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GASTROESOPHAGEAL REFLUX 2D AND 3D STEADY STATE CFD SIMULATIONS

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ABSTRACT

Gastro-Esophageal Reflux Disease (GERD) is a condition which affects up to 20% of the adult US population on a weekly basis. It is a condition where acid is allowed to flow from the stomach and into the esophagus where it causes damage to the local tissue. In chronic cases the condition can lead to cancer. Dysfunction of the Esophagogastric Junction is indicated as a primary cause. The recently developed Functional Lumen Imaging Probe (FLIP) is designed for assessment of the EGJ. It measures the cross sectional area at eight locations through the junction. This data has been used to construct a series of computational fluid dynamic simulations. These simulations showed a jet of fluid which squirts into the esophagus under the gastric pressure. This jet corresponds with previously gathered anecdotal evidence. The centerline velocities of this jet were measured and this suggested that the jet could travel up to 20 times the minimum diameter of the EGJ into the esophagus before decelerating to 25% of its original velocity. This means that if an EGJ was curved then this jet could impinge on the walls causing a localized area of increased damage to the mucosa compared to the surrounding tissue.

INTRODUCTION

Gastro-Esophageal Reflux Disease (GERD) is a condition which affects up to 50% of the adult US population on a monthly basis and 20% on a weekly basis [1]. It is a condition where acid from the stomach is allowed to travel through the Esophagogastric Junction (EGJ) and into the esophagus. The esophageal mucosa does not benefit from the same protection against acidic damage that the gastric mucosa does. This means that as a result of reflux damage is caused to the cells and the symptom of heartburn is experienced. In most individuals, reflux events are infrequent. However in some cases the condition becomes chronic and this is congruent with an increased risk of cancer development. The condition is ranked as the 9th most common cause of malignancy and the 6th most common cause of cancer mortality worldwide [2]. The condition is primarily caused by a defective lower esophageal sphincter which forms part of the EGJ. Over 50% of all reflux events are thought to be caused by inappropriate relaxations of the sphincter [3,4].

Measuring the quantity of reflux which occurs during an event is difficult in vivo. The normal method of assessing reflux is to use an indirect indicator as a form of measurement. One such method is to measure the time duration for which the esophagus is exposed to acid at several sites along the length of the esophagus. These studies are done using probes which record the pH surrounding them. It has been shown using these techniques that patients with symptomatic GORD reflux events experience a longer duration of acid exposure and that the acid tends to reach higher into the esophagus [5]. It has also been demonstrated that reflux is likely to reach a higher level in the esophagus following a meal.

Despite the difficulties involved, several studies have attempted to determine the volume flow experienced during reflux. Aspiration studies cannot capture the magnitude of an individual reflux event, though it can collect volumes over a specified time period. Results from these studies show that during fasting 2-7ml of refluxate can be gathered per hour. Following a meal this can increase to 9-15ml per hour. The data also suggests that this volume flow is higher in patients with GERD than in control subjects [6][7][8]. Another method used High Frequency Intraluminal Ultrasonography (HFIUS) to evaluate esophageal distention caused by reflux. From the images produced the cross sectional area (CSA) can be calculated and this would be in proportion to the volume of reflux in the esophagus. From this method is has been shown that reflux provokes a luminal opening that is similar to that observed during a 5ml swallow [9].

The Functional Lumen Imaging Probe (FLIP), shown in fig. 1, is a device which has been developed specifically for measuring luminal opening and the competence of the EGJ [10]. It works on the principle of impedance planimetry where, given a constant current, the voltage measured between a pair of electrodes is inversely proportional to the cross-sectional area (CSA) between them. A standard probe has multiple electrodes and so can read the cross-sectional area at eight locations through the EGJ. These readings are taken simultaneously at a frequency of 10Hz, thus providing a real time display of how the CSA varies through the junction. In addition to the CSA measurements, a FLIP probe also features two ports used to measure pressure. One of these is located within the saline balloon which encases the electrodes; the other is located above the balloon on the probe stem and measures the pressure on the esophagus side of the probe. The main use of this port is to provide a comparison with the widely use method of esophageal manometry.

