 12. The full narratives for the pH and X-ray misinterpretations are included in Appendix E.

8.5.1 Assessment of safety guidelines

Review of the adverse event narratives highlight problems inherent to relying on tube aspirate pH to indicate safe commencement of enteral feeding. In particular there may be misinterpretation of pH values between 6.0 and 5.5. Using a pH cut-off of 5.5 to indicate safe feeding did not prevent 5 incidents of respiratory tube misplacement and documented feed aspiration into the lungs. Lowering the pH cut-off to 4.0 would have prevented these incidents. A further case of tube misplacement into the lungs without administration of feeds occurred when the NPSA alert guideline was not adhered to and a sterile water flush was administered prior to tube aspiration.

The issue of X-ray interpretation is also highlighted by the adverse event data. It is vital to include correct interpretation of radiographs into the safety guideline, without dictating local policy on how to achieve correct X-ray interpretation.
Even lowering the pH cut-off to 4.0 and assuming correct interpretation of all radiographs does not eliminate the potential for tube feeding error: in 4 cases of tube misplacement the correct procedures were carried out but the tube migrated prior to commencing feeds, and in 1 case the tube aspirate pH was as low as 1.5 with the tube inserted to only 26cm. However we can conclude that 70/75 cases of tube misplacement would be prevented by following our recommendations. Applying the proposed guideline instead of previous NPSA safety alert guidelines to the NRLS adverse event report data avoids 6 cases of feeding into the lung, 2 cases of feeding into the oropharynx and 1 case of feeding into the oesophagus, an overall 14% reduction in tube feeding errors.
9 Overall discussion

The BBN model was built based on two different yet complementary sources of information, namely published literature and expert judgments. While for the purpose of developing evidence-based guidelines conditional probabilities described the effectiveness of each test, experts provided crucial inputs including the number of potential tube sites (i.e. the competing hypotheses) to consider, the consequence of tube placements in the tube sites other than stomach, the overall adequacy of the model, as well as the validity of model recommendations. It was the expert panel who helped to first define the scope and targets of this investigation, as well as providing safeguards to the quality of the model and the potential practicality of each test. Expert judgments are particularly valuable because these experts are also the potential users of the guideline. Their participation in the process of developing the guideline determines to a large extent how much practical value the guideline has.

The role of Bayesian networks, from this point of view, is to present probabilistic statements in a way that is easy to test, analyze and communicate. BBN models together with other techniques of decision analysis provided us with a structured way of thinking and dealing with uncertainties that went beyond this investigation.

Several practical issues and areas of controversy are worth discussing. When choosing a safe cut-off for tube aspirate pH, a reasonable approach is that values below 4.0 indicate gastric placement while pH values above 6.0 could indicate inadvertent respiratory tract placement. The grey area is for tube aspirate pH values of between 4.0 and 6.0. These values principally relate to the potential for tube feeding into the oesophagus. The consensus view is that delivery of enteral feeds into the oesophagus will increase the risk of pulmonary aspiration for all patients, and therefore oesophageal feeding should be avoided. Studies of pH monitoring demonstrate the prevalence of gastro-oesophageal reflux disease in asymptomatic patients. A volume of 2-3mls could easily come from gastric refluxate fluid in the lower oesophagus and be aspirated through a fine-bore feeding tube. Although there are concerns about extrapolating data from pH monitoring studies using a sensitive pH electrode to a scenario of testing tube aspirate pH, these data do indicate that the oesophageal pH will be higher than 4.0 on the majority of occasions. However, we cannot assume that pH will always be higher than 5.5 in the oesophagus based on these studies. Furthermore, studies of pH measurement accuracy show an increased incidence of disagreement between pH paper and pH meter with pH paper values above 4.0, such that readings of pH 5.0 from pH paper were read by pH meter at higher than 6.0. This could indicate respiratory tube misplacement but be misinterpreted as gastric placement on pH paper testing alone, leading to potentially harmful feeding errors. Although feeding into the lungs is very unlikely with a pH cut-off ≤5.5 there is a clear potential for error that can be eliminated with a lower cut-off of pH ≤4.0.
The major drawback of applying a lower pH cut-off is an increase in the likelihood of unnecessary X-rays. This raises concerns about practical issues, particularly the availability of X-rays in the community and the adverse harm caused to patients during the process of obtaining an X-ray – the so-called revenge effect or organisational drift. Lowering the pH cut-off to indicate gastric tube placement represents a trade-off between reducing both the incidence of tube feeding into the oesophagus and the potential for pH paper inaccuracy and a small increase in the number of X-rays required to verify tube position. No guideline is foolproof and without limitations, but the consequences of tube feeding errors will be far worse than any delay in commencing tube feeds or the increased exposure to X-ray required for a plain chest radiograph. Using a lower pH cut-off there is a cohort of patients with tube aspirate pH between 4.0 and 5.5 in whom X-rays will be requested. This same cohort will have tube feeding initiated without X-ray if the current NPSA alert guideline is applied. In terms of potential adverse outcomes, the safety of this cohort is enhanced with the lower pH cut-off: only the proportion of patients whose X-rays are misinterpreted or unable to be performed have the potential for catastrophic tube feeding errors as opposed to the entire cohort if the higher pH cut-off ≤5.5 is relied upon.

Incident reporting of feeding tube-related adverse events suggests that misinterpretation of X-rays is a prevalent cause of feeding errors. While this may reflect reporting bias, there is a clear need to recommend correct interpretation of X-ray films. A dogmatic approach is not appropriate as local policies and hospital facilities will dictate the action required.

Concerns have been raised about the potential for non-compliance with the safety guideline if the pH cut-off is lowered to 4.0. This is because practitioners may be easily discouraged from obtaining an aspirate if the initial pH paper reading is above 4.0. Compliance with any new guideline or change in practice is always a potential problem, and similar concerns have largely been overcome after introduction of the initial NPSA safety alerts, although adverse event incident reporting does suggest ongoing occurrences in which inappropriate methods (the “whoosh” test) are still being used to verify tube position. Human nature is always resistant to change: stakeholders will defend the currently-held position until the new position is taken up and subsequently defended. Efforts to improve the safety of tube feeding need not be discouraged by the inevitable natural resistance that meets initial guideline introduction.
Future research needs to include clinical outcome studies based upon different checking procedures, and should aim to answer the following questions: how the inaccuracies of pH paper and the differences between commercially available pH strips affect a safe cut-off to rule out respiratory tract placement; how and when oesophageal placement should be excluded; and the use of confirmatory X-rays as a safe and reliable gold standard.

The systematic review of checking procedures provides evidence to support the use of pH paper to exclude tube misplacement, albeit with several limitations. The evidence comes largely from one study group despite using multi-centre recruitment, with surrogates for respiratory tract placement. Several confounding factors affect pH measurement of tube aspirate. The conditions under which data were collected may not be reproducible in the clinical setting, and this must be reflected in any recommendations for relying on aspirate pH to verify tube position. The pooled data on aspirate pH suggest that tubes placed in the respiratory tract will always be identified by a pH reading of more than 5.5 as measured by pH meter or pH paper. The pH method is less accurate in identifying stomach placement and may lead to unnecessary X-rays to confirm gastric position.

Carbon dioxide detection techniques are useful for excluding respiratory tract placement but cannot provide valuable information about tubes coiled in the pharynx or oesophagus. Magnetic detection is promising but reported studies are limited by inconsistent standards and sample size. Further well-designed prospective studies are needed to evaluate the technology.

There is a lack of data regarding bedside methods to assess tube position in the oesophagus. The pH studies from Metheny’s group include only a limited number of oesophageal tube aspirate samples. Enteral feed delivery through a feeding tube placed in the lower oesophagus is a recognised risk for aspiration. Nasogastric tube misplacement in the oesophagus is more common than respiratory tract misplacement, although the consequences may not be so immediately apparent.
11 Conclusion

The aim of this project was to improve the safety of feeding tube insertion. The primary aim was to develop an evidence-based guideline for verifying nasogastric tube position in adult patients, with an emphasis on starting tube feedings safely. Through a unique process of literature review, construction of a Bayesian belief network model, decision conference analysis and expert group discussions we can identify the safest possible method to verify feeding tube position with the currently available bedside techniques. This involves obtaining a tube aspirate with a pH of equal to or less than 4.0 to verify gastric position. If this pH cannot be obtained despite best efforts then X-ray confirmation is required. Using this method minimises the potential for tube feeding errors into the oesophagus respiratory tract allowing for pH paper inaccuracies.

