Investigation into the design & development of colonic stents

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INVESTIGATION INTO THE DESIGN & DEVELOPMENT OF COLONIC STENTS

by

ANG KER SER

**SCHOOL OF
MECHANICAL & AEROSPACE
ENGINEERING**

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University in the fulfillment of the requirement
for the Masters of Engineering**

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Abstract

This research focuses on the design and development of a low-cost colonic stent for the purpose of temporary placement, the delivery system for it and a device to measure the length of the tumor causing obstructions. Mechanical and in-vivo tests were conducted to verify the effectiveness of the package.

Prior to the design work, a complete and thorough review of the relevant research publications on colonic stenting and stent designs was carried out to facilitate the design of the new stent. This review includes details of surgical procedures required in treating colorectal obstruction, which often involves the creation of a temporary stoma to decompress the colon before resection of the stricture and reconnection of the colon. Discussions on the currently used stents are also included in this report.

Four different designs of stents were suggested during the brainstorming session. The selected design is a short modular stent segment which can be connected to form a longer one. This modular design allows for quick customization of the stent's length and longitudinal flexibility that is required for the negotiation of the tortuous colon. The zigzagged design of the struts in the new stent allows high collapsibility which is crucial for the prosthesis to be slid to the stricture. A mechanical approach to the design of the stent was adopted and samples of the new stent were fabricated. The stents were able to collapse fully and offer ample strength to maintain an opening in the stricture for effective irrigation of the bowel.

The catheter designed to deliver was chosen from three suggested designs. The design is quite similar to those which are currently used. The device worked on bench top tests but failed to work during the in-vivo test due to a change in property of the material used to make the sleeve when it was in contact with the moisture in the colon. However its attachment to the colonoscope was able to fulfill its requirements.

The stricture length measuring device was also designed and developed. The prototype worked on bench top testing, although in-vivo testing was not conducted.

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INTRODUCTION

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1.1 BACKGROUND

1.1.1 INTRODUCTION

Colorectal cancer is one of the most common forms of cancer and it affects both men and women equally. This is especially true in developed countries where people commonly have diets that are rich in meat and fats. It was estimated that 65 out of every 100,000 people in Singapore suffer from this form of cancer and there are about 1000 new cases diagnosed each year [1-2]. It is currently the type of cancer that accounts for the most death here.

1.1.2 HOW CANCER CAN KILL

There are several ways in which cancer can result in death. Cancerous cells are known to absorb all available protein, sugar and nitrogen, leaving the body to starve to death. Protein starvation is one of the major causes of cancer deaths and accounts for 32% of all cancer death [3].

Together with starvation, the toxins produced by the cancerous cells can cause cachexia; a condition whereby the patient suffers from extreme fatigue, physical wasting and malnutrition. In the much weakened state; the body's defenses are unable to combat against infection. According to McKinnell et al, cachexia and infection are the leading causes of death in cancer patients [4]. Very often, the infections involved are unavoidable even with the administration of antibiotics.

Hemorrhaging is another way in which patients die of cancer. This happens in the hollow organs, such as the colon where severe ulceration and tumor growths have reached the blood vessels, thus causing the patients to suffer from anemia. In such cases, the patient can die when the loss of blood is excessive.

In cases where there are extensive tumor growths, death by organ failure may occur. For example, extensive tumor growths can result in obstructions in organs like the colon. When these happen, emergency surgeries will be necessary in order to save the patient's life.

1.1.3 COLORECTAL OBSTRUCTIONS

Colorectal cancer usually presents little or no symptoms during its early stages. 60% of the colorectal cancer cases here are discovered in the later stages (Duke stages III & IV) [5] and 9% to 30% of colorectal cancer patients will experience acute (complete or partial) colonic obstruction due to the tumor growth that occludes the lumen of the large intestine [6-15]. About half of the people diagnosed with colorectal cancer will die from it.

The most common remedy for colorectal obstruction is a temporary colostomy and resection of the cancerous colon. (Hartman's Technique) [14]. This involves the creation of an opening on the abdomen and the attachment of a stoma bag for the drainage of stool. The morbidity of such intervention is usually high and the presence of the stoma bag often affects some daily routine tasks. Another approach to clearing obstructed colon is the implantation of a stent.

1.1.4 STENTS

Stents are tubular splints (usually in the form of wired-mesh) used to maintain the patency of lumen and canals. The term stent was named after a late nineteenth century British dentist, Charles R. Stent (1845–1901), who developed a dental impression material that was later used as a template to support healing skin grafts. The device was first widely used in the treatment of patients with obstructed bile ducts in obstructive jaundice and ever since then, stents had been used to treat different conditions in different

parts of the body. Subsequent chapters will describe the types of stents that are commonly in use.

1.1.4.1 VASCULAR STENTS

The concept of endovascular stent was first tried out by Charles Dotter in 1969 using dogs, but it was not until 1991 that the first commercial endovascular stent was made available by Johnson & Johnson Corporation following clinical trials which started in 1987 [16-18]. However, within 3 years of its introduction, the company reported the sale of their 1 000 000th vascular stent [16] and by 1995; it was reported to be used in most coronary angioplasty procedures at leading centers and in 30–60% of all cases at other centers [17]. Developments of the stents are rapid and there are currently over 20 manufacturers producing different variations of such stents.

Vascular stents are used to keep blood vessels open following balloon angioplasty. Balloon angioplasty is a surgical procedure whereby obstructed blood vessels are dilated using a balloon. Obstructions in the blood vessel are often due to the deposition of cholesterol and calcium on the passage walls. In balloon angioplasty, a thin guide wire is introduced passed through the narrow or the blocked segment of the blood vessel under fluoroscopic guidance. The balloon with the stent over it is then moved to the narrow or blocked segment and inflated to dilate the blood vessel. When the balloon is deflated and removed, the stent remains in the blood vessel and acts as a scaffold preventing the vessel from collapsing to its original diameter due to the elasticity of the passage wall. This method has a clear advantage over conventional bypass surgery as it is much simpler and the hospital stay required is also shorter. It can also be applied to blood vessels in almost all parts of the body. Figure 1.1 illustrates the implantation of a stent using balloon angioplasty.

Figure 1.1 Deployment of a balloon expandable vascular stent. [19]

Vascular stents, such as those shown in Figure 1.2 can also be self expanding. Such stents are made of Nitinol materials (SMA – Shape memory alloys) which are temperature sensitive. The stents are introduced to the blood vessel after balloon angioplasty. They are moved to the obstruction site with the guidance of a guide wire after the balloon had been removed. When deployed, the body temperature will cause the stent to revert to the expanded form in which it was manufactured.

Figure 1.2 Vascular Stents [20]

1.1.4.2 TRACHEOBRONCHIAL STENTS

The use of stents to correct malignant airway obstruction was begun by W.B.Harkins in 1952 in which he used a metal alloy tube to relieve tracheostenosis [21]. Thereafter, extensive work had been carried out by surgeons and researchers to further improve the technique of insertion, as well as the design and material of tracheobronchial stents. Tracheobronchial stents are used both alone and with other techniques to correct central airway obstructions. They are used in cases of obstruction due to either intrinsic or extrinsic compressions.

There are several different types of tracheobronchial stents available commercially and these can be classified into 4 main categories, namely the wire-meshed metallic stents, the covered wallstents, the soft silicone stents and polyflex stents. All four types of stents, each having their pros and cons, serve a different purpose. The factors involved in the selection of stents include dimension, flexibility, tolerance, secretion evacuation, biocompatibility of materials and migration prevention.

Silicone stents, as shown in Figure 1.3, are flexible and more comfortable than the more rigid metal stents. They can be repositioned and removed after implantation should there be a need to. They are also relatively cheaper ($\approx$ US\$800) when compared with other

types of stents. However being soft and flexible, it lacks the strength of the other types of stents and thus it cannot be used to treat certain types of obstruction. It is also prone to migration and there is a tendency of re-stenosis. The wall thickness of silicon stents is also thicker, thus reducing the amount of flow in the airway.

Figure 1.3 Silicone tracheobronchial stents

Metal stents are strong and flexible with thin walls. However, metal stents are non-adjustable and difficult to remove. It is also difficult to control the inflated size during implantation. Unlike the silicon stents, they are hard and less comfortable. They are also more costly (>US\$1500) than silicon stents. Metal stents are made from wire mesh and are hence prone to re-occlusion by granulation through the holes of the mesh. Figure 1.4 is a picture of such a stent.

Figure 1.4 Metal tracheobronchial stents

A covered wallstent, as shown in Figure 1.5, is a metal stent covered with a thin layer of synthetic material that should prevent stent re-occlusion. It has all the advantages of a metal stent except that it is difficult to manufacture and costly. (>US\$2500)

Figure 1.5 Covered Wallstent [22]

The Polyflex stent shown in Figure 1.6 consists of a polyester wire mesh embedded in a silicone covering. It is the latest stent available commercially. Little is known about this stent, but based on work done by C T Bolliger [23] and brochure from Willy Rusch AG, the new stent is easy to remove, resistant to granulation, suitable for stent-in-stent insertion and has thin wall. However, C T Bolliger noticed that the stent does not always

re-open easily due to kinking of the mesh. Due to the more complex design, the new stent is also expected to be more expensive and difficult to manufacture.

Figure 1.6 Polyflex stent [24]

1.1.4.3 ESOPHAGEAL STENTS

Esophageal stents are used as a palliative measure for patients suffering from obstruction of the esophagus due to tumors which has an incidence rate of 7.5 in every 100 000 [18]. Obstruction in this part of the body causes dysphagia (inability to swallow), which can be very distressing and debilitating. The cause of obstruction in the esophagus can be intrinsic or extrinsic. Of these sufferers, 50%-60% are suitable for palliative remedies only and stenting the obstructions are a reliable palliative action [18, 25].

The esophagus stents that are used in current practice can be divided into two main categories, the rigid polymer stents and the metallic stents. As in the case of tracheobronchial, polymer stents are cheaper than the metal ones, but unlike polymer tracheobronchial stents, they are more difficult to implant due to their rigidity. Several studies [10, 18] have found that complications are more common with the use of such stents, such as difficulty in negotiating the strictures despite performing pre-dilation to the stricture, migration and perforation of the esophagus.

Metal stents, such as the Wallstent in Figure 1.7, are gaining popularity despite being more expensive than the rigid plastic stents. This is due to the much lower incidence of complication associated with the use of such stents and therefore shorter hospital stay.

There is also no need for general anesthesia (only sedation required) and post insertion test required is only X-ray. However, the placements of such stents are usually permanent and uncovered ones may suffer from granulations that can cause re-occlusion.

Figure 1.7 Boston Scientific Esophageal Wallstent [22]

Recently, there has also been a new type of polymer esophagus stent which is collapsible, called the polyflex stent by Willy Rusch AG. The stent is similar to the polyflex stents used for the tracheobronchial system. Little is still known about the performance of this stent when used in the esophagus.

1.1.4.4 URETHRA STENTS

The use of stents in the urinary tract started in 1985 with experiments on dogs by Siwart et al. [18, 26]. Stents are used in the treatment of strictures in the urethra which can be caused by abnormal growths, like scars, tumors and inflammation, either intrinsically or extrinsically. Patients suffering from urethral strictures are usually male and may experience symptoms like redness and swelling of the penis, decrease in urinary flow, pain during urination, increase in urine frequency, incontinence, blood in semen and urine, urethral discharge, etc. The implantation of a urethral stent for the treatment of urethral strictures can be either temporary or permanent.