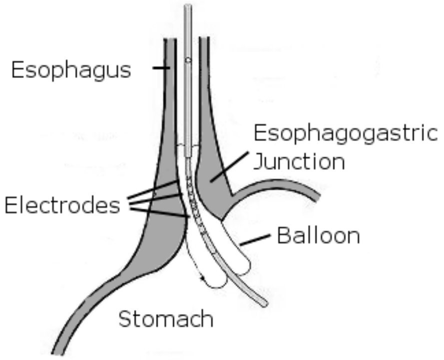

Fig. 1: a FLIP probe located with the esophagogastric junction, modified from McMahon et al [11]

In the last decade Computational Fluid Dynamics (CFD) has seen a rise in popularity within the medical sector. However, the majority of this interest is focused on the flow of blood through the arteries, the heart, and artificial hearts. The technique has so far seen very little application in the gastrointestinal system. With the advent of FLIP, data can now be gathered on the dynamic geometry of the EGJ and computational models of the flow through the junction can be constructed.

The objectives of this paper are to present a method for evaluating the flow through the EGJ. This will be done by using geometric data previously gather with a FLIP probe and using this to conduct a CFD simulation of the flow. Several of these simulations will be performed in order to investigate the effects of differing geometries and pressures.

METHOD

A number of FLIP studies have so far been performed on human volunteers [10][11]. A segment of one such study was selected as the basis for the computational models developed. This section was taken through a swallow sequence where the EGJ was seen to start tightly closed before opening up to a wide section and then closing off again.

By assuming that the CSA measured through the EGJ was circular throughout then it was possible to calculate the corresponding radii at each electrode location.

As can be seen from fig. 2 the raw data from the FLIP probe (blue line / circles) gives a very angular model of the EGJ. This is primarily due to the construction difficulties which limited the resolution of the probe used for the study. The EGJ itself, due to its nature, would not exhibit these angles and so it was necessary to smooth them out. For this a cubic interpolation method was used to add points between the existing ones. These points were added at intervals of 1mm and resulted in a much smoother profile through the junction (red line / diamonds of Fig. 2).

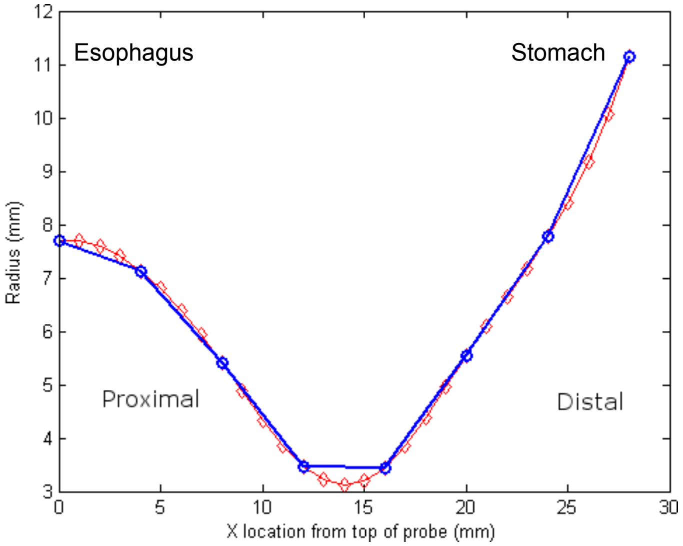

Fig. 2: Illustration of interpolated OGJ profile. Circles are original profile, diamonds are interpolated profile

With the FLIP data processed it could then be imported into a CFD simulation. In the case of the 2D studies this was done using the GAMBIT pre-processor which is included with the FLUENT CFD software. In these cases the FLIP data was used to create a curved wall offset from the x-axis. An axisymmetric condition was added along the x-axis, a pressure inlet was defined on the distal extent of the model, and a pressure outlet defined at the proximal extent to complete the domain [12]. This area was then meshed using a grid of cells with a spacing of 0.2mm. This grid was unstructured, meaning that it was generated automatically by the pre-processor and consisted of tetrahedral cells arranged throughout the problem in whatever manner best fit the geometry.