The added benefits of lowering the cutoff from 5.5 to 4 are two-fold. First, it reduces the incidence of oesophageal feeding as available data from pH measurements in healthy volunteers show that oesophageal pH is lower than 4 between 0.1% and 3.2% of the time. Second, a variety of pH papers are currently in use, some of which are not accurate enough especially when the pH is high. The true pH may be underestimated by pH paper when the tube is misplaced into the respiratory tract, and thus incur feeding errors. However, existing evidence indicates that underestimating pH is not a problem when the pH is lower than 4.

It is important to note that although lowering the cutoff from 5.5 to 4 will increase the number of patients being sent for x-rays, this does not equate to a larger number of x-ray misinterpretations. Note that using the two different pH cutoff values only makes a difference for patients with a tube aspirate pH between 4 and 5.5. For these patients, the current guideline recommends feeding whereas our recommendations entail an x-ray. These patients have a feeding tube either correctly placed or in an unsafe position. Under our recommendations, the danger to safety only occurs for patients whose tube is incorrectly placed and whose chest x-ray is misinterpreted. By contrast, all these patients will be fed under the existing guideline.

The safety recommendations address important questions regarding the safest site for tube feeding and potential for pulmonary aspiration. It includes clear exclusion criteria for the validity of the pH test for tube aspirates and also provides a stepwise approach to obtain the aspirate based upon best available data. The crucial step of correct X-ray interpretation is integrated into the decision-making process. The focus of our recommendations is on the safest outcome for patients requiring tube feeding. Limitations of this approach include the increase in the number of X-rays required for tubes that are positioned in the stomach. No single bedside test is perfect for verification of tube position and there is a need for large prospective clinical studies to further evaluate emerging technologies as well as the reliability of existing pH indicators. The project has demonstrated that, based upon current best evidence, the NPSA safety alert guidelines can be made safer.
Thus, taking into account the difficulties in obtaining chest x-rays in some circumstances, we propose the following checking procedure, which recommends feeding for patients with tube aspirate pH equal to or lower than 4, and x-ray for patients with aspirate pH higher than 5.5. For patients with pH between 4 and 5.5, we recommend feeding if the patient is deemed to be at a low risk of aspiration from oesophageal feeding.
Safety recommendations for blindly inserted nasogastric tubes

- Is it safe to feed in the stomach? Consider risk factors for aspiration
  - Yes
  - Is pH test valid? Consider medication and feeding status
    - Yes
    - Obtain an aspirate
      - Test pH of aspirates using pH paper, CE marked
      - Observe pH
        - pH less than 4
          - Is it safe to feed? Consider risk factors for feeding into the oesophagus
            - Yes
            - X-Ray WITH accurate interpretation
              - Yes
              - START FEEDING
              - No
              - DO NOT START FEEDING
        - pH between 4 and 5.5
        - pH higher than 5.5
      - No
      - Consider jejunal or post-pyloric feeding according to local expertise & local policy
  - No
1. Unsafe to feed in the stomach if:

Persistent high gastric residual volumes > 400ml

Vomiting

2. pH test not valid if:

Patient with documented GORD, or if

Patient fed OR given medications within 1 hour

3. To obtain an aspirate

1. Use 50/60 ml syringe – gently insufflate 20ml air

2. Aspirate using the same syringe – air and fluid

3. If no fluid, try a) Repeat Step 1; b) Aspirate using 10 ml syringe

4. If still no fluid, try

a) Wait 30 mins then repeat steps 1-3 (Only use large syringe to insufflate air gently)

b) Move patient to supine position/ left lateral / right lateral

4. High risk for oesophageal feeding if:

Documented previous episode of aspiration

Decreased level of consciousness – GCS <9

Prolonged supine positioning

Neuromuscular disease or structural abnormalities of the aerodigestive tract
Figure 6: pH distribution of gastric aspirates and fasting history
Figure 7: pH distribution of gastric aspirates & respiratory samples

Mean = 3.9082
Std. Dev. = 2.02031
N = 754
Figure 8: Lung sample pH readings pH meter

Mean = 7.8102
Std. Dev. = 0.5113
N = 279

meterph

Frequency

tubesite: lung

6.00 7.00 8.00 9.00
Figure 9: pH distribution for patients fasted at least 1 hour, no acid inhibitors
Figure 10: pH distribution of gastric aspirates & respiratory samples – pH paper

**pH STOMACH**
- $n=705$
- $M=3.992 \pm 2.22$

**pH LUNG**
- $n=280$
- $M=7.64 \pm 0.57$
Figure 11: Potential tube sites according to aspirate pH

Kruschal-Wallis test for comparing the three positions (1,2,4) : 985.846, 2df, p<0.001
Figure 12: Adverse event process mapping with proposed safety guideline (see attached as NPSA new guideline with failures mapped.pptx)
REFERENCES

Appendix A  Bayes’ theorem and effectiveness of tests

In this appendix, we demonstrate how to use likelihood ratios to assess discriminatory power of tests as long as these tests satisfy the assumption of conditional independence. We also show why, when it comes to hierarchical uncertainties, likelihood ratios do not describe belief updating equally well. In both cases, we rely on the BBN model constructed for the NG-tube project to provide key inputs and insights into the reasoning processes.

The impact of single evidence

The fundamental question we face in this investigation is how we should revise our beliefs about the location of a tube once we receive new information. In probability theory, this is equivalent to use certain diagnostic datum to discern among several competing hypotheses. Bayes’ theorem provides the answer to this.

Let \( H_i \) denote one of \( n \) mutually exclusive events, and \( D \) some diagnostic datum. Bayes’ theorem can be written as:

\[
P(H_i | D) = \frac{P(H_i)P(D|H_i)}{\sum_{i=1}^{n} P(H_i)P(D|H_i)}
\]

\[ (1) \]

\( P(H_i) \) is the prior probability of \( H_i \) before we learn anything of the datum; \( P(D|H_i) \) is the conditional probability of \( D \) given that \( H_i \) is true; \( P(H_i|D) \) is the posterior probability of \( H_i \) given that \( D \) has been observed. The nominator of the right-hand-side of Eq.1 is in fact the joint probability that \( D \) is observed and \( H_i \) is true; or \( P(D&H_i) \); the denominator is in fact the probability of \( D \), or \( P(D) \).

Bayes’ theorem can take many forms, including an odds-likelihood ratio formulation that is particularly useful when we want to distinguish between two mutually exclusive hypotheses, \( H_1 \) and \( H_2 \), with one diagnostic datum \( D \):

\[
\frac{P(H_1 | D)}{P(H_2 | D)} = \frac{P(H_1)}{P(H_2)} \times \frac{P(D|H_1)}{P(D|H_2)}
\]

\[ (2) \]

Or

\[
\Omega_1 \ (Posterior \ odds) = \Omega_0 \ (Prior \ odds) \times LR \ (Likelihood \ ratio).
\]

To obtain Equation 2, we simply apply Equation 1 twice, once to \( H_1 \) and once to \( H_2 \), then take their ratio and in the process cancelling out the common denominator \( P(D) \). Since the sum of the two posterior probabilities, \( P(H_1|D) \) and \( P(H_2|D) \), must be 1, normalization gives assign definite values of the two posterior probabilities.