Besides urethral strictures, urethral stents can also be used in the treatment of benign prostatic hyperplasia (BHP), which is a very common disease among men above the age

of 50. The procedure of stenting is carried out for BHP to relieve the outflow obstructions for patient who are deemed unfit and unsuitable for surgery. As in the case for urethral strictures, the placement of the stent can be either permanent or temporary.

Urethral stents can be either polymeric or metallic. The metallic ones are similar to those used in other parts of the body. (ie. wire mesh tube) However, there are several designs available for those made from polymers, such as the Nissenkorn stents and the Double J stent shown below.

Figure 1.8 Double J stent [27]

Urethral stents that are to place permanently are usually coated with urothelium and are metallic. The urothelium coating is added to prevent direct contact between the stent and the urine, which may result in infection. Polymer stents are only recommended to be implanted for 6-8 weeks as the urine flowing through them will cause the material to degrade. The degrading of the material can cause the stent to break and migrate, which can result in complications like incontinence.

1.1.5 STENTS IN THE TREATMENT OF COLORECTAL OBSTRUCTIONS

Stent are sometimes implanted in the colon for the preparation of the intestine for stricture resection and anastomosis, which is the surgical procedure to connect the severed colons to restore the continuous channel. The stents opens up the obstructed parts of the colon and allows the feces to be cleared through the anus.

The advantages of using a stent are that it:

- 1) solves the obstructions and allows elective surgery, thereby reducing morbidity rates,
- 2) avoids the discomfort of colostomy and thus improves the quality of life,
- 3) patients with unresectable tumours can be treated,
- 4) is faster and easier to perform than other treatment methods.

However, current stents for use in the colon are very expensive; costing a few thousand US dollars each and in cases whereby the use of the stent is for temporary relief of the obstruction, they are used only for a few days before they are discarded after the anastomosis have been performed.

With the high cost of conventional metal colorectal stents and the high morbidity of a temporary colostomy, it will therefore be beneficial to develop a new colorectal stent that is cheaper than the current available ones. It would not only reduce the cost of treatment of obstruction by stent implantation, but also replace the need for colostomy, as colorectal stenting would be more affordable and justifiable.

A more detailed overview on the use of stents in the colon and rectum will be covered in Chapter 2 of this thesis.

1.2 OBJECTIVES

The objectives of this project are:

1. to study the issues pertaining to the design of colorectal stents, so as to develop them economically,
2. to design a delivery and guidance system for the deployment of the new stents,

3. to produce samples of the new stents using rapid prototyping and tooling techniques,
4. to create working models of the delivery system,
5. to conduct test and measurements to evaluate the performance of the new stents.

1.3 SCOPE

This research will involve the study of stent designs and their deployment methods. These would include a literature review and patent search of current designs and manufacturing methodologies. Background of the application of stents will also be looked at to understand the needs for an effective stent.

With the insight obtained on the currently available stents, designs of a new stent will be built for use in the colon and rectum. Of the suggested design, the suitability of the designs would be evaluated and the best one would be chosen for fabrication.

Rapid prototyping techniques would be used to create the sample due to the method's cost efficiency for small scale production and the author's familiarity with the method.

In order for the stent to be of usefulness, a delivery system would have to be made. Current designs would be reviewed and designs suggested would be evaluated for their suitability.

The prototypes of this new stent system will be fabricated and mechanically tested to verify the design. Modification would be made during the process to improve the performance. Finally the system would be tested in an animal for a final evaluation.

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2.1 THE COLON

The colon shown in Figure 2.1 is the part of the large intestine that extends from the cecum to the rectum. Together with the rectum, it forms the large intestine, which is the lowest portion of the digestive system. The colon is about 1.5 m long and can be divided into four main parts:

1. the ascending colon,
2. the transverse colon,
3. the descending colon and
4. the sigmoid colon.

The colon's diameter is largest at its commencement at the cecum (about 65 mm) and gradually reduces until the rectum (about 25 mm). It is retained in contact with the posterior wall of the abdomen by the peritoneum (thin membrane lining that lines the walls of the abdominal cavity) at the right colic flexure and the left colic flexure.

Figure 2.1 The Human Colon [28]

The function of the colon is to transport waste material to the rectum by peristalsis and to absorb salts, vitamins and water in the process. Peristalsis, also known as intestinal motility, is the progressive wavelike contractions in the colon caused by involuntary movements of the longitudinal and circular muscles. The presence of foreign objects in the colon can stimulate the contraction of these muscles to clear the colon. Under normal circumstances, the frequency of peristalsis can be very slow with the period of each wave around ten minutes. Figure 2.2 illustrates the movement of organ contents by peristalsis.

Figure 2.2 Illustration of peristalsis [29]

The walls of the colon as shown in Figure 2.3 can be classified into 5 main layers [30-31], namely:

1. the mucosa, which is the inner lining that includes the epithelium, a thin muscle layer and the connective tissue between the two layers,
2. The submucosa, which is the connective tissue beneath the mucosa,
3. the muscularis propria, which is a thick layer of muscles that are responsible for the peristalsis process,
4. the subserosa, which is the connective tissues beneath the muscles,
5. and the serosa, which is a thin outer covering of the colon.

Figure 2.3 The layers of the colon wall adapted from [30]

To protect the epithelial tissues from the material moving through it, the colon secretes alkaline mucus that acts as a lubricant. This mucus also neutralizes the acids produced by bacterial metabolism.

Liquid absorption in the colon causes the faeces to harden as they move through the intestine and the contents that are finally left in the faeces when they reach the rectum are mostly cellulose, bacteria and bilirubin [31]. (A reddish-yellow bile pigment derived from the degradation of the deep red, non-protein, ferrous component of hemoglobin.)

2.2 COLORECTAL CANCER

Colorectal cancer is one of the most common forms of cancer in developed countries. Based on estimates by the World Health Organization [32], it accounted for 8.4% of all neoplasm deaths in the year 2000. About 303 000 men and 276 000 women died due to colorectal cancer that year. (Total of 0.58 million deaths due to colon cancer in 2000) It was the fourth most fatal form of cancer behind lung cancer (1.21 million), stomach cancer (744 000) and liver cancer (626 000).

The cells of adults' bodies grow and divide in an orderly manner to replace the worn-out and dying ones. Cancer or malignant growth is developed when abnormal cells at part of the body begins to grow in an uncontrolled way. Unlike normal cells, cancerous cells outlive normal cells and continue to form abnormal ones.

Cancer can occur at any of the 4 parts of the colon and will present different symptoms, but it usually starts at the innermost layer - the mucosa. These often come in the form of polyps. Polyps are abnormal growths that projects out from the inner walls of the stomach, colon and rectum, which are fairly common for adult above the age of 50 years old. By age 75, almost all humans will have some polyps in the colon. Polyps are usually benign, but over time, some of them can transform into cancerous ones, such as the adenomatous (of a glandular structure or of glandular origin) polyps shown in Figure 2.4. According to the American Cancer Society, over 95% of colorectal cancers are adenocarcinomas. [31]

Figure 2.4 Adenomatous polyps which can become cancerous over time. [33]

When a polyp becomes cancerous, it can spread through some or all the layers. When the blood vessels or lymph vessels are affected, it can also spread to other organs. Such a process is called metastasis. Therefore, it is always advisable for polyps to be removed during colonoscopy to prevent the development of cancer.

2.3 DETECTION OF COLORECTAL CANCER

It was found that 80% to 90% of all colorectal cancer can be cured if detected early and there are several methods that can detect colorectal cancer [30]. Many countries have their own set of guidelines of the type of screening that should be used for different people of the risk group they belong to. With proper screening methods, polyps can be detected and removed before they become cancerous.

2.3.1 DIGITAL RECTAL EXAMINATION

In this simple test, which is often also performed to check for prostate cancer, the medical practitioner inserts his/her gloved finger into the anus to feel for abnormal masses at the anus or lower rectum as shown in Figure 2.5. This is sometimes performed in routine clinical examinations, but due to the limited reach of the finger, the test cannot detect most tumors in the colon and rectum. It is therefore not recommended as a stand alone test.

Figure 2.5 Picture depicting Digital Rectal Examination [34]

2.3.2 FAECAL OCCULT BLOOD TEST (FOBT)

This is a simple test to detect blood traces in the faeces. The blood traces detected could be from damaged blood vessels at the surfaces of the polyps and tumor by the faeces moving through the colon. Such blood traces in the stool are often not visible to the naked eye. In this test a sample of stool is placed on a chemical strip that will change color if blood is present. Hidden blood in the stool is a common symptom of colorectal cancer, but having blood in the faeces does not imply that there are polyps or tumors in the colon. Several other factors, such as the consumption of partially/uncooked meat, can give a false positive results to the test. Despite the test's lack of accuracy, it is still recommended by physicians, as they are safe, painless and cheap (about S\$4.00 for each test kit in Singapore). Figure 2.6 shows an example of such a kit.

Figure 2.6 FOBT kit from Early-Care® [35]

2.3.3 FLEXIBLE SIGMOIDOSCOPY & COLONOSCOPY

Sigmoidoscopes and colonoscopes are slender, flexible fiber optic devices about the thickness of a finger that are inserted through the patient's anus to allow the physicians to

see the internal surface of the rectum and colon. Such tests are very effective in finding polyps in the colons as the doctors are able to visually see the abnormalities in the colons. In addition to their diagnostic capability, the scopes can also be used for treatment, such as for the removal of polyps and biopsy (taking samples). Pictures of a colonoscope and a sigmoidoscope are shown in Figure 2.7 and 2.8.

Figure 2.7 Endosheath S-F100 Sigmoidoscope [36]

Figure 2.8 A colonoscope [37]

For these tests, the patients are sometimes sedated and their colons had to be first cleansed by taking an enema. The patients often experience discomfort during the tests and occasionally there are even side effect, like bleeding, especially when the tests are not performed by well-trained colonoscopist. There is also a possibility of puncture of the intestine by the scope. Figure 2.9 shows the endoscopic view from a colonoscope.

Figure 2.9 Endoscopic view from a Colonoscope

The main difference between sigmoidoscopes and colonoscopes are in their lengths. Sigmoidoscopes are only about 60 centimeters long, whereas colonoscopes are usually about 1.5 meter long. Thus, the uses of sigmoidoscopes are limited to the lower part of the colon and can therefore detect colorectal cancer at the lower half of the colon.

2.3.4 DOUBLE CONTRAST BARIUM ENEMA X-RAY

In this test, barium sulfate is used to partially fill and open up the colon. The barium sulfate is introduced through a small tube placed in the patient's anus. The patient will then be turned on the x-ray table for the barium to spread throughout the colon. Air is pumped into the colon through the same tube to make it expand. X-ray pictures will then

be taken to show the lining of the colon. Cleansing of the bowel is also necessary prior to this test by enema. Figure 2.10 shows an example of a barium enema X-ray.

Figure 2.10 Example of a barium enema X-ray [38]

2.3.5 VIRTUAL COLONOSCOPY

Virtual colonoscopy is a relatively new diagnostic technology and is still widely regarded as experimental. Virtual colonoscopy uses CT scanner and computer virtual reality software to look into the colon without having to insert a scope into the body or filling the colon with liquid barium. However, in this test, air will be used to fill up the colon via a tube that is attached to the patient's rectum. Sedation for the test is not required, but cleansing of the colon prior to the scan is necessary as in conventional colonoscopy. This is probably more accurate than the barium enema but not quite as good as conventional colonoscopy for finding smaller polyps and should polyps be found from this test, conventional colonoscopy will still be necessary in order to remove them for histology. An image from virtual colonoscopy is shown in Figure 2.11.