The FLIP data was also used in defining the pressure conditions. During the FLIP study the probe is inserted down the esophagus into the stomach where it stays for a short time before being pulled back up into position at the OGJ. The pressure data recorded in the balloon during this time can be used to define the inlet pressure conditions to the problem. This implied the use of a pressure of 1000Pa; however it was decided to also model stomach pressures of 400Pa, 600Pa and 800Pa in order to assess the effect of the pressure on the flow. The pressure on the outlet of the problem was defined as being at atmospheric pressure. The fluid domain was defined as a single phase consisting of water.

All the 2D simulations were performed in the FLUENT commercial CFD code using the standard k-epsilon turbulence model and the SIMPLE pressure-velocity coupling. The standard pressure discretisation scheme was used with first order upwind schemes employed for the momentum and turbulence parameters. Finally, convergence was judged to have occurred when the residuals dropped below $1e^{-5}$.

As well as the 2D simulations, a number of 3D simulations were also performed. The purpose of these simulations was to investigate the effects of individual features of the EGJ. In order to investigate these features in a controlled test, it is necessary to keep all other geometry parameters constant during the tests. Whilst the FLIP data is anatomically accurate, it cannot be controlled. To go a full analysis it was then decided to replace the EGJ geometry, acquired using the FLIP probe, with an artificial profile which was computer generated. This profile could then be changed as required to enable a large range of studies to be performed. An example of one of these geometries is shown in fig. 3.

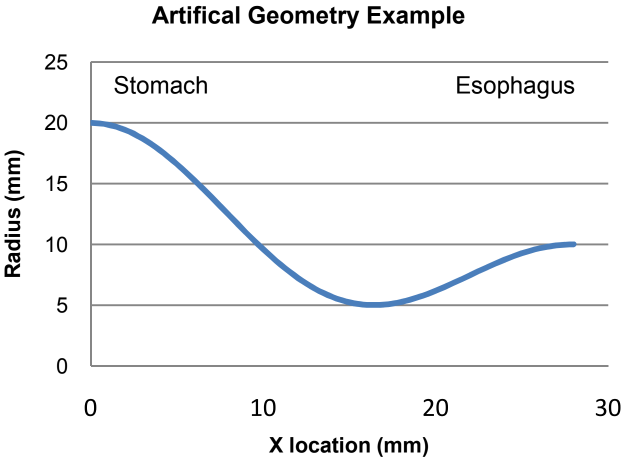

Fig. 3: Illustration of an artifical geometry with diameter 10mm

In addition to the way in which the walls of the problem were defined, changes were also made to the ways the boundary conditions were defined. Most literature on fluid dynamics defines flows in terms of the Reynolds number experienced at a defining location of the problem. In order to conform to this method the boundary conditions were specified as velocity inlets and velocity outlets. This meant that the Reynolds number at the point of minimum diameter could be controlled, thus allowing a better comparison with existing fluid dynamics literature. The use of velocity based boundary conditions as opposed to pressure conditions has the additional benefit of creating a more robust problem definition. This means that the convergence of results happens faster than with pressure conditions.

RESULTS

Once a solution has solved, the steady state simulations velocity contour and velocity vectors were plotted to illustrate how the flow varied through the EGJ. An example of one of these plots, highlighting the axisymmetry of the 2D model, is shown in fig. 4. In this plots, blue indicates areas of low velocity flow whilst red indicates areas of high velocity flow. The direction in which the fluid is moving at any point is indicated by the black arrows overlaid on the image; these are termed the velocity vectors.