Equation 2 predicts a simple, straightforward relationship between posterior beliefs\(^5\), prior beliefs and evidence, when each of the three is expressed in relative terms between the two competing hypotheses. Prior odds describe how strong our prior beliefs are in one hypothesis relative to the

\(^5\) This report uses belief and probability interchangeably.
other; likelihood ratio describes how consistent the evidence is with one hypothesis relative to the other. The key phrase here is ‘relative to’; a datum can be highly consistent with one hypothesis (e.g. a high $P(D|H_1)$) but still useless – if it is equally highly consistent with the other hypothesis (e.g. a high $P(D|H_2)$). That is, the power of evidence is expressed in its likelihood ratio; the more different this ratio is from 1, either very large or very small (close to 0), the more discriminative it is. The most diagnostic tests are those with the likelihood ratios of 0 or infinite, which happen when the evidence cannot be observed when $H_1$ is true or when $H_2$ is true. As a result, the observation of the evidence can provide definite ideas of a hypothesis.

One of the biggest advantages of Eq.2 is that it allows us to test the impact of prior beliefs or evidence when one of them is held constant. For instance, suppose a finding favouring $H_1$ with a likelihood ratio of 4, we immediately know that in order for $H_2$ to stand any chance of being the dominant hypothesis, our prior beliefs have to favour $H_2$ with the same magnitude (i.e. prior odds smaller than $\frac{1}{4}$).

Equation 2 provides insights into how uncertainties transmit within BBNs. Put differently, BBNs can be used to demonstrate how Bayes’ theorem works. For instance, imagine the simplest case where we have to determine whether the tube is in the lung ($H_1$) or stomach ($H_2$), given findings of aspirates pH ($D$). A BBN describes this situation is:

**Figure AppA1: A BBN with one hypothesis and one piece of evidence.**

<table>
<thead>
<tr>
<th>Tube site</th>
<th>pH</th>
</tr>
</thead>
<tbody>
<tr>
<td>lung</td>
<td>0</td>
</tr>
<tr>
<td>stomach</td>
<td>75%</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Tube site</th>
<th>pH</th>
</tr>
</thead>
<tbody>
<tr>
<td>lung</td>
<td>80.0</td>
</tr>
<tr>
<td>stomach</td>
<td>20.0</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Tube site</th>
<th>pH</th>
</tr>
</thead>
<tbody>
<tr>
<td>lung</td>
<td>five or less</td>
</tr>
<tr>
<td>stomach</td>
<td>greater than 5</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Tube site</th>
<th>pH</th>
</tr>
</thead>
<tbody>
<tr>
<td>lung</td>
<td>五 or less</td>
</tr>
<tr>
<td>stomach</td>
<td>greater than 5</td>
</tr>
</tbody>
</table>

The numbers and ‘belief bars’ inside each node (box) indicate the probability distribution of each uncertain event. The matrix in Fig.1 is called a *conditional probability matrix*, which we will use to compute the likelihoods. Equally important is the direction of the arc, which has to be consistent with the conditional probabilities. In this case, the arc points out from ‘tube site’ while into ‘pH’, reflecting our assumption that pH depends on tube site rather than the other way around.
The network on the top depicts the initial situation, i.e. when we start with an equal belief in lung and stomach as the potential tube site (i.e. 50/50). These are prior probabilities of tube placements before we learn anything about the pH. By contrast, the network at the bottom shows the impact of the finding that pH is greater than 5. Now, the (posterior) probability of lung increases from 50% to 80%. Together, these two networks demonstrate the process of belief updating. The odds-likelihood ratio form of Bayes’ theorem shows why:

\[
\frac{P(\text{stomach}|pH > 5)}{P(\text{lung}|pH > 5)} = \frac{P(\text{stomach})}{P(\text{lung})} \times \frac{P(pH > 5|\text{stomach})}{P(pH > 5|\text{lung})} = \frac{.5 \times 25}{1} = 4
\]

Since \( P(\text{stomach}|pH=6) \) and \( P(\text{lung}|pH=6) \) sum up to 1, normalization gives \( P(\text{stomach}|pH=6) = .20 \) and \( P(\text{lung}|pH=6)=.80 \). The important thing here is that when the prior beliefs are non-informative (i.e. equal to 1), the posterior beliefs depend on the data alone. Since the pH test has a likelihood ratio of 4, the hypothesis that is consistent with the finding increases its chance in four-folds relative to the one that is not.

**The impact of cumulative evidence**

Equation 2 is easy to understand and use; it however handles just one datum. Expanding it to account for the power of multiple ones is possible, as long as these data satisfy conditional independence; that is, given the perfect knowledge of the hypothesis, the information of one datum cannot influence that of the other, or

\[
P(D_1,\ldots,D_n|H_i) = P(D_1|H_i) \times \ldots \times P(D_n|H_i).
\]

This property allows us to express the joint conditional probability of data, \( D_1, \ldots, D_n \), as the product of the individual ones:

\[
P(D_1,\ldots,D_n|H_i) = P(D_1|H_i) \times \ldots \times P(D_n|H_i)
\]

The odds-likelihood ratio form for multiple evidence can be deducted likewise, by replacing \( D \) in Eq.2 by \( D_1, \ldots, D_n \), as in,

\[
\frac{P(H_i|D_1,\ldots,D_n)}{P(H_j|D_1,\ldots,D_n)} = \frac{P(H_i)}{P(H_j)} \times \frac{P(D_1,\ldots,D_n|H_i)}{P(D_1,\ldots,D_n|H_j)} = \frac{P(H_i|D_1,\ldots,D_n)}{P(H_j|D_1,\ldots,D_n)} \times \frac{P(D_1|H_i)}{P(D_1|H_j)} \times \ldots \times \frac{P(D_n|H_i)}{P(D_n|H_j)}
\]

The left-hand side of Eq.3 is the posterior odds of the two competing hypotheses after \( n \) pieces of evidence are taken into account. We can also express the right-hand side of Eq.3 as a function of the most recently updated belief \( \Omega_{n-1} \) and the newest data \( LR_n \):

\[
\Omega_i = \Omega_{i-1} \times LR_i
\]

This gives the generalized odds-likelihood ratio formation:

\[
\Omega_n = \Omega_0 \times LR_1 \times \ldots \times LR_n
\]

---

6. This assumption is an exaggerating of the actual feeding errors but serves to illustrate the process of ‘belief updating’ and the logic underlying it.
Two important insights emerge from these formulations. First, the order in which we consider the evidence does not influence our final beliefs. Second, the impact of cumulative evidence can be decomposed into a series of sequential belief updating based on single evidence once a time. That is, the discriminatory power of a portfolio of conditionally independent tests can be expressed by the product of their individual likelihood ratios.

Again, let us use BBNs to demonstrate this. Assume that in addition to pH we observe that the appearance of the aspirates indicates lung. For the BBN to take account of this additional test, we simply add ‘appearance’ as another child of ‘tube site’ (Figure 2). Importantly, no arcs connect the two tests, ‘appearance’ and ‘pH’, reflecting the conditional independence assumption that given the tube site, how likely the pH is below or above 5 has no influence on how likely the aspirates have a lung or stomach appearance, and vice versa.

Figure AppA2: A BBN with one hypothesis and two pieces of evidence.

<table>
<thead>
<tr>
<th>Appearance</th>
<th>Lung</th>
<th>Stomach</th>
</tr>
</thead>
<tbody>
<tr>
<td>lung</td>
<td>100</td>
<td>0</td>
</tr>
<tr>
<td>stomach</td>
<td>0</td>
<td>100</td>
</tr>
</tbody>
</table>

Figure 2 shows that a lung appearance increases the chance of lung further from 80% to 81.8%. Nevertheless, compared to a high pH, the impact of a lung appearance is very small. To see why this is the case, we compute the likelihood ratios of lung appearance:

\[
\frac{P(\text{lung appearance}|\text{stomach})}{P(\text{lung appearance}|\text{lung})} = \frac{.40}{.45} = \frac{8}{9}.
\]

This likelihood ratio is close to 1; by contrast, pH has a likelihood ratio of 4. The impact of both tests is simply the product of the two likelihood ratios, or \(2/9 = 8/9\times.25=2/9\). This means, starting with the same non-informative prior belief, evidence consistent with lung will increase its chance in 4.5 times (\(=9/2\)), which is exactly the ratio of 81.8% and 18.2%.