Figure 2.11 Image from Virtual Colonoscopy [39]

2.4 COLORECTAL OBSTRUCTION

In cases of colorectal cancer, 9% to 30 % of patients will suffer from colorectal obstruction due to the growth of large tumors [6-15]. Colorectal cancer accounts for more than 50% of all colorectal obstructions. [11, 30, 40] The growth of the tumors slowly occludes the colon, causing intermittent constipation and narrow stools. When fully occluded, the accumulation of faeces can cause the colon wall to stretch, causing abdominal pain and distention. Without proper treatment, the patient will suffer from dehydration, rapid pulse, rapid breathing, fever, agitation, confusion, urinary incontinence or even death due to organ failure.

Figure 2.12 Endoscopic view of a fully occluded colon

Other common causes of large bowel obstructions are Volvulus (abnormal twisting of a segment of bowel around itself) and Diverticular disease (formation of scarred tissues after infection of the diverticuli).

In addition, 60% of colorectal obstructions all occur at the sigmoid where the lumen are smaller, the walls are thicker and less distensible, the fecal content are less moist and harder, and the frequency of obstructing lesion, such as cancer and diverticulities, is the highest. [11]

2.5 TREATMENT OF ACUTE COLORECTAL OBSTRUCTION

Colorectal cancer patients that present with obstruction of the large bowel that requires emergency treatment are usually in very poor condition. Treatment for such conditions usually involves surgical resection of the affected segment and colorectal anastomosis (The surgical connection of severed colon to form a continuous channel). A primary end to end anastomosis is usually not advisable due to elevated risk of anastomotic leak involved. This is because swellings are often present in the obstructed colon due to

prolonged stretching of the tissues. To stitch the severed ends of the colon would risk leakage of the colon when the swelling heals. There is also a high risk of infection if the surgery is done on an unprepared colon. When done, such high risk procedures are usually mandatory.

Under most circumstances, the surgeons will treat these patients on an emergency basis with a temporary colostomy using a technique known as Hartman's Technique. The colostomy is for clearing the faeces while the swelling tissues heal. A second operation will then be performed to close the colostomy and for full anastomosis of the colon. This approach carries a high morbidity and is reserved for selected patients. The use of a stoma bag also lower the self esteem of the patient and cause much inconvenience. There is also a risk of infection if the stoma is not properly maintained. This is especially common in older patients. Furthermore, there is also a mortality rate of around 22%-23% associated with such surgery. [8, 14-15] Other techniques that are being applied to treat colorectal obstruction include:

- 1) permanent colostomy,
- 2) subtotal colectomy,
- 3) cecostomy followed by anastomosis,
- 4) and stent placement.

Permanent colostomy involves opening a hole (stoma) in the patient's abdomen for the fitting of a stoma bag. Fecal waste from the body will be discharged from this hole to the stoma bag. Such technique is usually reserved for patients that are in very poor general state and advance age. These patients are too weak to go through anastomosis to reconnect the colon. There are also instances whereby the tumors are irresectable and permanent colostomy would be used. Sometimes, a temporary colostomy may become permanent when the patient refuses to undergo another surgery to reconnect the colon. As mentioned, the need to wear a stoma bag degrades the patient's quality of life, causing

inconveniences and lower self esteem. The cost of having to buy stoma bags also adds to the cost of treatment. Pictures of stomas are shown in Figure 2.13 and Figure 2.14.

Figure 2.13 Patient with stoma bag [41]

Figure 2.14 Picture of a stoma.

The intestine is fold it inside out so only the inside touch's the waste [41]

Subtotal colectomy with ileo-rectal or ileo-sigmoid anastomosis involves more aggressive, excessive resection of the colon. However, such treatment is not preferred due to the high morbidity associated with it. Patient that had undergone such surgery will suffer from greater frequency of bowel movements and fecal incontinence.

Cecostomy before resection is a controversial technique that is quite widely performed. In this technique, a catheter, as shown in Figure 2.15, is inserted into the cecum through the patient's skin to create a temporary diversion of fecal waste, before surgical resection and anastomosis. However, this technique is fraught with complications and the tubes are often obstructed. According to Nicholl et al, cecostomy alone accounts for 15% morbidity and 24% mortality. [42]

Figure 2.15 Cecostomy catheter [43]

A newer approach of dealing to with acute colorectal obstruction is to use a stent. The stent can be used to open up the obstructed section of the colon and thereby allowing the faeces to be discharged through the anus. The removal of the trapped fecal content would allow the stretched tissues to relax to their original state and recover from the swelling. Without the swelling, the obstructed portion of the colon can be surgically removed and a primary end to end anastomosis can be performed without the elevated risk of an anastomotic leak. However, current stents are expensive, costing a few thousand dollars a piece, and suffer from migration problems.

2.6 SOME HISTORY AND WORK DONE ON COLORECTAL STENTING.

The idea of stenting the colon was first tried out by Lelcuk et al in 1986. [44] However, there were no dedicated colonic stents then and the process was carried out using a nasogastric tube. The process did not gain popularity as these tubes have very small luminal diameter and are therefore not effective in clearing the obstructions. It was not until 1991 that a report on the use of metal stents in the rectum was published by Dohmoto [7, 12, 14, 45]. Then in 1992, the feasibility of the use of a self expandable metallic stent to treat acute colorectal obstruction due to tumors was confirmed by Spinelli with a small series of test conducted on 4 patients [14, 46]. Thereafter several institutes had published results of trials they had conducted using metallic stents.

Mainar et al [9] conducted trials on 71 patients between October 1993 and December 1996 at three European hospitals. Of these 71 patients, 48 had colorectal obstructions at the rectosigmoid region, 22 had them at the descending colon and only one had obstruction in the transverse colon. The mean length of the stricture in this series of trial is 46.2mm with the longest stricture at 65mm and the shortest at 35mm.

A total of 72 metal stents were successfully implanted in 69 of the patient within 24 hours of diagnosis. 5 of these stent were poorly placed, but only 3 cases require the replacement of stent. The initial technical success of 90% (64 of 71 patients) was achieved was therefore improved to 97% (69 of 71 patients). The time for implanting the stents range from 28 minutes to 180 minutes and the mean time for the stent placements was 75 minutes.

All but one of the stents used in the trials were Wallstents from Schneider, Bulach, Switzerland as shown in Figure 2.16. These stents have diameter between 20mm to 22mm and length from 40mm to 100mm. The other used was a Memotherm stent from Angiomed, Karlsruhe, Germany as hown in Figure 2.17. This stent has a diameter of

25mm and a length of 55mm. Of the two cases whereby the stents were not implanted, one has obstruction at the transverse colon. The stent was not used as the delivery catheter was not long enough to reach the tumor site. The reason that prevented the use of the stent in the other case was caused by the inability of the delivery catheter to negotiate the tortuous rectosigmoid region. However, these may no longer be a problem as there are longer catheters and endoscopes can be used to help negotiate the tortuous sigmoid colon.

Figure 2.16 Colonic Wallstent [22]

Figure 2.17 Memotherm stent [47]

The bowel obstructions in 60 of the patients were resolved within 24 hours of the implant whereas six others were relieved of the obstruction within 96 hours of the placement. The stents failed to perform their task in 3 of the patients and emergency surgeries were required to remove the obstruction. In all a clinical success rate of 96% (66 of 69 patients) was achieved.

Of the 66 successful cases, all but one patient with Duke Stage D colon cancer, underwent a single stage surgery with partial colonic resection and primary end-to-end anastomosis. The stents were left in the 65 patient for 6 to 16 day (mean 8.6 days) and observations after removal showed no evidence of tumor ingrowth in all the stents removed. Most of the patients have uneventful postoperative course, with only 9 patients having minor complications. Most of them were discharge from the hospitals within 8 days, whereas the other seven were discharge within 12 days.

L. Paul Diaz et al [48] inserted 20 stents in 16 patients between April 1994 and February 1998 using esophageal wallstents with diameter from 20mm to 22mm and length 70mm to 100mm. All but one of the stents were successfully placed. The procedure to implant the stent took between 15 minutes and 50 minutes.

Follow up examinations of the patients was performed from 1 to 44 months: until the death of patient or termination of study. There were 3 cases of stent migration and 3 cases of stent occlusion reported. The stent migrations were discovered using plain radiograph and CT scan 24 hours after insertion, but the clinical symptoms of colorectal obstruction did not recur during the follow-ups and no re-intervention was performed.

As for the 3 cases of stent occlusion, additional interventions were needed. In one case, the blockage is caused by fecal masses 16 months after implantation and balloon dilatation was performed to break up the occluding faeces. In the second case, which occur 20 days after implantation, the obstruction was not visible by barium enema, but nevertheless balloon dilation was performed to the patient. In the third case, it was found that the lower end of the stent had turned against the posterior wall of the rectum and tumor overgrowth was also present at the lower portion of the prosthesis. A second stent was inserted to relieve the obstruction.

Between May 1995 and July 1999, Montes et al [9] conducted trials on 24 patients. The stents were placed as permanent and palliative treatment in 14 of the patients and as a bridge to elective surgery in the other ten. The stents used in these trials were also diameter 22mm Wallstents with length from 70mm to 100mm. However, stents were not placed in one of the patients from the first group, as they were unable to pass the guide endoscopically due to the bending of the tumor in the splenic flexure. Granulation was reported in 2 patients and re-intervention by implanting a stent within the occluded on performed. This trial also yielded encouraging results with no migration and little complications.

Almost all the trials found that stenting is an effective way of relieving obstruction in the colon. However many are still concerned that the stents would suffered from migration and occlusion due to the in growth of tumor through the wire meshed stent walls.

To tackle the problem of migration, several stent makers had added flanges to the ends to the stents to act as anchors, but these features are often insufficient to overcome the effect due to the peristalsis caused by the colon muscles. Migrations of colonic stents usually occur during the first few hours of deployment. However the problem is less serious after some time when part of the tumor had grown through the meshes of the stent wall. Therefore surgeon using the stent would usually use one which is longer than the obstructing tumor to give some allowance for migration. On the whole, many still feel that migration of stents implanted in the colon is still a problem that had not been effectively dealt with.

Although the ingrowth of the tumor through the wire mesh can help in preventing migration, it can also be a problem when the tumor ingrowth re-occludes the lumen. This especially applies to stent that are use for palliative purposes, which will stay in the colon for a longer period of time. To solve this problem, Choo et al.[49] conduct trials on metallic stents with polyethylene sleeve covers. Two types of covered colonic stents were used in his trials. The first was a fully covered and the other was covered only at the center third of the total length. The results reported showed that 50% of the fully covered stents migrated whereas none of the latter mentioned stent migrated after 5 months.

Table 2.1 gives an overview of some of the clinical trials conducted on colorectal stenting over the pass few years.