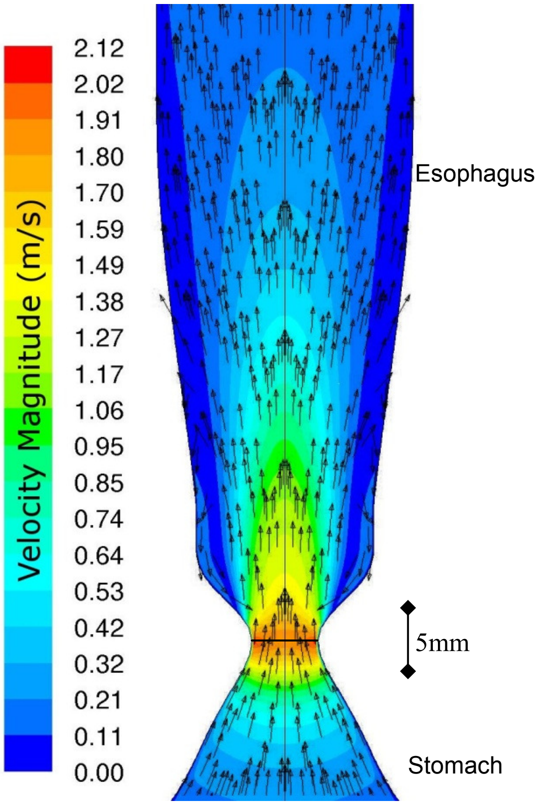

Fig. 4: Vector diagram of flow through 2d axisymmetric model ofthe EGJ

From fig. 4 it can be seen that the velocity accelerates as it approaches the point of minimum diameter. Once past this point, the velocity breaks away from the walls forming a jet of fluid that extends into the esophagus. Fig. 5 shows the velocity vectors for the 2D case where the minimum diameter is 4.8mm. This figure is concentrated on the area immediately above the point of minimum diameter. Indicated on this diagram is the point of separation where the flow breaks away from the wall and creates the jet. This occurs at about 2mm above the point of minimum diameter.

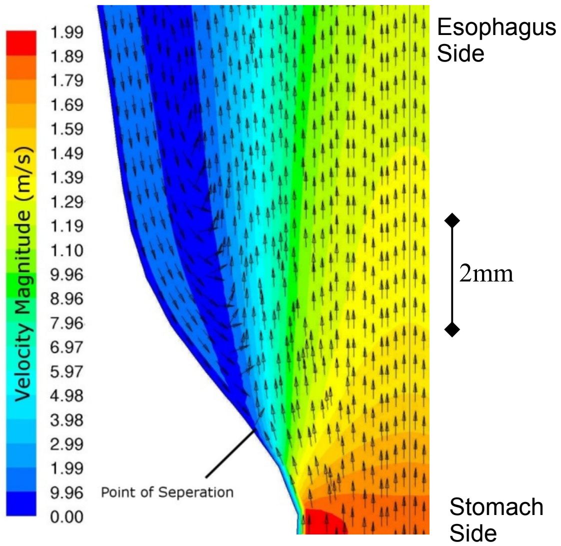

Fig. 5: Vectors of velocity above a minimum diameter of 4.8mm

A comparison of the volume flow rates observed for the different simulations performed is shown in fig.6. This image illustrates how an increase in the minimum diameter causes an increase in the volume flow rate observed. The image also shows that an increase in the pressure experienced in the stomach will likewise cause an increase in the volume flow rate of reflux through the EGJ. The presence of the kink observed at 6.4mm will be discussed later.