This discussion demonstrates how, in the face of isolated as well as multiple findings, we can employ conditional probabilities or likelihood ratios (which are the ratios of conditional probabilities) to select the most discriminative tests.
Hierarchical uncertainties

So far our discussion focuses on the simple case where we consider only one layer of uncertainty, i.e. the one between hypotheses and data. BBNs representing such cases are sometimes called ‘naive Bayes’. In reality, uncertainty is often hierarchical and exists at many levels. For instance, the observation of pH per se might be inaccurate, such as due to the use of different makes of pH paper. How do we handle uncertainties when this is the case?

Denote A as tube site, B as true pH and C as pH paper. Each of the three has two states, depicted by the subscripts. Suppose we are interested in the posterior odds of A given the observation of C1 (a pH paper reading higher than 5). It can be shown that

\[
\frac{P(A_1|C_1)}{P(A_2|C_1)} = \frac{P(A_1,B_1,C_1) + P(A_1,B_2,C_1)}{P(A_1,B_1,C_1) + P(A_1,B_2,C_1)} = \frac{P(A_1) \times P(B_1|A_1) \times P(C_1|B_1) + P(A_1) \times P(B_2|A_1) \times P(C_1|B_2)}{P(A_2) \times P(B_1|A_2) \times P(C_1|B_1) + P(A_2) \times P(B_2|A_2) \times P(C_1|B_2)}
\]

Let \( \Omega_1 = \frac{P(A_1|C_1)}{P(A_2|C_1)} \), \( \Omega_0 = \frac{P(A_0)}{P(A_0)} \), \( LR(C_1) = \frac{P(C_1|B_1)}{P(C_1|B_2)} \). Since \( P(B_1|A_1) \) and \( P(B_2|A_1) \) sum up to 1, we can rewrite the equation as:

\[
\Omega_1 = \Omega_0 \times \frac{1 + P(B_1|A_1) \times (LR(C_1) - 1)}{1 + P(B_1|A_1) \times (LR(C_1) - 1)}. \tag{5}
\]

That is, the posterior probabilities of A depend on both its child (B) and the child of its child (C). If the relationship between B and C is perfect, \( P(C_1|B_1) \) and \( P(C_1|B_2) \) take the value of 0 and 1 respectively. This transforms Equation 5 into Equation 2.

A BBN describes such a situation is shown in Figure 3; ‘pH paper’ is added as a child node to ‘pH’. The conditional probability matrix depicts the (lack of) accuracy of using pH paper to measure the ‘real’ pH.

Figure AppA3: A BBN handling hierarchical uncertainty.

<table>
<thead>
<tr>
<th>tube site</th>
<th>pH</th>
<th>pH paper</th>
</tr>
</thead>
<tbody>
<tr>
<td>lung</td>
<td>74.4</td>
<td>6.98</td>
</tr>
<tr>
<td>stomach</td>
<td>25.6</td>
<td>93.0</td>
</tr>
</tbody>
</table>

As shown, the observation of a high pH based on pH paper leads to an increase in the prediction of lung, from the original 50% to 74.4%. The magnitude is however smaller when the information is in terms of the real pH (80%, bottom panel, Fig. AppA1). The difference reflects the impact of the
uncertainty in information, or the value of certainty in information. BBNs demonstrate that how pH paper first leads to a partial update in the real pH (‘pH’), and then an update in the tube site.

Using Eq.5, we have

\[
LR(pH_{paper} > 5) = \frac{P(pH_{paper} > 5 | pH > 5)}{P(pH_{paper} > 5 | pH \leq 5)} = \frac{.80}{.10} = 8
\]

and

\[
P(\text{stomach}|pH_{paper} > 5) = \frac{.5 \times 1 + 1 \times (8 - 1)}{1 + 0.25 \times (8 - 1)} = \frac{8}{2.75} = 2.91
\]

, which is exactly the ratio of 74.4% and 25.6% (Fig. AppA3).

The key thing here is that when more than one layer of uncertainty is involved, the computation of posterior odds becomes complex – they no longer have a straightforward relationship with prior odds and the likelihood ratios. It follows that we cannot investigate the impact of likelihood ratios and prior beliefs in the same way as before. The capacity of BBNs for handling such cases with ease however allows us to gain unique insights into the reasoning process when the reliability of evidence is in doubt.

As a final remark, in reality, we often consider more than two competing hypotheses at once. To use the odds-likelihood ratio formulation, we first convert such cases into binary ones. This is the method used in this investigation. A blindly inserted tube can be in the lung, stomach, oesophagus or intestine. To select tests that are most effective at discerning the tube site, we divide the problem into multiple stages – first between lung and elsewhere (i.e. not lung or ¬lung), and then between oesophagus and non-oesophagus (¬oesophagus). The assumption is that a test should be able to detect lung intubation as the priority, followed by to detect oesophagus intubation and at last to confirm whether the tube is in the right place. This assumption is based on experts feedback elicited during decision workshops held for the project (see the section on Expert Consultation).
Appendix B  Making decisions

BBNs are powerful tools of assessing uncertainties. However, the decision of whether or not to feed depends not only on probabilities of different tube sites but also on consequences of feeding versus no feeding in each tube site. For instance, BBNs might predict stomach to be the most likely tube site; this alone cannot justify feeding because feeding into the lung could have disastrous consequences. In decision analysis, we make decisions by comparing the expected values (EVs) of alternative courses of action, expressed as the sum of the value of each possible outcome of an action weighted by the chance an outcome takes place (von Neumann & Morgenstern, 1944). One action is preferred to another if it generates higher expected value.

This Appendix develops decision strategies of how to choose between feeding versus no feeding. We start by discussing a case where (1) a tube is believed to be either in the oesophagus or stomach with the probabilities of \(P(\text{oesophagus})\) and \(P(\text{stomach})\), respectively, and (2) the alternative courses of action are either ‘feeding’ or ‘no feeding’. The following table summarizes this decision:

<table>
<thead>
<tr>
<th>Alternatives</th>
<th>Oesophagus (P(\text{oesophagus}))</th>
<th>Stomach (P(\text{stomach}))</th>
</tr>
</thead>
<tbody>
<tr>
<td>Feeding</td>
<td>(F_E)</td>
<td>(F_S)</td>
</tr>
<tr>
<td>No Feeding</td>
<td>(N_{FE})</td>
<td>(N_{FS})</td>
</tr>
</tbody>
</table>

Here, \(F_E\), \(F_S\), \(N_{FE}\) and \(N_{FS}\) denote the value of the outcome when the row action is taken given that the column tube site is true. For instance, \(F_E\) is the value of feeding into the oesophagus, and \(N_{FS}\) is the value of no feeding in the stomach. As noted, all values in decision analysis are measured on interval scales, meaning that the definition of 0 point on the scale is arbitrary. Conventionally, outcome values are non-negative, and the higher the value, the more desirable an outcome is. For stomach, feeding is more desirable than no-feeding and the reverse is true for oesophagus. Thus, although we do not know the exact value of the four outcomes, we know that \(F_S\) must be larger than \(N_{FS}\) whereas \(N_{FE}\) must be larger than \(F_E\). This means that \(F_S-N_{FS}\) as well as \(N_{FE}-F_E\) are both positive.

The expected value of feeding and that of no feeding is given by:

\[
EV(\text{feeding}) = F_E P(\text{oesophagus}) + F_S P(\text{stomach})
\]

\[
EV(\text{no feeding}) = N_{FE} P(\text{oesophagus}) + N_{FS} P(\text{stomach}).
\]

Feeding is preferred to No Feeding if \(EV(\text{feeding}) > EV(\text{no feeding})\), or

\[
\frac{F_S - N_{FS}}{N_{FE} - F_E} > \frac{P(\text{oesophagus})}{P(\text{stomach})} \tag{6.1}
\]
To see what this means, the left-hand-side of Ineq.6.1 is the ratio of two value differences; the right-hand-side is the ratio of two probabilities. The value difference in the nominator, i.e. $F_S - NF_S$, can be interpreted as the benefit of feeding over no feeding given stomach; and the value difference in the denominator, $NF_E - F_E$, can be interpreted as the benefit (or the reduction in the cost) of no feeding over feeding given oesophagus. The right-hand-side is the *probability odds favouring oesophagus over stomach*. Thus, Ineq.6.1 says that if we are not sure whether a tube is in the stomach or oesophagus, feeding is only preferred to no feeding if the ratio of the benefit of correct feeding over correct no feeding exceeds the odds of tube misplacement.