TABLE 2.1: SUMMARY OF COLORECTAL STENTING LITERATURE SERIES

Ref	Authors	Year of Paper	Sample Size	Stent type (Number)	Site of obstruction (Number)	Success Rate	Purpose (Number)
[6]	Lamah et al	1998	6	Esophageal Wallstent	Rectosigmoid (1) Sigmoid (3) Descending (2)	83% (5/6)	Preoperative
[9]	Mainar et al	1999	71	Wallstent (71) Memotherm (1)	Rectosigmoid (48) Descending (22) Transverse (1)	93% (66/71)	Preoperative (65) Palliative (1)
[14]	Montes et al	2001	24	Wallstents	NA	93% (14/15)	Preoperative (10) Palliative (14)
[48]	Diaz et al	1999	16	Esophageal Wallstent	Rectum (2) Rectosigmoid (7) Sigmoid (7)	94% (15/16)	Palliative
[49]	Choo et al	1998	20	Self-designed covered metal stent	Rectum (3) Rectosigmoid (10) Sigmoid (5) Descending (2)	90% (18/20)	Preoperative (1) Palliative (8)
[50]	Camunez et al	2000	80	Esophageal Wallstent	Rectosigmoid (31) Sigmoid (41) Descending (8)	84% (67/80)	Preoperative (33) Palliative (35)
[51]	DeGregorio et al	1999	24	Wallstent (22) Z-stent (1) Memotherm (1)	Rectosigmoid (23) Descending (1)	96% (23/24)	Palliative
[46]	Binkert et al	1998	13	Vascular Wallstent (14)	Rectosigmoid (6) Sigmoid (5) Descending (1) Ascending (1)	92% (12/13)	Preoperative (10) Palliative (3)

TABLE 2.1 (CONT.): SUMMARY OF COLORECTAL STENTING LITERATURE SERIES

Ref	Authors	Year of Paper	Sample Size	Stent type (Number)	Site of obstruction (Number)	Success Rate	Purpose (Number)
[53]	Baron et al	1998	27	Wallstent (20) Ultraflex (8) Esophacoil (2)	Rectum (2) Sigmoid (16) Descending (6) Transverse (3)	89% (24/27)	Preoperative (10) Palliative (17)
[54]	Mishima et al	1999	4	Z-stent (2) Ultraflex (2)	Rectum (3) Sigmoid (1)	75% (3/4)	Palliative
[55]	Tejero et al	1997	38	Wallstent	Rectum (9) Sigmoid (21) Descending (8)	92% (35/38)	Preoperative (25) Palliative (13)
[56]	Canon et al	1998	27	Wallstent	Rectum (NA) Sigmoid (NA) Transverse (2)	85% (23/27)	Preoperative (10) Palliative (17)
[57]	Rupp et al	1995	9	Esophageal plastic tube	Rectum	78% (7/9)	Palliative
			10	Wallstents (10) Strecker (1)	Rectum	100%(10/10)	Palliative
[58]	Saida et al	1996	15	Z-stent	Rectum (6) Sigmoid (8) Descending (1)	80% (12/15)	Preoperative
[59]	Dohmto et al	1997	8	Nasogastric plastic tubes	Rectum	100% (8/8)	Palliative
			11	Wallstent (6) Endocoil (5)	Rectum	100% (11/11)	Palliative
[60]	Arnell at al	1998	7	Wallstent	Rectum (NA) Sigmoid (NA)	86% (6/7)	Palliative

TABLE 2.1 (CONT.): SUMMARY OF COLORECTAL STENTING LITERATURE SERIES

Ref	Authors	Year of Paper	Sample Size	Stent type (Number)	Site of obstruction (Number)	Success Rate	Purpose (Number)
[61]	Wholey et al	1998	10	Wallstent	Rectosigmoid (5) Descending (5)	90% (9/10)	Preoperative (6) Palliative (4)
[62]	Rey et al	1995	12	Ultraflex (11) Wallstent (1)	Rectum (NA) Rectosigmoid (NA)	92% (11/12)	Palliative
[63]	Itabashi et al	1993	2	Z-stent	Rectosigmoid	100% (2/2)	Palliative
[64]	Tejero et al	1994	2	Wallstent	Sigmoid	100% (2/2)	Preoperative
[65]	Turegano-Fuentes et al	1998	11	Wallstent	Rectosigmoid	64% (7/11)	Palliative

2.7 CURRENT PRACTICES OF DEPLOYING COLONIC STENTS

Insertion of stent into the colon is much more difficult than that of the tracheobronchial system or the esophagus. This is because the colon is tortuous, floppy and its movement is almost unconstrained. The catheter delivering the prosthesis has to first negotiate the bend in the colon. This is especially difficult in the rectosigmoid and sigmoid where there could even be 180° bends. In several trials conducted, the stents could not be placed due to the inability of the instrument used to pass through these bends. [9, 14, 56]

Even when the catheter managed to reach the site of the stricture, the surgeon still has the difficult task to pass the stent through this obstructing tumor before the implant can be deployed. This step of the procedure is difficult due to the floppy and unconstrained nature of the colon, as a slight application of force would be enough to cause the colon to move. Pushing the stent against the tumor would cause the whole stenotic site to move together with the catheter. Thus, all catheters for colonic stent deployment are slender with a pointed pilot head to allow them to bore through the stenotic tumors.

As the use of stents to treat colorectal obstruction is still new to many surgeons, there is no fixed protocol for the deployment of the stents. The procedures practiced by this project's consultant surgeon, Dr Charles Tsang (National University Hospital, Singapore) are as follows.

Before the stent can be implanted, there is a need to determine the length of the tumor. A guide wire is inserted through the obstruction until the wire starts to coil under fluoroscopy. The coiling shows that the head of the wire has passed the obstructed region, but it does not show where the obstruction ends. This is illustrated in Figure 2.18. Figure 2.19 shows the endoscopic view of guide wire passing through stenotic site

Figure 2.18 Picture depicting passing of guide wire through stenotic site

Figure 2.19 Endoscopic view of guide wire passing through stenotic site

Using the guide wire, a catheter is inserted through the obstruction. Radio-opaque contrast fluid is sprayed to show the outline of the obstruction. The contrast is also injected at the entrance of the obstruction using the other working channel of the colonoscope. This will determine the length of the obstruction.

Figure 2.20 Spraying of contrast to measure stricture length

With an estimation of the length of the stricture, the surgeon will pick a suitable stent from a range that is on standby. The length of the stent to be used is about 3 cm longer than the obstruction with 1.5 cm of overhang on each side. This length of the stent is the length after deployment. The project's consultant surgeon uses colonic Wallstents from Boston Scientific Incorporated. Upon deployment, the length of Boston Scientific stents reduces by about 30%. A 6 cm stent is actually about 9 cm before deployment.

The contrast catheter is then removed and replaced by the stent-catheter system that enters the colon with the guidance of the guide wire and colonoscope. Colonic stents from Boston Scientific Incorporated which are sold compressed in a sleeve with a pusher. Positioning of the stent is guided by fluoroscopy. The sleeve has fluoroscopic markers at both ends to make it visible under the fluoroscope.

Figure 2.21 Picture depicting the pusher-sleeve assembly used by Boston Scientific Incorporated

Figure 2.22 Endoscopic view of stent entering obstructed site

The stent is inserted into the obstructed region as shown in Figure 2.30 and is deployed by pushing it out of the sleeve. During deployment, the compressive force acting on the stent causes it to move up the colon and therefore, there is a need to pull back the stent delivery system. The stent can be retracted back into the sleeve if less than 60% of it has been deployed, but there were instances reported whereby the sleeve kinks. When this happens, the stent maybe deemed unusable, the next best stent size would be used.

Upon successful deployment, the stent would force an opening across the obstructing tumor as shown in Figure 2.23 and the faecal masses were accumulated would be clear through this opening, as shown in Figure 2.24.

Figure 2.23 Endoscopic view of deployed stent

Figure 2.24 Fecal waste exit through stent seconds later

Although there are variations in the ways colonic stents are implanted, certain steps are common amongst all literature the author had reviewed. These include:

- 1) preparation of the rectum, sedation, analgesia and position of the patient which are common with normal colonoscopic procedure,
- 2) insertion of guide wire,
- 3) measurement of stricture length with fluoroscopy,
- 4) and deployment of stent.

Other procedures that are being practiced include:

- 1) Canalization when the stenosed lumen does not allow the guide wire or catheter to pass. This can be done using an endoscopically directed Nd:YAG laser to create a hole in the obstruction or by mechanically dilating the lesion with an endolumenal balloon catheter. [6, 12, 51] However, balloon dilation is suspected to have caused perforation in some cases. [12, 15, 51]
- 2) Straightening of the sigmoid with a stiff guide wire. (Seldinger's technique) [9, 12, 14, 48, 52]
- 3) Stent expansion by using a balloon catheter to help the stent open. [12]
- 4) Use of colonoscope or endoscopes.

Although many trials conducted do not use them, it is widely agreed that a combination of both endoscopy and fluoroscopy is highly advisable. [7, 12, 14-15] This is especially true for lesions above the rectosigmoid region. The use of endoscopy not only allows the surgeon to see the process, it helps ease the passage guide wire in the tortuous portion of the colon, allows biopsy of the lesion, and adds stiffness to ease deployment of the stent. The shortcoming of this method is that the working channel of endoscopes and colonoscopes are usually very small ($\approx 3\text{mm}$ diameter) and thus restricting the size of the collapsed stent to be used.

2.8 FEASIBILITY OF POLYMERIC COLONIC STENTS

Besides migration and re-occlusion, the main reason why colonic stent had not gain popularity despite numerous publications that praised its effectiveness in relieving colorectal obstruction is cost. Patients who experience acute colorectal obstruction that requires emergency surgery to relieve the blockage are usually in the later stage of cancer and not many will live beyond one year of the surgery. Colorectal stenting serves as a palliative procedure and a bridge to prepare the colon for anastomosis. For the latter, the period in which the device is implanted is only a few days. Currently, almost all colonic stents are metallic and cost a few thousand dollars a piece. Therefore, the costs involved are sometimes deemed to be unjustifiable for a device that would be discarded a few days later during anastomosis.

Although metallic stents are usually stronger and more collapsible than polymeric stents with similar design, they are also usually more expensive and difficult to manufacture. The procedures of making of metallic stent, which will be covered in Chapter 3 of this report, often involve a number of steps and sometimes even heat treatment whereas a polymer one can be molded directly from a mould. Therefore, a polymeric colonic stent would be less costly than a regular metallic stent and thus making it more suitable for use as a bridge for the preparation of the colon for anastomosis.

By using a cost efficient stent, more patients would not be required to undergo the conventional two-staged surgery procedure to remove the obstructing tumor. Instead, the stent can be used to clear the colon for the second operation, rather than performing a temporary colostomy. This would cut down on treatment cost and the risk involved, as the number of surgical procedures is reduced by one.

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3.1 INTRODUCTION

The development of a polymer colonic stent is the main motivation in this project and as discussed in Chapter 1 and 2, the first step to be taken was to conduct a literature review and study of stent designs. The literature review was presented in Chapter 2 of the report and this chapter will start off with the approach to be used to tackle this project.

3.2 METHODOLOGY

The developing the new polymeric stent would require some background to stent design and this knowledge would be acquired through literature reviews together with a study of patents of stents designs. From there, a list of the needs of a colonic stent would be defined. Various designs would then be suggested for consideration and the most suitable would be further developed. Prototypes of the design would be fabricated for bench-top testing to study the performance of the device. Improvements would then be made to the design which would in turn be fabricated and tested again. This iterative process would be carried out and a suitable one would be tested out in an animal. An outline of the process is as shown in Figure 3.1. Details of these are found in the following chapters.

Figure 3.1 Approach to stent development

In order for the new stent to be used, a delivery system would be required to bring it the stricture in the colon and deploy it. Therefore, there is also the need to develop a suitable deployment catheter for use with the designed stent. Current colonic stent catheters are sold with the stent and are not reusable. One of the aims of this project was to create a stent system is economical enough that it can also be used for training purposes. As such, a new delivery catheter would be part of this system. This new catheter could be either reusable or cheap.

In addition to the delivery system, the difficulties involved in determining the length of the obstruction (and therefore the length of stent to be used) were also discussed in

Chapter 2. Thus, a device to that can determine the length of the stricture easier and without the need for fluoroscopic apparatus would be beneficial. This can also be added to the package. Hence, this project would consist of 3 parts as shown in Figure 3.2.