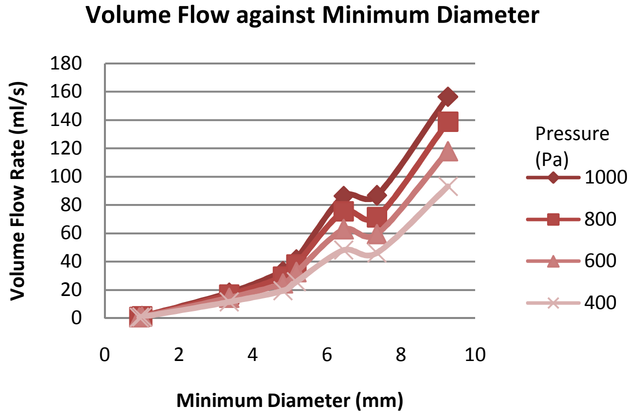

Fig. 6: Volume flow rates through the EGJ

For the 3D simulations, a virtual plane was drawn down the center of the problem. Contour plots of the velocity were drawn over this plane with vectors again overlaid to improve the clarity of the image. This was done for a number of the simulations. Results are shown in fig. 7 for the case with a minimum diameter of 2mm. The Reynolds number of this flow at the point of minimum diameter is 10,000.

The 2mm case shows a small thin jet extending from the point of minimum diameter with a large area of slow, recirculating flow between it and the walls.

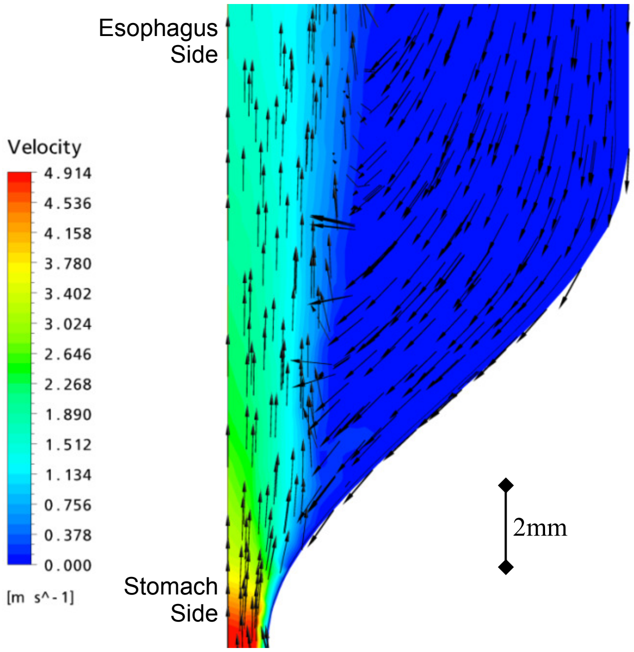

Fig. 7: Contour plot of velocity magnitude above a minimum diameter of 2mm with velocity vectors overlaid.

For the 3D simulations the centerline velocities for the jets were also extracted. When dealing with jets it is common practice to present the centerline decay of the jet as it travels downstream.

$$Decay(x) = \frac{Nozzle\ Velocity}{Centerline\ Velocity\ (x)} \tag{1}$$

To obtain these values the centerline velocities are normalized with the velocity measured at the point of minimum diameter. These normalized velocities were then inverted to produce the centerline decay as shown in eqn. 1.

$$Downstream\ Position = \frac{x - x_n}{D_n} \tag{2}$$

These decays were then plotted against the position downstream of the minimum diameter, normalized against the minimum diameter itself as calculated using eqn.2. An example of one of these plots is shown in fig. 8 for the 2mm case. These results are shown for varying Reynolds numbers, defined at the point of minimum diameter in both cases. Also shown on these figures is an overall trend line from the data gathered from existing literature on axisymmetric turbulent jets as a point of comparison [12][13][14].