Note that the outcome values of feeding and no feeding in stomach and oesophagus are fixed. Hence whether the inequality holds true or false depends entirely on the probability odds. Suppose we can perform a test to learn more about tube sites. Before we know the result of this test, the probabilities are *prior probabilities* that reflect the initial distribution of the tube sites. After we know the result, however, these probabilities become *posterior probabilities* and the odds become *likelihood ratios*, as in

$$\frac{F_S - NF_S}{NF_E - F_E} > \frac{P(\text{oesophagus|test \_ finding})}{P(\text{stomach|test \_ finding})} \quad (6.1')$$

Thus, 6.1’ says that the higher the likelihood ratio that favours oesophagus over stomach, the less likely feeding will be recommended. As Appendix C shows, a test is only worth performing if its finding can be used to recommend feeding. Thus, we can use the likelihood ratios to select tests, that is, as long as we can identify the two competing tube-sites that we want the tests to discriminate.
Appendix C  Test assessment

We can assess tests by comparing the expected values of the decisions made in light of their findings. The basic idea is that the better a test is, the higher the expected value of the decisions (feeding and no feeding) made under the findings of this test will be. This expected value is the smallest if a test is non-diagnostic, in which case the decisions are essentially made under no information. For safety reasons, no feeding should be the default decision in such cases (the first row of Table AppC1). By contrast, this expected value is the highest if a test provides perfect information. Using a test like this, we are able to identify and feed all patients with the tube correctly placed in the stomach (the second row of Table AppC1). Correctly interpreted x-rays is one such ideal test. Any other test or their combinations generate expected values that lie in between these two extremes (the third row of Table AppC1), in which case the decisions should be made based on an assessment of the values versus probability odds (Appendix B).

Table AppC1. Decisions made under no information, perfect information and imperfect information.

<table>
<thead>
<tr>
<th>Decisions</th>
<th>Stomach</th>
<th>Lung</th>
<th>Oesophagus</th>
<th>Intestine</th>
</tr>
</thead>
<tbody>
<tr>
<td>No information</td>
<td>No feeding</td>
<td>No feeding</td>
<td>No feeding</td>
<td>No feeding</td>
</tr>
<tr>
<td>Perfect information</td>
<td>Feeding</td>
<td>No feeding</td>
<td>No feeding</td>
<td>No feeding</td>
</tr>
<tr>
<td>Imperfect information</td>
<td>Feeding only if certain conditions are met</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

(Ineq.6.1', Appendix B).

Denote the prior probability of a certain tube site \(X\) by \(P_X\) and the outcome value of feeding (no feeding) given this tube site by \(F_X (NF_X)\), where \(X\) can be \(S\) (stomach), \(L\) (lung), \(E\) (oesophagus) and \(I\) (intestine). The expected value of the decisions made with no information \((EVwNI)\) and that of the decisions made with perfect information \((EVwPI)\) are therefore:

\[
EVwNI = P_S NF_S + P_L NF_L + P_E NF_E + P_I NF_I \\
EVwPI = P_S F_S + P_L NF_L + P_E NF_E + P_I NF_I
\]  

(7)

The expected value of perfect information \((EVPI)\) is their difference, or:

\[
EVPI = EVwPI - EVwNI = P_S (F_S - NF_S)
\]  

(8)

Here, \(P_S\) is the prior probability of stomach, i.e. the maximum proportion of patients that can potentially receive feeding. As noted in Appendix B, \((F_S - NF_S)\) is the benefit of feeding over no feeding given stomach. Thus, the value of x-ray is equivalent to the maximum expected value of a correct decision given stomach.
It is worth noting that this value does not take into account the costs of performing an x-ray, nor the risks of ionizing radiation patients might be subject to. To justify the use of x-ray, this expected value (Eq.8) must exceed the sum of these costs as measured on a common scale.

**Value of imperfect information**

Other than correctly interpreted x-rays, tests can only provide imperfect information as to tube sites. To assess the value of a test, imagine we face a decision of whether or not to use the test in order to decide to feed. As discussed, the default decision is no feeding, which happens when we use no tests and therefore having no additional information in terms of tube sites other than the prior distribution. This also means that unless one or more findings of the test can increase the chance of stomach intubation and potentially justify feeding, this test would be worthless. We refer to such findings as **positive**, denoted as finding, in contrast to **negative** findings, denoted as ¬finding, which do not increase the chance of the stomach. For instance, suppose we use a pH test with cut-off of 4. Any pH equal to or lower than 4 is positive (refer to Table 1) and any pH greater than 4 is negative. The expected value of not using any test is given by EVwNI, which in this case is:

\[
EVwII = P(\text{finding})EV(\text{feeding} | \text{finding}) + P(\text{¬finding})EV(\text{no feeding} | \text{¬finding}),
\]

where

\[
EV(\text{feeding}) = P(\text{stomach} | \text{finding})F_S + P(\text{lung} | \text{finding})F_L + P(\text{oesophagus} | \text{finding})F_E + P(\text{intestine} | \text{finding})F_I, \text{ and}
\]

\[
EV(\text{no feeding given ¬finding}) = P(\text{stomach} | ¬\text{finding})NF_S + P(\text{lung} | ¬\text{finding})NF_L + P(\text{oesophagus} | ¬\text{finding})NF_E + P(\text{intestine} | ¬\text{finding})NF_I.
\]

Bayes’ theorem predicts that \( P(\text{finding})P(\text{stomach} | \text{finding}) = P(\text{stomach} & \text{finding}) \) and \( P(¬\text{finding})P(\text{stomach} | ¬\text{finding}) = P(\text{stomach} & ¬\text{finding}) \). To facilitate interpretation, we rewrite \( EVwII \) as the sum of four terms, \( A + B + C + D \), where

\[
A = P(\text{stomach} & \text{finding})F_S
\]

\[
B = P(\text{lung} & ¬\text{finding})NF_L + P(\text{oesophagus} & ¬\text{finding})NF_E + P(\text{intestine} & ¬\text{finding})NF_I
\]

\[
C = P(\text{lung} & \text{finding})F_L + P(\text{oesophagus} & \text{finding})F_E + P(\text{intestine} & \text{finding})F_I
\]

\[
D = P(\text{stomach} & ¬\text{finding})NF_S
\]

We can present them in a 2x2 contingency table as in Table AppC2.

As shown, \( EVwII \) consists of four values, each being the product of the joint probability of the row finding and the column tube site and the corresponding outcome value given the row decision and the column tube site. So we can say that a test is valuable because it maximizes the expected value of correct feeding \( (A) \), maximizes the expected value of correct non-feeding \( (B) \), minimizes the expected cost of false positives \( (C) \) as well as minimizes the expected cost of false negatives \( (D) \). Since the outcome values \( (F_X \text{ and } NF_X) \) are independent of the tests, the difference in \( EVwII \)s can be attributable entirely to the discrepancies in the joint probabilities.
Table AppC2. A breakdown of the expected value of decisions made under Imperfect information

<table>
<thead>
<tr>
<th>Finding</th>
<th>Decision</th>
<th>Actual tube site</th>
<th>Stomach</th>
<th>¬Stomach</th>
</tr>
</thead>
<tbody>
<tr>
<td>Finding</td>
<td>Feeding</td>
<td>A</td>
<td>C</td>
<td></td>
</tr>
<tr>
<td>¬finding</td>
<td>No feeding</td>
<td>D</td>
<td>B</td>
<td></td>
</tr>
</tbody>
</table>