Figure 3.2 Three main portions of project

3.3 STUDY OF PATENTED DESIGNS

The use of stents to treat obstructed lumens has gained popularity over the years and areas in which the device can be applied had increased. From the initial use of stents to treat blocked arteries, the use of stents has spread to the trachea, bronchus, esophagus, urethra, bile ducts, colon, etc. It has even been used in some of places which were previously unthinkable, such as the vaginal and nostrils. To cater to these new applications, new stents have been introduced. Early stents were just simple polymer tube and metal spirals, but today there are a wide variety of stents available in the market and many more new designs are still being filed for patents.

This innovation in stent technology is not restricted to just the stent itself. New approaches to deploying the stents have also evolved over the years to suit the characteristics the environment in which the stent has to be implanted.

To have a better understanding of stent designs, a patent search was done for stent designs that were filed from 1973 to 2002. The stent designs can be classified under 3 main categories.

- i) Balloon expandable stents
- ii) Self-expandable stents
- iii) Non-Collapsible stent

3.3.1 BALLOON EXPANDABLE STENTS

Balloon expandable stents are usually made of metal and appear as tubes with meshed walls. They are mounted on a balloon catheter and during deployment. The force from an inflating balloon opens up the stents to its final diameter. Commercially, there are several types of balloon expandable stents available. Some of the commonest balloon expandable stents include the Palmaz stents (Johnson & Johnson Interventional Systems, USA), the Strecker stents (Boston Scientific Incorporated, USA), the Gianturco-Roubin stents (Cook in Corporated, USA) and Wiktor stents (Medtronic Incorporated, USA).

3.3.1.1 PALMAZ STENT AND SIMILAR DESIGNS

The Palmaz stents [66], as shown in Figure 3.3 and Figure 3.4, were first filed in 1985 and were initially made of annealed steel [18]. Current ones are made of a stainless steel alloy (304) which offers better physical performance and more stable crystallographic structure. In its unexpanded state the stent is a tube with numerous slots in its longitudinal direction. When fully expanded, the slot opens up to become diamond in shape, forming a tubular lattice with the struts of the lattice embedded in the vessel wall.

This stent is popularly used in the coronary system. A drawback of this stent is that it offers limited longitudinal flexibility and thus cannot be used for tortuous lumens. Being an uncovered mesh stent, the Palmaz stent also suffer from granulation through the mesh.

Figure 3.3 Picture of Palmaz stents in their collapsed and expanded form [67]

Figure 3.4 Picture showing the expansion of Palmaz stents [68]

Many designs similar to the Palmaz stents have been patented over the years. S Jayaraman [69] proposed flexible inter connectors to join up short sections of Palmaz stents to improve the longitudinal flexibility of the stent. Several designs of the interconnections were studied in this patent. Figure 3.5 shows the last embodiment of the stent.

Figure 3.5 Stent design proposed by S Jayaraman in US Patent 5755781 [69]

Numerous similar works to this were patented with different connecting joints, including some by Palmaz himself.

Marin et al [70] proposed the modified Palmaz stent with barbs for improved anti-migration effect, as shown in Figure 3.6. These barbs were to anchor to the wall of the lumen. With the barbs, the inventor hopes to reduce the dependence on friction to hold the stent in place and therefore stents with thinner wall can be used. A thinner wall would mean a larger lumen and the inventor also felt that lesser radial acting on the vessel wall may result in lesser injuries.

Figure 3.6 Stent design proposed by ML Marin et al in US Patent 5397355 [70]

Whereas Marin et al opted to design a stent with lesser radial strength and thinner wall, Yadav [71] went for one with more resistance to axial compression. In US Patent No. 6083258, he described a stent which can lock itself when expanded by using overlapping with teeth as illustrated in Figure 3.7. However with overlapping surfaces and teeth, the walls of the stents are expected to be thicker which also mean smaller stent lumens.

Figure 3.7 Illustration of locking stent describe by Yadav in US Patent 6083258 [61]

Beside the few that were mentioned, there are many more patented stents that are similar to the Palmaz stent. Many of these have more intricate mesh patterns such as the one shown in Figure 3.8. Many of these patents claimed better flexibility, strength, smaller reduction in the length after deployment and anti-granulation coating.

Figure 3.8 Drawing of stent with more intricate mesh design [72]

3.3.1.2 STRECKER STENT

The first Strecker stents, as shown in Figure 3.9, were introduced in 1987. [18, 73] Strecker stents are tubular meshes knitted from stainless steel (316L) or tantalum wires. The filament used are loosely knitted in such a way that they overlap at their intersections as shown in Figure 3.10. By virtue of this knitted design, the stents are highly flexible and compressible in both radial and longitudinal directions in both its expanded and collapsed state. Thus they are suitable for use in tortuous channels and even those with kinks. Like the Palmaz stents, Strecker stents are loaded on a balloon catheter, but they also have their ends covered by silicon sleeves to prevent the stents from slipping on the balloons during delivery. When the balloons are inflated, the silicon sleeves would roll back off the ends of the stents to allow for full expansion.

Figure 3.9 Picture of Strecker balloon expandable stents [74]

Figure 3.10 Drawing depicting knitting characteristic of Strecker stents

3.3.1.3 GIANTURCO-ROUBIN STENT AND SIMILAR DESIGNS

The Gianturco-Roubin stents [75] are made of stainless steel filaments folded in a series of loops to shape like the spiral of notebooks and are therefore sometimes called “Bookbinder stents”. These stents are sold pre-mounted on the balloon catheter and slightly embedded into the balloon material to prevent slipping during delivery. Like the other stents mentioned in this chapter, this type of stent is deployed by inflating the balloon catheter. Advantages of this type of stent include high flexibility and smooth edges which can help prevent injuries to vessel wall. However, the stents have poorer collapsibility ratio when compare with most other metallic stents, lack stability in length and stress points are formed at the bends of the wire.

Figure 3.11 Drawing of Gianturco-Roubin stent [75]

A rather similar design was filed in the US by Boatman and Brunett. [76] In this design, the stent is to be formed from a sheet of biocompatible material that had been shaped to have a wavelike pattern. The sheet is to be rolled around a balloon catheter to obtain the tubular shape of the stent. The inventors of the stent claimed improved length stability and the elimination of the problem of stress points that are common with stents formed by wire bending. Figure 3.12 shows a drawing of this design.

Figure 3.12 Boatman et al's design in US Patent No. 5632771 [76]

3.3.1.4 WIKTOR STENT AND SIMILAR DESIGNS

The Wiktor stents [77] are another type of stent that are formed by folding wires. The stent was invented by an engineer, DM Wiktor, after he underwent open heart surgery in 1984 [78]. This was the world's first coronary stent. For these stents, the wires are wound to get a zigzag profile and are then tightly wrapped around the balloon catheter in helical fashion. This type of stents is known to have good flexibility and trials conducted on the cardiovascular system had shown encouraging results. Deployments are performed by inflating the balloons on the catheter. Figure 3.13 illustrates the deployment of the stents.

Figure 3.13 Illustration of the deployment of a Wiktor stent [77]

While Wiktor used zigzagged wire to form a helical stent, others proposed other designs that can be formed with the zigzagged wires. Hillstead [79] proposed a stent that can be formed by folding a zigzagged wire into a sequence of loops with interconnections, similar to those in the Strecker stents, at their intersections. With such a design, the proposed stent is believed to have good flexibility longitudinally, but collapsibility should be similar to those to the Gianturco-Roubin stents. Figure 3.14 shows a drawing of the proposed stent.

Figure 3.14 Drawing of stent designed by Hillstead [79]

In another of his patent (US Patent No 5135536) [80], Hillstead proposed forming an already zigzagged wire in a zigzag manner, as shown in Figure 3.15, before rolling it up to form a stent as shown in Figure 3.16.

Figure 3.15 Profile of wire before rolling to form stent [80]

Figure 3.16 Stent formed after rolling wire [80]

3.3.1.5 OTHER DESIGNS OF BALLOON EXPANDABLE STENT

In US Patent No. 4877030, Beck and Nanko [81] proposed a vascular stent consisting of synthetic woven material attached to a metal wire frame support. The design is simple, but the author feels that such a stent will lack flexibility and collapsibility. Figure 3.17 shows the design of this prosthesis.

Figure 3.17 Stent designed by Beck et al

- (a) Woven material with metal frame before being rolled to form stent,
 (b) stent in its collapsed form, and (c) expanded stent [81]

Derbyshire [82] proposed another C-shaped stent. This stent, shown on Figure 3.18 has the ability to lock at a fixed diameter and thereby improving its strength. By ratcheting means, the stent can be expanded to a required diameter and be locked in place. Therefore there may not be a need to have a range of stent sizes. The stent also possesses a large surface area which can reduce tissue injuries due to localized stresses. The inventors also claimed that the stent can be removed after temporary use. However, like the previous design, the author feels that the stent's use will be limited by its lack of longitudinal flexibility. The protruding teeth of the ratchet may also cause perforation of the vessel walls.

Figure 3.18 Ratcheting stent described by Derbyshire [82]

A stent using similar ratcheting principle is patented in 1995 [83]. This stent, by MS Williams, has V-shaped cuts on its outer surface, as shown in Figure 3.19. When rolled, the V-shaped cut protrudes from the surface to become the teeth to lock the stent. These protrusions also roughen the surface of the stent and act as anchors to prevent migration.

Figure 3.19 Stent patented by MS Williams (US Patent No.5423885) [83]

In another patent, Carpenter et al [84] described a ratcheting stent formed from a series of tubular bands. This is shown in Figure 3.20. Using the same concept of a cable tie, the stent can be expanded by a balloon catheter fitted through it and lock itself in the expanded position. The bands are held together by a connecting tube that stretches from one end to the other end of the stent. The banded design allows axial flexibility to the stent which are missing in the previous three designs mentioned. The bands also help prevent the dislodging of the stent from the stenosis site. However, a possible disadvantage of this could be that it is susceptible to granulation between the bands. The author also feels that the stent could fail if the radial forces acting on the stent cause the bands to collapse sideways as depicted in Figure 3.21.

Figure 3.20 Stent patented by Carpenter et al [84]

Figure 3.21 Possible failure mode when the bands of the stent collapse sideways

3.3.2 SELF-EXPANDABLE STENTS

There is a very wide variety of self expandable metal stents that are currently being used. Most of these make use of elastic deformation of the material to collapse the stents and are deployed by releasing the constraints used to hold them in their closed form. Others more advanced versions uses shape memory alloys. These stent would return to its open form when heated the body temperature. For metallic self-expandable stents, the two most well-established designs are the Wallstents (Boston Scientific-Schneider, USA) and

the Gianturco Z-stents (Cook Incorporated, USA). Other well-established self expandable stents includes, the Strecker Ultraflex stent (Boston Scientific Incorporated, USA) and the Memotherm stent (Bard-Angiomed, Germany).

3.3.2.1 WALLSTENT

The original Wallstent (US Patent No. 4553545) [85] was a cylindrical tube made of helical filaments that were braided together. The device was invented by Hans Wallsten of Medinvent SA, Switzerland which was later bought over by another Swiss company Schneider AG in 1989. The bought over saw further developments in the research and development in the stent such as coating to prevent ingrowths, better radio-opacity, better delivery catheter and the availability of variants for the tracheobronchial tree, esophagus, vascular system and biliary system. A wallstent is shown in Figure 3.22.

The braided design of the stent gives it the flexibility to conform to the lumen in which it is implanted, but like all most meshed stents, the Wallstent shorten when it is deployed and this can cause difficulties in the accurate deployment of the stent. The manufacturer of the stent can however increases the pitch of the helical spring to improve the consistency in length but this come in the expense of radial strength. A compromise would have to be reach depending on the requirements of the applications. Currently, this is the most popular self-expandable metal stent and is sold by Boston Scientific Incorporated after the acquisition of Schneider AG from Pfizer Incorporated in 1998.