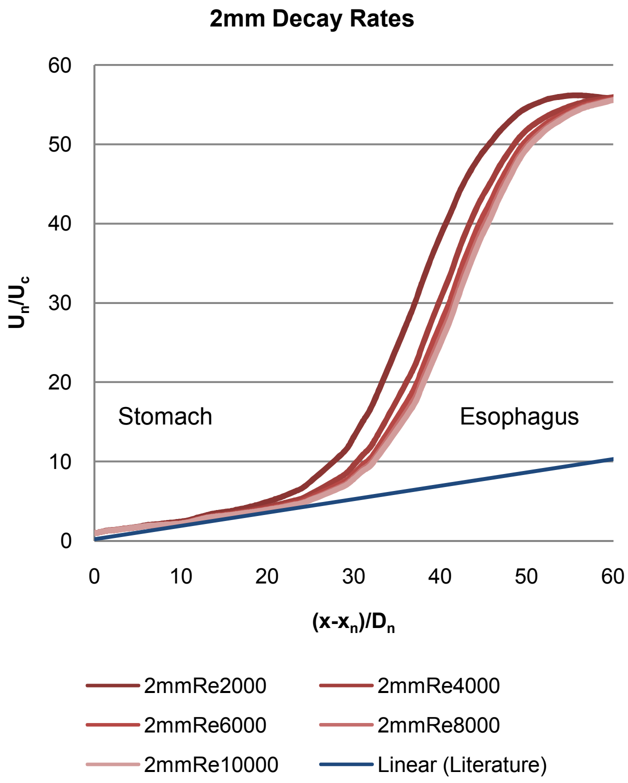

Fig. 8: Predicted centerline velocity decay downstream of a minimum diameter of 2mm with trendline from literature experiments

DISCUSSION

The results from fig. 4, fig. 5 and fig. 7 show that, as would be expected when the stomach is under a greater pressure than that present in the esophagus, fluid will be driven up through any opening in the EGJ. If the opening is narrow, then this flow will take the form of a turbulent jet. The width of the jet created is dependent on the width of the minimum diameter found through the EGJ. This finding corresponds to anecdotal evidence which describes reflux squirting into the esophagus in a manner reminiscent of a water pistol.

The general case predicted by the simulations is one where the flow begins moving under a pressure difference between the stomach and esophagus. As the flow approaches the point of minimum diameter it is accelerated by the decrease in diameter according to the continuity equation shown in eqn. 3

$$Volume\ Flow\ Rate = Velocity\ \times Area \qquad (3)$$

As the flow passes the point of minimum diameter it reaches its maximum velocity. It then continues into the esophagus. As it does the simulation predicts that the boundary layer will attempt to follow the curve of the EGJ wall. However, due to the pressure gradient caused as a result of the wall slope, the boundary layer will detach creating turbulent flow. The point where this occurs is referred to in fluid dynamics as the point of separation. As a consequence of this detachment, the flow will move into the esophagus away from the walls and create the observed jet. Between the point of separation and the walls of the EGJ the area of recirculation noted earlier occurs. In this area the flow is moving downwards contrary to the main jet.

The predicted presence of the separation of the flow from the walls has an influence on the volume flow rate. In one case, where the minimum diameter of the EGJ was 6.4mm, the walls of the junction had a smoother slope; as a result the flow remained attached and no separation, or jet, was experienced. As can be seen from fig. 6 the volume flow rates recorded for this geometry are higher than would be expected based on the other simulations performed. This suggests that along with the minimum diameter of the EGJ, the slope of the walls plays a role in determining the amount of fluid refluxed.

The volume flow rate experienced through the EGJ has an effect on the amount of potential damage caused by acid during a reflux event. Knowledge of the volume flow rate possible through the EGJ, for a given minimum diameter and stomach pressure, could help clinicians in diagnosing the severity of GERD. The data could also be used in surgical treatment of the condition by providing the surgeon with information on how tight to make the EGJ during a fundoplication procedure.

The results shown in fig. 8 show how the decay of one of these jets behaves above the EGJ. Until 20 minimum diameters after the origin of the jet the results obtained from the simulation correspond with those from similar flows seen in the literature for unconfined jets. In this area the jet is relatively free of the influence of the walls. The main factor affecting the jet's structure in this region is the velocity experienced at the minimum diameter.