We can further simplify the expression by combining $A$ and $D$, as well as $C$ and $B$. This is because the sum of the joint probabilities in $A$ and $D$ must be $P_S$, and the sum of the joint probabilities in $C$ and $B$ must be $P_{¬S}$, or the sum of the probabilities of lung, oesophagus and intestine, or $P_L + P_E + P_I$. Rewrite the joint probabilities as the product of prior and conditional probabilities; EVwII becomes:

$$P_S [NF_S + P(finding | stomach)(F_S - NF_S)] + P_L [NF_L + P(finding | lung)(F_L - NF_L)] + P_E [NF_E + P(finding | oesophagus)(F_E - NF_E)] + P_I [NF_I + P(finding | intestine)(F_I - NF_I)].$$

(9)

Since EVwII must be smaller than EVwPI, we can assess a test by computing the expected advantage of x-ray over a certain test, which is simply the difference between Eq.7 and Eq.9 as in

$$P_S (F_S - NF_S) [1 - P(finding | stomach)] + P_L (NF_L - F_L) P(finding | lung) +$$

$$P_E (NF_E - F_E) P(finding | oesophagus) + P_I (NF_I - F_I) P(finding | intestine).$$

(10.1)

Here, $P_S (F_S - NF_S)$ is essentially the maximum expected benefit of a correct decision given stomach, and we denote this as $EB(stomach)$. Similarly, we define $EB(tube site)$ as $P_X (NF_X - F_X)$, where $X$ is either lung ($L$), oesophagus ($E$) or intestine ($I$). Insert this into Eq.10.1, we have

$$EB(stomach)[1 - P(finding | stomach)] + EB(lung)P(finding | lung) +$$

$$EB(oesophagus)P(finding | oesophagus) + EB(intestine)P(finding | intestine).$$

(10.2)

X-ray as the gold-standard has the highest expected value of information; thus Eq.10.2 must be positive. For a given test, the greater (smaller) the advantage of x-rays, the less (more) valuable the test is. Holding the expected benefits constant, i.e. $EB(tube site)$, this advantage is smaller if $P(finding | stomach)$ is larger or if any of the $P(finding | ¬stomach)$s is smaller; $P(finding | stomach)$ is the sensitivity of a test, and $P(finding | ¬stomach)$ is 1-specificity of a test. Eq.10.2 confirms our intuition that the higher the sensitivity and specificity of a test, the more valuable it is. The more sensitive a test, the fewer correct feeding it misses, the more specific a test, the fewer incorrect feeding it recommends.
Appendix D Search terms

All incidents from ART_C.CLEAN since inception of reporting to The Reporting and Learning System in October 2003

WHERE

Created date is less than or equal to 28 February 2009

AND

Incident date, reporting date (createddt) and Exportdt are all greater than or equal to 01 January 2003

AND

Care setting is Acute/General Hospital OR Community nursing, medical and therapy services (Incl. Community Hospital) OR Mental Health Service

AND

(Either Incident Category level 1 is Clinical assessment (including diagnosis, scans, tests, assessments) OR Documentation (including records, identification) OR Implementation of care and ongoing monitoring/ review OR Medical device/equipment OR Medication OR Treatment, procedure OR Incident category level 2 is Discharge - delay/failure OR Extended stay/ episode of care

AND

Incident location level 1 is Community hospital OR General/ acute hospital OR Mental health unit/ facility

AND

Freetext fields (IN07, IN10, IN11 and IN05_TEXT) are searched for keywords: “Nasogastric tube” OR “Naso-gastric tube” OR “NG tube” OR “Feeding tube” OR “Enteral nutrition” OR “Enteral feed” OR “Tube insertion” OR “tube placement” OR “Tube misplacement” OR “tube malposition” OR “Fine-bore tube” OR “Ryles tube”
## pH misinterpretation narratives – NRLS database

<table>
<thead>
<tr>
<th>IN07 Description of what happened</th>
<th>IN10 Actions Preventing Reoccurrence</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 Obtained aspirate from NG tube, reaction registered pH 1.5. Commenced to give medication via tube and noted pt was gagging then fluid came from mouth. Stopped giving medication checked NG positioning only at 26cm</td>
<td>Dietician team informed of incident They are looking at a better quality pH paper to test the appropriate decision to be made by team whether to go back to x-ray post insertion of tube again. Medications given at 22.00, 8.00, 12.00 hrs IV antibiotics started at 14.00hrs IV fluids started at 15hrs Unable to restart NG feeding this afternoon as feed could not be found. Blood stained fluid aspirated from NG tube prior to setting. Tube not used. NG tube placement now confirmed by aspirate pH. Patient reviewed by SHO and Chest x-ray arranged Check x-ray confirmed tube in wrong place Concurrently situated in right main bronchus Nursing staff informed and tube removed immediately.</td>
</tr>
<tr>
<td>2 NG tube placed on day of admission to ward 10.12.07. pH indicated 'ok' 5.5. Feed set up 19hrs as 10/12/07 Feed tolerated until 23.00hrs felt nauseated and retching - refused to continue. Patients chest was x-rayed. Noted NG feeding tube appeared to lie in the right lung base not the stomach where it should have been. There were other abnormal appearances to the right lung base suggesting aspiration</td>
<td></td>
</tr>
<tr>
<td>3 Checked pt nasogastric tube prior to feeding. Aspirate pH was 5 and the marker pen line was clearly visible, hence we proceeded to flush the tube. On starting to flush the tube, pt began to cough so we stopped and he stopped coughing. We then whoosh tested the tube because we were unhappy to carry on using it. The whoosh test failed so we didn’t continue to use the tube. Eventually managed to get pt to open his mouth the tube could be seen curled over in the back of his throat. Despite following the trust protocol for Nasogastric tubes, pt tube was not safe to use.</td>
<td></td>
</tr>
<tr>
<td>4 Pt transferred from ITU 3/7/07. Feeding had been in progress via a wide bore NG tube for &gt; 24 hours. Prior to commencing the feed in ARC the tube was aspirated and fluid was pH 5.0. Pt complained of discomfort from the tube. Therefore I removed tube to find very little was in pt. My concern was that the tube had changed position from time of testing and commencing the feed on the previous evening to its removal, and potential for aspiration of fluid present.</td>
<td></td>
</tr>
<tr>
<td>5 When giving pt his medication staff aspirated his NG tube prior to administering his medication and gained a pH of 1.5 NG position was then marked with a permanent marker and medication given. There had been no sign that NG had moved prior to this. When pt was reviewed by neuroanatomists due to worsening medical condition, he sited a guerdal airway and stated that</td>
<td></td>
</tr>
</tbody>
</table>
it looked like it was at the back of his throat. Aspirate was obtained from the NG, it had a pH of 4.0 aspirate and had a pink colour. The anaesthetist repeated that it looked like it was in the back of his throat. It had not looked displaced, it may have been dislodged when pt had had yanker suction and nasopharyngeal suction.

| 6 | This patient had a nasogastric tube inserted during the night of the 08.07.06. The tube was a 'silk' tube that requires 10 mls of water to be passed prior to removing the stylet. After this had been removed aspirate was obtained from the tube and the pH was 4.5. According to the protocol this allowed staff to commence a nasogastric feed and to give medication. Despite this staff were unhappy to feed the patient as there were problems passing the tube. He also had an existing chest infection which made them cautious about starting the feed without an x-ray. He did not appear to be in additional respiratory distress after the insertion of the tube. His O2 saturation was 94%. A chest x-ray was carried out in the afternoon of the 09.07.06 and the x-ray showed that the tube was in the right lung. Nothing had been given by the tube due to the nurses concern. The nurses have also expressed concern that the water used to flush the tube has a pH of 4.5 and according to the protocol the patient could have been given the feed. |
| 7 | NG tube aspirated before giving drugs and flush. <1ml fluid obtained, but pH=5.0. 165ml water and drugs given. Patient began to cough violently then NG tube came up into mouth. Signs of aspiration into lungs. SHO informed and advice given. |
| 8 | NG tested by taking aspiration and testing with pH, received results pH=5.0 on 2 occasions. O2 SATs monitored continuously as requested, when problems noticed with feed being suctioned from patient’s mouth, feed was stopped immediately. Chest x-ray requested and NG tube removed when found to be in right lung. reported to Clinical Governance Manager - advice sought re potential service incident. All pH test strips on Clandon removed to await advice re accuracy testing (not user error) Advice sought from microbiology re potential of co-existing pathology and infection giving pH level recording. Report incident to national body as per NPSA alerts for nasogastric tube events. Continue investigation re pathology / infection altering aspirate Root cause: not yet ascertained. |
| 9 | Patient had NG tube passed - condition deteriorated. Reviewed by medical SpR, x-ray performed - NG tube in bronchus not stomach . . Patient had NG tube passed - condition deteriorated. Reviewed by medical SpR, x-ray performed - NG tube in bronchus not stomach . . NPSA=feeding into lungs via NG tube said to be post pH=5.5 but ?After aspiration of vomit |
| 10 | Fine bore nasogastric tube placement in right lung (placed on Max Fax ward) on chest x-ray through which 700mls of feed had been passed. NG Tube removed resus commenced. Pt deteriorated and died. NPSA : pH interpreted wrongly "acidic" used on report rather than 5.5 |
### X-ray misinterpretation narratives – NRLS database