Figure 3.22 A Wallstent [22]

During deployment, the stent is constrained in a sleeve in its collapsed form. At the stricture, the stent is deployed by withdrawing this sleeve. Figure 3.23 shows a half deployed Wallstent.

Figure 3.23 A half deployed Wallstent [86]

3.3.2.2 GIANTURCO Z-STENT AND SIMILAR DESIGNS

The original Z-stents (US Patent No. 4580568) [87] that were introduced back in 1985 were made of 0.018mm diameter stainless steel wires [18] and as the name would suggest, the wires were bent in a zigzag manner. The wires in the Z-stents are bent six to eight times in opposite directions and the ends are then joined by solder to form a loop as shown in Figure 3.24.

Figure 3.24 Side and front side view of the Z-stent [87]

Early Z-stents were plague with many problems. They were difficult to place in the central position when used in short strictures. When improperly place, one end of the stent would have to bear all the force applied by the stricture on it, causing that end to expand lesser than the other end. This causes the stent to adopt a conical shape instead of being cylindrical. The deformation in shape will make the stent more vulnerable to migration. To overcome this problem, a double stent was designed, but it was notices that the stent was weakest at the link between two segments and fails to open fully sometimes. This however can be easily overcome by placing another stent at the junction involved. Many modifications were introduced to the stent design to improve its characteristics even after the death of its inventor. Today, there are many version of this stent and they are used to treat stricture in many parts of the body due to their versatility. Strengths of these stents are determined by the diameter of the wires used.

Figure 3.25 Double Z-stent with eyelets at the wire bends which are threaded together by suture [88]

The spiraled Z-stent (US Patent No. 5507767) [89], as shown in Figure 3.26, is one of the newer variants of the Z-stents and was introduced in 1998. It is shaped like the Wiktor stent, but the bends are threaded together to constrain the length of the stent, as shown in Figure 3.27. The spiral design gives the stent a more even distribution of load. Results of a multi-center randomized comparative trial between the spiral Z-stent and the Wallstent were presented at the American Society for Gastrointestinal Endoscopy (AGSE) Annual Meeting [90]. The result showed that the spiral Z-stent is comparable to the Wallstent in terms of placement, occlusion rates, and overall stent patency with the spiral Z-stent having a slight advantage in terms of flexibility [90]. However, the main advantage of the spiral Z-stent is that it does not shorten much upon deployment.

Figure 3.26 Picture of Cook Inc.'s spiral Z-stent [91]

Figure 3.27 Drawing showing joining method used in the spiral Z-stent [89]

3.3.2.3 SHAPE MEMORY ALLOY STENT

Stents made from shape memory alloys expand and contract on the effects of temperature. The alloy, known as nitinol, is usually made of titanium and nickel. The alloys are known

to be of high elasticity and corrosion resistance, thus giving the stents good collapsibility and biocompatibility. Common stent that are made of such alloys are the Memotherm stent from Bard-Angiomed and the Strecker Ultraflex stent from Boston Scientific Incorporated. The designs of these stents are generally similar to those of wire meshed balloon expandable stents, but due to the shape memory effects of its material, the stent are able to expand without the need of an angioplasty balloon and deployment methods of such stents are usually similar to that of self-expandable stents. However the stents are usually more expensive because of the higher cost high-tech alloy and the technology required in processing them.

The Memotherm stent and the Strecker Ultraflex stent are two of the commonest type of nitinol stents available today. They are both sold with the deployment catheter which the stent was fitted into at low temperatures. Deployment methods for both types of stent are by withdrawing a sheath constraining their expansion. The heat from the patient's body will cause the stents to restore to its expanded state. The design of the Memotherm stent is similar to that of the diamond lattice structured Palmaz stents whereas the design of the Strecker Ultraflex stent is the same as that of the Strecker balloon expandable stents.

3.3.2.4 NON-METALLIC STENTS

Non-metallic stents are usually made of elastomer. They are usually used in the tracheo-bronchial system. These are usually just simple tubes sometimes with studs on their external surfaces to prevent migration of the stent.

Non-metallic tracheo-bronchial stent are usually made of soft silicone and are sold without the delivery catheter. They are folded and fitted to a rigid metallic tubular introducer device with a pusher that will be used to eject a stent for deployment. Such stents are often preferred for use in the respiratory system as they are cheaper, more comfortable, adjustable and removable, and do not cause any perforation of the tissue walls. However, the use of such stent are very limited as they have thick walls which

decrease the size of the lumens and poor collapsibility ratio when compared with the metallic wire meshed stents. Figure 3.28 shows two different types of silicone stents.

Figure 3.28 Picture of a Dumon (left) and Hood (right) tracheo-bronchial stent

3.3.2.5 OTHER SELF EXPANDABLE STENT DESIGNS

A simple expandable stent that had been patented [92] is the helical coil. This design was similar to the first stent that was to be used to treat vascular obstruction by Charles Dotter [93]. The stent is flexible and do not shorten upon deployment, but it is not very collapsible and may fail if the forces acting from different directions on it are uneven. Such a failure is depicted in the drawing in Figure 3.29. As such, more complex designs were required to properly stent strictures in the body.

Figure 3.29 Drawing showing possible failure
if a simple helical design stent is used [92]

Another simple design that is seen in several patents is that of a flexible sheet of material being rolled to form a tube. Upon release, the material will unroll itself and takes up the

shape of the lumen. However these designs do not offer much flexibility in the longitudinal direction.

3.3.3 NON-COLLAPSIBLE STENTS

Non-collapsible stents are polymer tubes with features at its ends for anti-migration purposes. There are not many stents that fall into this category. The polyurethane Double J stent, as shown in Figure 3.30, is one of such stents. These stents are used for the urethral. They are tubes with loops at its ends, which the manufacturer called 'pigtailed'. The purpose of these "pigtailed" is to prevent movement of the stent after deployment. During deployment a steel rod is passed through the center of the stent to straighten it. To deploy the stent, the tube would be withdrawn allowing the ends to coil up to form the 'pigtailed'.

Figure 3.30 Double J stent

3.3.4 CONCLUSION

Majority of stent design patents filed are for metallic stents and most of these are meshed. These stents are formed by weaving filaments, bending of wires, rolling of metal sheets or cutting of patterns on metallic tubes or sheets. Strength, collapsibility and longitudinal flexibility are some of the attributes that are of concern to the designers of these stent.

Non-metallic stents are usually made of elastomer and there designs are just simple tubes with features added to prevent stent migration after deployment. The main focus is in the prevention of stent movement.

3.4 STENT FABRICATION METHODS

Although the designs of stents are often very simple, the cost of buying such implants are usually quite high, costing from a few hundred to a few thousand dollars per piece. Contributing factors to the high cost of the stent includes the cost of experimentation, insurance, shipment, consultancy, bureaucracy, etc. The materials used to make these implants also play a very important role in determining the cost of the stent and the manufacturing technique also has a contributing factor to the cost. This part of the report examines some of the fabrication methods of stents that may have contributed to the high cost of the device.

The cheapest stents available commercially are the polymer and silicone stents. Some of these stent can cost less than US\$100 [94]. These stent are usually made of injection molding. This process only involves one step and is generally quick and the technology required is common. Recent work by Lim et al [95] also used rapid prototyping and vacuum casting to customize polymer stent. As stents are usually not produced in large numbers, this may be a suitable method of producing stents economically as there is no need to invest in a metal mould.

There are several methods that are used to produce metal stents depending on the design of the stents. Some stent, such as the Z-stents, the Wiktor stents and the Gianturco-Roubin stents are formed by bending wires. The bent wires are then rolled into shape round a mandrel to get a cylindrical shape. Although the procedure of making such stents is simple, the high cost of the stents (A 10mm diameter Z-stent cost around US\$1000 [94].) maybe due to the material of the cost of the catheters that comes along with the implants.

The Wallstents, which are US\$100 to US\$500 more expensive than a similar size Z-stent [94], are formed by weaving steel wires in the required manner to obtain the tubular shape of the stent. The Wallstent is form by braiding numerous helical filaments together which maybe difficult to make. The difficulty in making these stents make account for part of the high cost, but the author feels that much of these may be due to the cost of the catheter.

Other methods that are mentioned to make stents are laser cutting and photochemical etching to produce the mesh for the stent wall. Such methods are applied to stents that involves the cutting of patterns on tubular or sheet material, such as in the case of the Memotherm and Palmaz stents. As expected, the use of such expensive techniques may also contribute to the high costs of the stent. A vascular Palmaz stent as quoted in [96], costs US\$2000.

3.5 REQUIREMENTS OF NEW STENT

From the information gathered in the literature search, the proposed new stent must have the following qualities for it to be deemed suitable for use in the treatment of colorectal obstruction.

- A1) The new stent must have adequate distending strength to force open the tumors that are causing the obstructions.
- A2) The stent must also be flexible along its length for it to be place at the bends of the colon.
- A3) Even when fully collapsed, the stent together with the catheter must also be flexible longitudinally for it to negotiate the bends in the tortuous colon.
- A4) The collapsed stent should be slender enough for it to be inserted into the obstructing tumor mass.
- A5) The materials used must be biocompatible (ISO 10993 certified) and radio opaque.

- A6) The stent must not be too rigid to cause perforation.
- A7) Sharp pointed features that can puncture the colon must not be present.

Besides the five qualities mentioned, it is also desirable for the new stent to have the following properties. These are arranged in order of importance.

- B1) The new stent should be economical to produce.
- B2) The length of the stent should be customizable quickly.
- B3) The new stent should have good anti-migration properties.
- B4) The deployment method of the stent should be simple and preferably close to the current one to avoid the need for extra training.
- B5) Changes in the length of the stent during deployment should be minimized to ease accurate placement of the stent.
- B6) The catheter of the stent should be reusable to cut down cost.
- B7) The stent should be covered to prevent ingrowths.

To achieve point (B1) on the list, it is advisable that a one step process be used to manufacture the stent. This process should be simple and feasible for small scale manufacture. Plastic molding would be excellent as parts can be shaped by melting the plastics or by mixing components of chemicals at room temperature.

For point (B2), the diameters of the colons do not vary much as compared to many of the lumens that are currently being treated with stents. Therefore, there is not much of a need to vary the diameter. Current manufacturers of colorectal stent do not provide variants of different diameters too, as an opening of about 20 mm would be adequate for the decompression of the colon.

With regards to the strength of the stent, many early works started with esophageal and trachea stents which worked out fine and no published work on the amount distending strength required was found. There had been very few reports of stent having inadequate

strength to open up the stricture and thus with regards to the issue of the strength of new stent, the author feels that the strength of current stent would be a good enough gauge.

The only specification of the stent in which the author feels that quick customization would be of good benefit is the length of the stent. The length of the strictures can vary by a lot. The shorter strictures can be only 20 mm to 30 mm long whereas the more severe ones can be above 200 mm long.

Currently, the surgeon has to have the whole set of stents of different lengths ready before implantation, as the length of the stricture is usually not known until measurement with fluoroscopy is carried out. Occasionally mistakes are made during deployment or the stent delivery catheter system fails to operate properly, then a new stent would have to be used. Often, the surgeon would not have a spare stent of the same size ready and the next longer stent would have to be used instead. This compromise could lead to some complications. It is believed that stents that are longer than required are more prone to migration and fecal impaction. As such, it would be beneficial if only one long stent is needed to be prepared and customization can be quickly performed by cutting down the stent to size. Another alternative is to have short segments that can be joined up quickly to form one longer stent.