After approximately 20 minimum diameters the predicted decay results begin to diverge from the literature as the effect of the walls on the flow increased. The eddy diffusion, the ability of the turbulence to spread through the flow, becomes restricted. This causes the decay of the jet to increase rapidly and the jet to quickly develop into pipe flow. The exact point where this divergence from the literature occurs is dependent on the Reynolds number of the flow. Lower Reynolds numbers will diverge earlier. For example, a jet with a Reynolds number of 2000 will have decayed to 10% of its original velocity 5 nozzle diameters earlier than a flow with a Reynolds number of 10,000.

These decay results suggest that given a pressure of 1000Pa, and a minimum diameter of 2mm, a jet can reach up to 40mm into the esophagus before slowing to 25% of its original velocity, and 60mm before reaching 10% of its original velocity. Consequently, if an individual has an EGJ with a curvature, it is quite possible that the jet of reflux will contact, and impinge on, the esophageal walls. This would in turn present a localized area of the esophagus where the damage caused by acidic reflux would be greater than in the surrounding area.

CONCLUSION

This paper demonstrates how CFD can be used to gather information about intricacies of gastroesophageal reflux that is difficult to acquire by any other means. A key component in developing these simulations is the ability to extract meaningful data on the geometry of the EGJ. This is done through the use of a FLIP probe which provides cross sectional areas at a number of locations through the EGJ. Using this data it has been possible to build up both 2D and 3D models of the junction and import these into CFD packages.

The results from these simulations correspond with anecdotal evidence which describes reflux ‘squirting’ from the EGJ into the esophagus like a water pistol. The simulations found that under pressure conditions typical of the stomach, acid is driven through an open EGJ into the esophagus where it forms an axisymmetric turbulent jet.

The velocity of the jet observed is dependent on the pressure in the stomach and on the geometry of the EGJ. The minimum diameter of the EGJ is one of the key criteria in defining the flow through the junction. The slope of the EGJ walls also have an effect on the type of flow experienced. A comparison of the decay rates observed along the centerline of the problem with results from the literature on turbulent jets has shown a correspondence between these results. This is particularly true in the area close to the minimum diameter.

These decay results also highlight the length which the jet can travel into the esophagus as it slows down. It is quite possible that if the EGJ of a patient is curved as it passes though the diaphragm then the resulting jet could impinge on the esophageal walls. This would present a localized area where the risk of damage is greater than the rest of the esophagus.

Finally, knowledge of the volume flow rate through the EGJ could help clinicians in diagnosing the severity of GERD in patients. It could aid in surgical treatment of the condition by providing the surgeon with guideline information on how tight to make the EGJ. The data could also provide useful information to clinicians when prescribing drug quantities to patients who suffer from chronic GERD.

NOMENCLATURE

CFD	Computational Fluid Dynamics
CSA	Cross Sectional Area
D_n	Diameter of Nozzle
EGJ	Esophagogastric Junction
FLIP	Functional Lumen Imaging Probe
GERD	Gastroesophageal Reflux Disease
U_c	Centerline Velocity
U_n	Nozzle Velocity
X	Centerline Location
X_n	Nozzle Location