<table>
<thead>
<tr>
<th>IN07 Description of what happened</th>
<th>IN10 Actions Preventing Reoccurrence</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 NG feeding started on pt despite check X-Ray clearly showing - tube in wrong place. Feeding started with water &amp; stopped when pt began coughing. Nursing notes sat CXR 'checked by house office on call - confident NG tube in correct place'.</td>
<td></td>
</tr>
<tr>
<td>2 CRN [Number] Patient had NG tube sited for NG feeding in accordance with management of decompensated liver failure. Nursing staff were unable to aspirate from tube therefore check x ray was performed. No documentation of X ray being reviewed in medical notes although nursing NG pathway has documentation of medical review. NG feeding was therefore commenced however patient began to cough and felt it was related to feed therefore feed terminated. On review the following morning the CXR of ng tube clearly not in oesophagus but L main bronchus, follow up CXR shows evidence of consolidation in the Left lower zone.</td>
<td></td>
</tr>
<tr>
<td>3 Pt re-intubated at 21.05 by Anaesthetic SHO as in respiratory distress, fine bore ng tube inserted past intubation, ICU SHO called Anaesthetic SHO to assess placement of NG on CXR, written in notes that the CXR reviewed by Anaesthetic SHO who assessed NG tube as in place, at 03.30 02 stats down noted noisy air entry L.side at 08.00 reviewed by ICU Consultant who identified that in fact the NG tube was in the L.lung - feeding had been commenced, enteral feed in lung, feed stopped urgent bronchoscope. Incorrect interpretation of X-ray, X-ray clearly shows tube not below diaphragm.</td>
<td></td>
</tr>
<tr>
<td>4 PATIENT WAS ADMITTED FROM WARD 14 ON 8 / 11 / 07 AT 22 HRS IN ITU. SOON AFTER ADMISSION TO ITU HE WAS INTUBATED AND VENTILATED. NASOGASTRIC TUBE WAS INSERTED BY DR [Staff Name]. CHEST XRAY WAS TAKEN. SISTER [Staff Name 2] WAS INFORMED BY DR [Staff Name] THAT POSITION OF NASOGASTRIC TUBE WAS CORRECT AND NOT TO START FEEDING OVERNIGHT. NURSING DOCUMENTATION CONFIRMS THIS BUT NO MEDICAL DOCUMENTATION COMPLETED. THE PATIENT HAD ANOTHER XRAY AT 10 AM FOLLOWED BY CT SCAN AT 2 PM. FEEDING WAS STARTED AT 35 ML AT 5 PM BY STAFF NURSE [Staff Name 3]. SISTER [Staff Name 4] WAS RELIEVING STAFFNURSE [Staff Name 3] FOR HER EVENING BREAK WHEN THE PATIENT STARTED DESATURATING TO 88 TO 90 %. ON SUCTION THERE WAS EVIDENCE OF FEED IN THE SUCTION TUBING. FEED STOPPED IMMEDIATELY. MYSELF SISTER [Staff Name 5] ) AND ITU REG DR [Staff Name 6] WAS INFORMED. THE PATIENT WAS BAGGED AND SUCTIONED BY DR [Staff Name 6] AND STAFF NURSE [Staff Name 3] AND PATIENT SPO2 IMPROVED TO 95%. THE PREVIOUS TWO CHEST XRAY WAS REVIEIVED AND ALL SHOWED THE POSITION OF THE NASOGASTRIC TUBE IN THE RIGHT LUNG. THE NG TUBE WAS IMMEDIATELY REMOVED.</td>
<td></td>
</tr>
<tr>
<td>5 On checking pt NG tube - unable to aspirate. NG feed stopped - CXR checked - NG tube not in stomach in left lung. SHO had seen XRay and had confirmed placement overnight. Pt received 25 mls of deia overnight.</td>
<td></td>
</tr>
<tr>
<td>Page</td>
<td>Text</td>
</tr>
<tr>
<td>------</td>
<td>------</td>
</tr>
<tr>
<td>6</td>
<td>Phoned SHO to check position of NG tube on xray. He was happy that it was below diaphragm and that I could use it. He then had to go on a transfer to RSCH. We had another critical patient that was keeping us busy. I gave Zopiclone with 70 mls of sterile water down the NG tube at 10pm and commenced his feed. The patient was agitated (head injury) and normally wears a boxing glove to stop him from pulling at his lines (hence the renewal of yet another NG tube). He wanted to have his bowels opened. I turned and checked him and cleaned him up. Passed a large solid stool. Initially I thought this was causing him to become more agitated, increase in respiratory rate, excessive secretions (blood stained), tachycardia and change in colour. The Registrar was busy with a bradycardic patient on the ITU and Maternity was waiting for her.</td>
</tr>
<tr>
<td>7</td>
<td>Patient required enteral feed via nasogastric tube. Placement of tube checked by x-ray prior to commencing feed. Enteral feed given via nasogastric tube. Patient condition deteriorated. Tube was found to be displaced, in the left main bronchus. Patient aspirated enteral feed.</td>
</tr>
<tr>
<td>8</td>
<td>This patient had a NG tube inserted for feeding – she underwent an x-ray to check whether the tube was intragastric or not. The Doctor on call (Dr [Staff Name]) checked this and felt it was satisfactory – feeding was commenced – patient had a respiratory arrest – had about 40ml of feed – Needed intubation and ventilation (X-ray reported by consultant radiologist Dr [Staff name2] as NG being in chest (endo bronchial). Feed was stopped immediately – prompt medical attention – feedback to be given to Dr [Staff Name] completed Mr [Staff name3] to talk to patient once improved.</td>
</tr>
<tr>
<td>9</td>
<td>NG Tube inserted by SN. [name], checked by on call medical team and informed by Bleep 500 Mat. NG in place to commence feed. Patient became unwell. Sats down, Pulse Up, BP down, NG discontinued. Medic's renewed. Seen by night HO advised to remove xray rechecked by Dr, NG in lung.</td>
</tr>
<tr>
<td>10</td>
<td>Unexpected outcome of treatment.</td>
</tr>
<tr>
<td>11</td>
<td>Sister[Staff Name] - Dr who reviewed CxR[Staff name2]. Discussed with Dr [Staff name3] / Consultant responsible for Mr[Patient name], I am satisfied that SN [Staff name4] followed correct procedure and acted promptly when Mr [Patient name] health began to deteriorate. - Dr [Staff name5] has investigated and written response.</td>
</tr>
<tr>
<td>12</td>
<td>Unexpected outcome of treatment.</td>
</tr>
<tr>
<td>12</td>
<td>[Patient name] had Nasogastric tube inserted by Burns ICU nurse. Chest x-ray taken to confirm position of NG tube. X-ray reviewed by ICU trainee doctor - permission given to commence feeding. Patient respiration deteriorated over following hours. Reviewed and re-x-rayed by Myself and Dr [Staff Name]. X-ray showed NG tube in R side of chest - along with new pneumonic changes. NG tube also seen in chest from previous x-rays.</td>
</tr>
<tr>
<td>13</td>
<td>Nursing staff has asked me to check Xray position of fine bore NG tube, kindly placed by nursing staff on 23 / 02 / 2007. [Patient name] had few NG tubes replaced over last 2 weeks. I checked CXR of [Patient name] dated 18 / 02 / 2007 - I did not realise that it was not the latest CXR (23 / 02 / 2007). On CXR dated 18 / 02 / 2007 fine bore tube was in correct position. I have given the indication that NG tube is in right place and OK to use. Retrospectively, on 24 / 02 / 2007, I looked at CXR of [Patient name] dated 23 / 02 / 2007 - the NG tube was in right bronchus. Misplacement of NG tube was noted on 23 / 02 / 2007, about 4 hours later and it was removed. Clinical course of [Patient name] recovery has shown that he hasn't had any significant damage to lungs secondary to misplaced NG tube.</td>
</tr>
<tr>
<td>14</td>
<td>Patients NG tube fell out. NG tube replaced. Chest X-ray confirmed in incorrect place therefore tube removed. Another NG tube inserted. Chest x-ray carried out. Dr informed nurses tube is in correct position and to start NG feed. Feed commenced. Patient respiration deteriorated. Reviewed by Dr who realised NG tube is in incorrect place. This incident will be used as education and a change in the practice on the unit. No verbal orders will be carried out by a nurse unless documented in the patients note.</td>
</tr>
</tbody>
</table>
X-Ray report delivered to ward stating that NG tube was in the Bronchus and that it had been phoned through . . Feed stopped and awaiting review by on call . Informed by Night Staff that HO took phone call on Friday 13 / 10 and felt that NG was appropriately placed and feed could start as documented in case notes .