Migration is a common problem in colonic stent. The peristalsis of the colon is believed to be the major cause of this problem. Features such as flanges at the ends of stents have been added in attempts to reduce the amount of migration in colonic stent, but most often migration are not bad enough to cause reocclusion of the stenosis. If necessary, they are often treated by restenting. Migration is most common in the first 24 hours of the stent deployment, but it will be greatly reduced once part of the tumor grows through parts of the mesh of the stent, thus giving it better anti-migration properties when compared with covered stents. A guide to reducing migration is not to use excessively long stents and stent with inadequate diameter. Therefore, as pointed out previously, a stent with

customizable length can help in preventing migration. A wire meshed design may also help by allowing some granulation.

A problem with the very popular Wallstent is the high reduction in length when it is deployed. The Wallstent shortens by about 30% after deployment, so positioning the stent accurately may be a problem because of this.

With regards to point (B6), current stents are sold inserted into the catheter. Once deployed, the stent cannot be reinserted back into the catheter. Therefore any error made or equipment failure during the deployment process could cause the stent to be deemed useless. Even if an insertion is successful, the catheter would be discarded after that. As such, having a reusable catheter may reduce the cost of having to buy a new one every time.

Although granulation through the mesh of a stent can prevent migration, too much of it can lead to reocclusions of the lumen. However, it would take some time for the ingrowths to fully block the stent lumen. The current stent is designed as a bridge to surgery by allowing preparation of the colon before surgery and would only be in the body for a few days to a couple of weeks. Thus it would unlikely be a problem. However it would be ideal if it does not allow excessive ingrowths.

3.6 CONCEPTUAL DESIGNS OF NEW STENT

Based on the findings of the literature review, five possible designs of the new stent were conceptualized and the merits and pit falls of each are discussed.

3.6.1 DESIGN 1

Figure 3.31 Drawing of Design 1

This stent design is based on those of current polymeric stent used in airway management. Triangular grooves are cut onto the exterior surface to help reduce migration. These grooves also give the stent longitudinal flexibility which is absent in conventional self-expandable polymer stents. The stent would be collapsed just like the polymeric tracheobronchial stents by folding. Fabrication of this stent should not be difficult and the length of the stent should be easily customized by cutting the stent down to its required length. The strength of the stent may be customized when required by increasing the wall thickness but this will come in the expense of having smaller lumen

size. The increase in wall thickness will also affect the stent's collapsibility and thus its ability to bore through the stricture. Having to be collapsed by folding, the material would have to get high flexibility and able to bend 180° without any plastic deformation. Therefore the material that is suitable for making the stent is restricted to the elastomers which may not provide adequate strength unless there is a thick wall.

3.6.2 DESIGN 2

Figure 3.32 Drawing of Design 2

Design 2 is also a modification of current self-expandable polymeric stents. It has 'C' shaped cuts on its exterior surface. These cut should give the stent great longitudinal flexibility and the through cuts would allow some granulation through its walls. Granulation of tissue through is one of the reasons why meshed stents are less prone to migration. Therefore by allowing granulation through the 'C' shaped cuts on the stent wall, the new design should be better at preventing migration. However like design one, the stent is collapsed by folding and this would require a large deformation of the material which will restrict the suitable materials to just rubbers. For a design with that many cuts

in its wall, the wall stent is likely to be very weak in strengths unless it has thick wall which will then lead to smaller lumens.

3.6.3 DESIGN 3

Figure 3.33 Drawing of Design 3

This design of the proposed colonic stent is as a helical ribbon. Coiled stents have been tested in numerous applications with fairly good results. The stents are simple and the problem of stents shortening after deployment can be controlled. However, these stent were prone to collapse sideways, causing the stents to flatten (as mentioned in Chapter 3.3.2.5). This design has rectangular filaments instead of round ones. The width of these rectangular cross sections may prevent the stent filament from collapsing sideways and thereby solving that problem. The stent is likely to be very easy to fabricate and can be collapsed simply by twisting the stent. By virtue of this, there is only the need to secure the ends of the stent and a sheath to prevent the stent from opening would not be necessary, thus reducing the cross-section of the delivery system. The design should also have very good longitudinal flexibility to allow it to negotiate the tortuous segments of

the colon. However a possible drawback of this design is the lack of control over its length after deployment.

3.6.4 DESIGN 4

Figure 3.34 Drawing of Design 4

Design 4 is a wire meshed stent formed by loops zigzagged filaments and straight ones along its length. The zigzagged filaments have flexible hinges at their bends to allow the stent to collapse and the long straight filaments keep the length of the stent constant. Meshed stent are known to be better at resisting migration, thus the stent is not covered for part of the tumor to go through and thereby improving its anti-migration property. It also incorporates the flanged ends found in many of the colonic stent to help prevent dislocation of the stent. The stent should be able to have good collapsibility and longitudinal flexibility would be dependent on the material used. However, the hinges are designed to bend and that may have a negative effect on the distending strength of the stent.

3.6.5 DESIGN 5

Figure 3.35 Drawing of Design 5

For this design of the new stent, the main focus was on the collapsibility. The design started off in its collapsed form. When fully collapsed, the stent would take the form of a solid cylindrical rod. Upon release, the stent will open up to the wire frame structure as shown in Figure 3.35. The design is in some ways similar to the Gianturco vascular Z-stent except that in this case, the strut of this stent is curved instead of being straight as in the Gianturco Z-stents. The curved profile is to distribute the strain of the material when it is fully collapsed. Deformation required by the material is a lot lesser to collapse the stent as compared with other design which means that stiffer materials can be used to get a stent with greater strength. Like normal meshed stent, the stent should be able to allow some granulation which can help in preventing the migration of the stent. As for longitudinal flexibility, this stent may be inferior in this aspect. However, by making the stents into short segments that can be joined, flexibility of the stent can be greatly improved. This can also help in the customization of the stent length as these short modular segments can be joined to form longer ones.

3.7 CHOSEN DESIGN

The five designs are compared to the required and desired qualities listed in Chapter 4.2.4 to determine the most suitable design to be selected for further development. The

qualities to be examined are re-listed below and the comparison of the designs is shown in Table 3.1.

Required qualities:

- A1) The new stent must have adequate distending strength.
- A2) The stent must also be flexible along its length.
- A3) The undeployed stent must also be flexible longitudinally.
- A4) The collapsed stent should be slender.
- A5) The materials used must be biocompatible and radio opaque.
- A6) The stent must not be too rigid to cause perforation.
- A7) Sharp pointed features that can puncture the colon must not be present.

Desirable qualities

- B1) The new stent should be economical to produce.
- B2) The length of the stent should be customizable quickly.
- B3) The new stent should have good anti-migration properties.
- B4) The deployment method should be simple.
- B5) The length of the stent should not change during deployment.
- B6) The catheter of the stent should be reusable.
- B7) The stent should be covered to prevent ingrowths.

Table 3.1 Comparison of the designs against required and desired qualities

Quality	Design 1	Design 2	Design 3	Design 4	Design 5
A1	Doubtful	Doubtful	Unsure	Doubtful	Likely
A2	Yes	Yes	Yes	Yes	Yes
A3	Doubtful	Yes	Yes	Yes	Yes
A4	Unlikely	Unlikely	Yes	Yes	Yes
A5	Possible	Possible	Possible	Possible	Possible
A6	Yes	Yes	Yes	Yes	Yes
A7	Yes	Yes	Yes	Yes	Yes
B1	Yes	Yes	Yes	Yes	Yes
B2	Yes	Yes	Yes	No	Yes
B3	Doubtful	Likely	Likely	Likely	Likely
B4	Possible	Possible	Possible	Possible	Possible
B5	Yes	Yes	No	No	No
B6	Possible	Possible	Possible	Possible	Possible
B7	Yes	No	No	No	No

It is evident from Table 3.1 that design 5 is the only one that can fulfill all the requirements needed. It is therefore chosen despite not fulfilling qualities B5 and B7 which are desirable. Its wire meshed design can allow high collapsibility ratio to allow the penetration of the stent through the lesion. Collapsing the stent in this design would involve the bending of the struts. The stent will be produced in short segments that will be joined together to get a longer stent. The joining of short segments will allow greater longitudinal flexibility and customizability in the length. In this way only one length of stent will need to be produced and therefore tooling cost will be reduced.

3.8 STENT DEVELOPMENT METHODOLOGY

Having decided on one design, embodiment will be performed. Considerations such as the dimensions and material used will need to be discussed.

3.8.1 EMBODIMENT OF STENT DESIGN

The diameter of collapsed stent will need to be considered. The collapsed stent should be as slender as possible for it to be inserted through the stricture in the colon easily. A review of the current colonic stents and their collapsed diameter will be used as a guide to consider this dimension of the new stent. Recommendations from the project's consultant surgeon will also be considered.

Having decided on a diameter for the stent in its collapsed form, the number of struts in each section of the new stent will then be considered next. More struts will reduce the mesh size in the stent and therefore provide more even distribution of load and better support of the lumen wall. With a fixed compressed diameter, the more number of struts would also mean a smaller and thinner cross section for each strut. The smaller struts will be more difficult to fabricate and will also break more easily. A broken strut can have catastrophic consequences, as it may puncture the colon walls. Thin struts will also cause the ends of the struts to be sharp and may also cause perforation of the colon wall.

On the contrary, if the struts are made larger, the number of struts will be reduced and this will lead to larger gaps between the struts. This gap may be big enough for the tumor to go through it and therefore defeats the purpose of the stent. A study of the current colonic stent will be performed to determine the size this gap and some calculations will be done to determine the thickness of the strut for the decided number of struts in the stent to ensure that the resultant dimensions will not be too difficult to manufacture.

The stent is designed in short modular segments for ease for customization and longitudinal flexibility. Flexibility is needed for the stent to be suitable for use in the tortuous portions of the colon. The colon is about 22 mm in diameter and at the most tortuous portion of the sigmoid, the bends can be as much as 180°. Therefore each segment should not be more than 44 mm for it to negotiate the bends assuming the connections between segments can bend up to 90°. Therefore, the fully collapsed segment of the stent should be no longer than 44 mm. This is illustrated in Figure 3.36.

Figure 3.36 Drawing showing stent negotiating 180° bend in colon

The struts of the stents are formed by circular arcs. The circular arcs will give equal curvature at all points of the struts and therefore the maximum strain endured by the material should be equal throughout the strut. Figure 3.37 shows the curvature profile of each strut.

Figure 3.37 Schematic drawing of the curve profile of each strut

There are two 5 mm straight portions at the end for joining with adjacent struts. Calculations will be performed to determine the profile of the curved portion of the struts and the resultant length of the stent when it is fully deployed.

Features that will be used to join the segments of the stent will also be examined and the possible deployment technique will also be discussed.

3.8.2 SELECTION OF MATERIAL

The material to be used to make the stent will be plastic as this research is focused on from the start. This is because plastic would be easier to mould and by creating a plastic colonic stent that can be mould, the author hopes to reduce the cost of the stent, as the expensive processes, such as laser cutting, chemical etching and metal weaving, used to make current metal stents are avoided. There are many types of plastics available, but most are not certified to be biocompatible. One polymer that has variants that are biocompatible is polyurethane (PU). The author chooses to use PU to make the stents, as PU can be formulated to give a wide range of mechanical properties and had been used to make stents for the urethra, the airways, the bile ducts and also as coating for metal stents. PU is also available in a liquid mixture forms. Thus, fabrication of the samples can be done at room temperature.

To determine the property that is needed by the polymer, some calculations will be carried out. The properties obtained from these calculation will be used a guide to select a suitable PU for this application.