Units
1 mm = 0.03937 inches
1m = 3.28 ft
1ml = 0.0338 fluid ounces

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ANNEX A

LITERATURE ON TURBULENT JETS

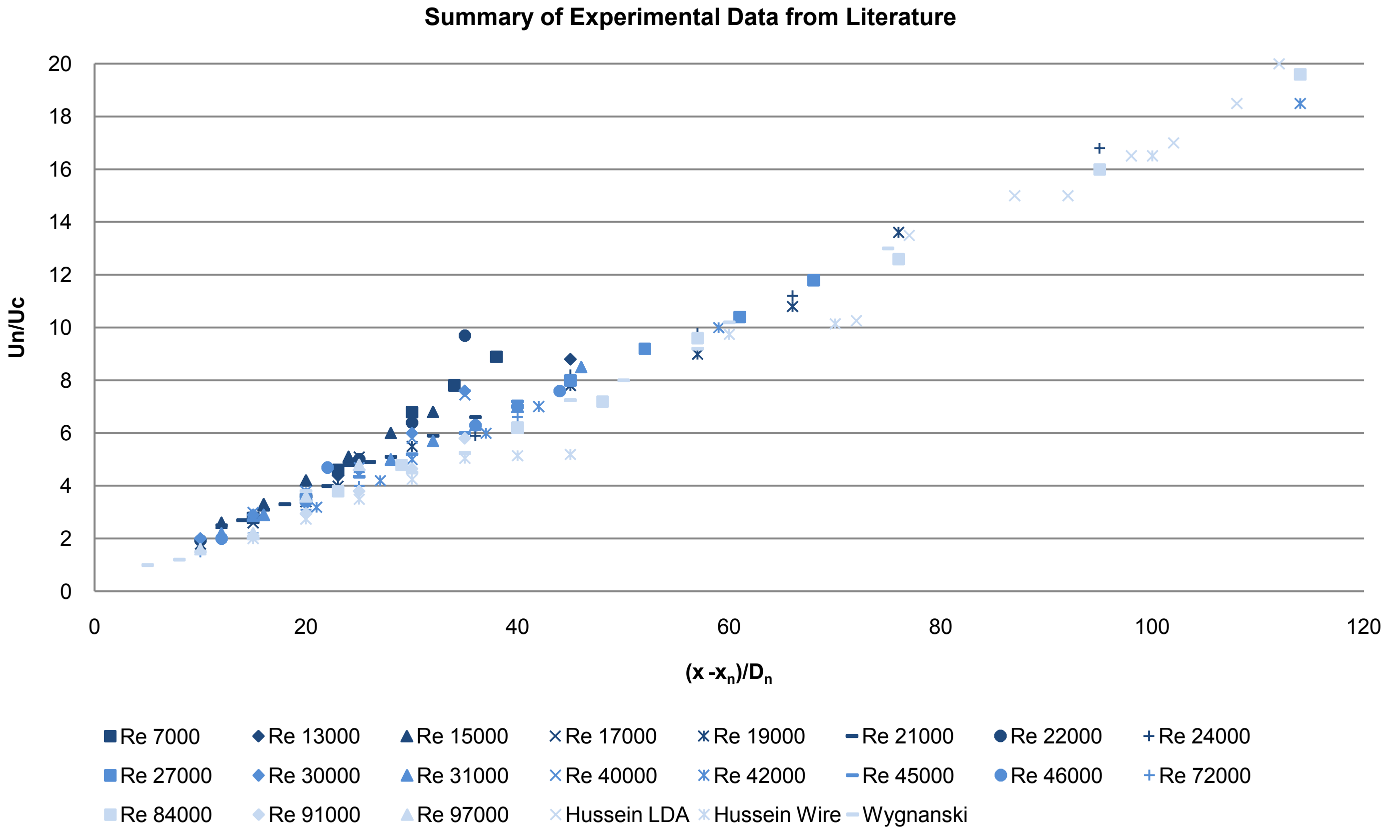

Figure 9 – Decay rates for turbulent jets from literature. all data from malmstrom et al [14] unless otherwise stated.

Figure 9 shows that an axisymmetric turbulent jet decays at a constant rate as it travels downstream from the nozzle where it originated. It can also be seen that if the results for decay and downstream distance are non-dimensionalised with the nozzle velocity and nozzle diameter respectively, then these results are relatively co-linear. Some variation based on Reynolds number is observed in these results. Those cases with lower Reynolds numbers tend to have higher decay rates than those with higher Reynolds numbers.

It has been observed by Hussein et al. [12] that when walls are present in close proximity to the centerline of the jet, the eddy diffusion is restricted. This causes a hindrance to the flow as the turbulent kinetic energy of the flow is increased as a result. It would be expected then that the presence of the walls would result in the termination area being encountered earlier than would be expected if the jet was unenclosed.