High respiratory rate noted breathing noted to be more erratic . Checked ventilator , found to be ok , then went to suction patient and on suctioning found to have loose creamy secretions noticeably feed like in consistency . Feed stopped straight away . ICU SPR informed came to see . Looked at CXR , ordered another CXR . Reviewed by RSO cardiac surgery , reported the NG Tube to be in Right Lung and was subsequently removed . Patients earlier CXR had been seen on ward round and noted that it was in the correct place and informed to commence feeding . The patient had in total 3 hours feeding running at 10 ml . / Hr .

Investigated as a SUI . Please see Datix Report 70988.

It was identified that patient NG Tube was not in the correct place which had been previously reported as normal by Radiology .

Incident passed to Dr [Staff Name] , Clinical Director for review and Investigation 18 / 05 / 06 Full root cause analysis being lead by GF ( Surgery ) . 05 / 06 / 07 - Root cause analysis completed and reported to CD and MD and R&CG Manager . Please see attached Root Cause Analysis document ( SG 05 / 06 / 07 ) .

The patient was transferred from the North Middlesex Hospital to the intensive care unit at St Thomas ' Hospital on 23 / 6 / 06 with a diagnosis of an infective exacerbation of COPD . She was intubated , ventilated and had a surgical tracheostomy performed on 30 / 6 / 06 . On ICU , her respiratory condition improved , she was weaned off the ventilator and transferred to Victoria HDU on 9 / 7 / 2006 . She was self ventilating via a tracheostomy tube . On Victoria HDU , she continue to be weaned off respiratory support and had had her tracheostomy tube downsized . She was nil by mouth and was fed naso - gastrically . On the night of 14 / 7 / 06 , the patient pulled out her naso gastric tube twice . At 10 am on 15 / 7 / 06 , the naso gastric tube was reinserted with significant difficulty which was exacerbated by the patient agitation . The nurse ( quote - see nurse statement)'deflated the tracheostomy tube cuff with intent to minimise potential oesophageal obstruction and to maximise the efficiency of the patient swallow ' . The nurse stated that the patient did cough on insertion of the NG tube but settled quickly . The nurse was unable to pass the NG tube further than 49 cms and was unable to obtain any NG aspirate . The nurse was concerned about the position of the naso gastric tube and the decision was made by the senior staff on the unit to perform an X-ray as per unit protocol . No fluids or drugs were given via the NG tube until the position was checked on X-ray by the medical team - as per unit protocol . The chest X-ray
was performed and reviewed by the RMO. The RMO was satisfied that the NG tube was positioned in the patient stomach and this was documented in patient notes at 13:05. The patient was given water and her 8am drugs down the NG tube and then was commenced on naso gastric feed at 90mls per hour. At this stage the patient saturations were 96%. New antibiotics had been prescribed and these were given down the NG tube at 14:00. During insertion of these drugs, the patient coughed. This caused concern to the nurse and to the daughter who was visiting but as the tube had been cleared on X-ray and the patient stopped coughing, the nurse completed the administration of the medication. This was followed by the patient having a bout of coughing. The nurse stopped any fluids via the NG tube and informed the nurse in charge. The patient condition deteriorated - she had blood stained fluids on suctioning and she dropped her saturations requiring CPAP and increased FIO2. The NG tube was removed by the nursing staff whilst waiting for the RMO to review the patient. The nurse auscultated the chest and found diminished breath sounds over the right lung. The ECG cables had misled the RMO. The patient daughter was with her during the day and was informed of the misplaced NG tube.

| 19 | Changed patients feed from water to multifibre as prescribed. Shortly afterwards suctioned the patients secretions, looked like light coffee grounds. Patients O2 saturation decreased and appeared distressed. Further suctioned. Catheter appeared to be full of Nasogastric feed. Informed Dr who came and saw the patient. The Nasogastric tube had been inserted on a previous shift and had been -rayed, and the X-ray had been checked. Dr rechecked the X-ray, NG tube in bone of right lung. NG tube removed. |
| 20 | Received pt with NG tube. CXR was done and reviewed by Dr X. I was told by her that NGT is in right place. At 15.00 hrs feeding started. At 16.30 hrs doctors managing pt came and reviewed the CXR and I was told the NGT is in the lung. |
| 21 | Patient returned from theatre. X-rayed for line and nasogastric (NG) tube position. NG tube at 30cms. Doctor on duty reviewed the x-ray and said the NG tube could be used. Tacrolimus, mycophenolate and senna given via NG tube. A further member of staff reviewed the x-ray and said the NG tube was unsuitable for usage. |
| 22 | Feeding NG tube inserted 22/10/05 CXR - right bronchus - tube removed and resited. CXR 23/10/05 - checked by HO (not recorded in medical notes) but in nursing notes. Happy to feed. Blood and sputum aspirated by nursing staff prior to feeding at 13:00hrs. S/b Doctor feed to start. 18:00hrs became acutely unwell. Tube fed into lungs. This incident has been referred to a learning panel within clinical governance team and awaiting for this to occur. |
| 23 | A thin feeding tube was inserted which is not possible to aspirate from and its position was checked by x-ray. As the ECG/leads were left on the patient while x-ray was taken the feeding tube was confused with one of them and nutrition was started and given to her lungs, unfortunately. |
| 24 | New fine bore Ng tube passed 14.30. CXR done & position confirmed by Dr [Staff Name]. Multifibre feed 65mls per hour commenced at approx 16.30. 17.30 k+ on ABG analyser 3.3 - Sandol x 2 given as prescribed on administration. Sats down 78%, BP raised, heart rate irregular. |
| 25 | Medical SHO asked by nursing staff to review patient chest x-ray and position of NG tube. SHO checked most recent x-ray assuming it to be the latest taken and confirmed tube in correct position and to commence feed. Re-contacted a couple of hours later by ward staff to say that patient coughing and dropping sats. SHO advised staff to stop feed immediately and re-checked x-ray by which time a further film was available showing NG tube in right main bronchus. SHO advised Registrar immediately. |

Update training plan Doctors training needed. No further information received despite contact with reporting organisation.
Appendix F  Scientific papers generated out of this project


   Appended as
   Clinical applications of BBN.pdf


   Appended as
   Checking procedures for Nasogastric tube insertion – systematic review.pdf