3.8.3 FABRICATION OF STENT SAMPLES

The stent sample will be produced by vacuum casting technique. Vacuum casting is chosen as the author had experience in this technique and is especially suitable for low quantity production. Also changes to the design of the stent are also expected. Rapid tooling techniques like vacuum casting do not involve the machining of a metal mould. The mould to be used will be made of silicone rubber which is poured over the master pattern of the stent to get the required cavity. These moulds can be fabricated quickly and are much cheaper when compared with metal moulds and therefore time and money that are incurred due to changes in the design will be kept to a minimal.

3.8.3.1 FABRICATION OF STENT MASTER PATTERN

The stent master pattern will be made by rapid prototyping (RP) technique. The RP method that is readily available in the institute which this research is carried out is selective laser sintering (SLS). This technique involves the use a laser beam to selectively fuse powdered materials, such as wax, nylon, elastomer, polycarbonate and metal, into a solid object. Parts are built on a platform, which sits just below the surface in a bin of the heat-fusible powder. The laser traces the pattern of the first layer, sintering it together. The platform is lowered by the height of the next layer and powder is reapplied. This process continues until the part is complete. Figure 3.38 is a schematic diagram of the process.

Figure 3.38 Schematic diagram of selective laser sintering [97]

The stent master pattern consists of the stent geometry with a cylinder fitted through it as shown in Figure 3.39. This cylinder will be replaced by a cylindrical core insert during casting of the stent. The reason for using a core insert is to make the master pattern more rigid. This rigidity is required to enable the pattern to be removed from the mould for reuse. If the cylinder is not included in the design of the pattern, the lattice structured

will break during the cutting of the mould. This is due to the porous nature of the pattern and for such a thin section; the struts of this pattern will turn out to be very brittle. The core insert will also make it easier to cut the mould, as less cutting is needed.

Figure 3.39 Design of stent master pattern

However, due to the rough surface finish and porosity of SLS parts, the RP master patterns will have to be coated before they can be used as the pattern to make the silicone mould. This will be done by spraying a thin layer of lacquer on the surface of the RP model evenly. The lacquer will be applied in thin layers so as to minimize the effects on the dimension of the pattern, but because the porous part will absorb some of the lacquer, many layers will be needed.

3.8.3.2 VACUUM CASTING METHODOLOGY

The fabrication method used to make the stent samples for this research is vacuum casting, as polyurethane that is widely used in this method can be formulated to have a wide range of mechanical properties and had been used in making medical implants. It can also produce intricately shaped parts within a few days. The process is carried out at

room temperature and is one of the least expensive and fastest way to create duplicates of prototype parts made by rapid prototyping machines. In this research, the German HEK 001-ST vacuum casting system is used.

MOULD MAKING PROCESS

The vacuum casting technique begins with the building of the room temperature vulcanization (RTV) silicone rubber mould. This starts with the preparation of the casting frame whereby the SLS RP models, that are to be used as the pattern for making the mould, will be placed and secure, with adhesives, in a molding box assembled from pieces of Perspex. The model for the sprue is also placed and glued in the appropriate places.

Measurements are then taken to determine the amount of silicone resin needed to make the mould. The volume of silicone found from these measurements in cubic centimeters will be multiplied by a factor of 1.1, which is the specific weight of the resin, to determine the mass of silicone resin required. This calculated amount of silicone resin is to be poured into a container. A catalyst would be required to cause the hardening of the silicone resin. For every 10 part of the silicone resin, 1 part by weight of the catalyst is added to it. The mixture will then be thoroughly mixed and degassed in a vacuum chamber to remove the air bubbles that are entrapped in the viscous mixture before the slurry can be poured into the casting frame carefully. After pouring, the pattern in the molding box must be fully encapsulated in the silicone mixture.

The silicone mixture will subsequently be placed in the vacuum chamber for degassing again to remove the air that is trapped in the mixture during the pouring process. Any bubbles left in the mixture may result in unwanted voids in the cavity and will affect the shape and quality of the parts produced. After degassing, the silicone rubber slurry is to be left to bake in an oven at 70°C for about four hours. The baking will accelerate the curing of the mixture.

Upon curing, the mould will be removed from the casting frame and dissected using a knife and mould splitter as shown in Figure 3.40. The cutting of the mould is done in a wavy manner to aid the alignment of the mould parts during assembly, as in the case of a jigsaw puzzle. The RP pattern will be removed from this mould and runners connecting the sprue and the part cavity will be added to the mould by cutting away pieces of material from the mould to form it. Venting will also be added to the mould using the same method. With the RP pattern removed and the addition of the required gatings, a RTV silicone rubber mould will be ready for use. Figure 3.41 illustrates the steps involved in the making of a silicone rubber mould.

Figure 3.40 A mould splitter used in the cutting of the silicone mould

Figure 3.41 Steps involved in the making of a silicone rubber mould

CASTING OF STENT SPECIMENS

To ensure that foreign objects do not be embedded in the part and affect the performance of the stent, the silicone mould of the stent has to be thoroughly cleaned prior to casting. It will then be sprayed with releasing agents, assembled and tightly secured using adhesive tape. The assembled mould is then preheated in an oven to 70°C.

Next, the estimated amount of polyurethane resin and catalyst required will then be poured into two different cups according to the ratio recommended by the manufacturer. Thereafter, the two cups of chemicals will be put in place in the vacuum chamber together with the mould and all other required tools, as shown in Figure 3.42.

Figure 3.42 Setup of equipments in vacuum casting chamber

The door of the vacuum chamber will then be shut and the mixing and pouring of the resin components will be done at a pressure of 10^{-2} torr inside the vacuum chamber. When all the resin have been poured into the mould, the vacuum is switched off and air is allowed to leak slowly into the chamber for 30 seconds to enhance the flow of the resin. This is to help the cavity to fill better. Thereafter, the fast leak button is to be pressed to return the pressure in the chamber to that of the atmosphere. The mould will be removed from the chamber and put into an oven for curing at 70°C . Demoulding time varies depending on the chemical used and the stents can then be removed from the mould after the resin had cured. The sprue, gating and venting system in the part will then be removed from the stent specimen. Figure 3.43 shows the processes that are involved in the casting of the stent specimens.

Figure 3.43 Steps involved in casting the stent samples

3.8.4 CONNECTIONS BETWEEN SEGMENTS

The stent is formed by short modular segments to cut cost and allow quick customization of the stent length. Customization of the stent's length is to be done by end to end joining of stent segments. This joint that holds the stent segments together has to be flexible for the stent to be able to bend longitudinally, but it should also not interfere with the collapsibility of the stent.

A possible way of joining the stent segments together is to use sutures. This method is currently practiced to join up segments of Z-stents, as shown in Figure 3.44. For this to be done, there is a need for holes on each segments for the suture to pass through. These tiny holes can be made at the straight portion of the struts at the ends of each segment. The purpose of these straight portions in the stent were only to join adjacent struts together and they do not undergo much deformation because the forces from the lumen walls that are acting on the stent are absorbed by the curved portion of the struts by straightening themselves. Therefore the straight portions are likely to be less stressed and thus problem of stress concentration due to the addition of a hole may be avoided if these holes were made there, as shown in Figure 3.45 and Figure 3.46.

Figure 3.44 Joining method used in a Z-stent

Figure 3.45 Drawing of proposed holes at straight portions of strut

Figure 3.46 Drawing showing two segments
of stent joined together with suture

The use of suture to join the segment allows loose connection which can give the stent longitudinal flexibility. The diameters of sutures ranges between 0.07 mm to 0.7 mm, and the radial thickness of the stent is about 2 mm. The author decides that the holes would be 1 mm in diameter for all sutures to pass through easily.

4

STENT DEVELOPMENT

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4.1 EMBODIMENT OF DESIGN

4.1.1 DIAMETER OF COLLAPSED STENT

The collapsed stent should be as slender as possible for it to easily bore through the stricture in the colon. Based on findings from literature and catalogues for colorectal stents, the diameters of current deployment catheters range from 3 mm, for the Boston Scientific-Schneider's Wallstents, to 10 mm, for the Cook Inc.'s Z-stents. Therefore this proposed new stent should have a collapsed diameter not more than 10 mm.

However, based on feedback from the project's consultant surgeon, it was preferred that the catheter be introduced through the instrument channel of the colonoscope. Figure 4.1 shows the working channel of a colonoscope. A search was performed on colonoscopes that are currently available commercially. The results on the search showed that the largest working channel that can be found on a standard commercially available colonoscope is 3.7 mm. Thus, deducting an allowance for sliding the catheter through this surgical channel, the largest diameter for the stent catheter system should be about 3.2 mm. Only one of the commercially available colorectal stents (The Boston Scientific-Schneider's Wallstent) has catheters with diameters below 3.2 mm. However, the author feels that it is not possible to make a plastic stent that can be compressed in such a small diameter and yet have adequate strength to open up the stricture to 22 mm.

Figure 4.1 Instrument channel of a colonoscope [36]

Comments of the Z-stent from literatures are that they are more difficult in deploy which may be partly attributed to its large catheter diameter, so it was decided that the new stent be collapsed to a diameter of about 5 mm before deployment, which is similar to that of a Memotherm colorectal stent (Another commonly used colorectal stent).

4.1.2 NUMBER OF STRUTS

With the collapsed size of the stent fixed at 5 mm, the number of struts in each section of the new stent was considered next. Ideally the more number of struts will give more distribution of load on the stent. However more stent struts would also mean smaller dimension that can cause difficulties in fabrication and higher risk of perforation. On the other hand, if there are too few struts, the gaps between adjacent struts will be large which may allow the tumor to penetrate through. The size of tumors can vary by a lot, thus it is difficult to be sure that a gap size is good enough for the job, but this can be based upon stents that are currently used to treat colorectal obstructions. The Gianturco Z-stent is one of these tested designs. Base on photographs of 25 mm Gianturco Z-stents for use in the colon such as the one in Figure 4.2, the stent has 16 struts per section and

the distance where the gap between adjacent struts is largest is at the intersection of the strut. This distance is calculated using the Cosine rule.

Figure 4.2 Maximum distance between gaps in a colonic Z-stent [91]

At the points of intersection where the gap are largest, the 16 struts are combined into 8 struts and the circular cross section of the stent can be seen in Figure 4.3. Joining lines to the center of the circle will give 8 identical sectors and joining adjacent struts will give isosceles triangles. The angle for each sector would be $\frac{1}{8}$ of 360° which is 45° .

Figure 4.3 Cross section of Z-stent at intersections of struts

With this information, by cosine rule, the maximum gap between adjacent struts, $G_{\max}$ is

$$\begin{aligned}
 G_{\max} &= \sqrt{2\left(\frac{25}{2}\right)^2 - 2\left(\frac{25}{2}\right)^2 \cos 45^\circ} \text{ mm} \\
 &= 9.57 \text{ mm}
 \end{aligned}$$

Therefore, if the new stent has 16 struts as in the Gianturco Z-stent, the thickness of each strut can be calculated by similar means. The circle below represents the cross section new stent when it is fully collapsed.

Figure 4.4 Cross section of the new stent when fully collapsed

$$\begin{aligned} \text{Thickness of each strut, } T &= \sqrt{2\left(\frac{5}{2}\right)^2 - 2\left(\frac{5}{2}\right)^2 \cos 22.5^\circ} \text{ mm} \\ &\approx 1 \text{ mm} \end{aligned}$$

Based on past experience with vacuum casting, the author thinks it is possible to fabricate the struts with this technique which is readily available in the institute where the project is conducted. The 1 mm thick strut would also mean that the ends of the stent will be of 2mm thick which should not be sharp enough to cause perforation of the colon.

4.1.3 LENGTH OF EACH STENT SEGMENT

The stent is designed in short modular segments for longitudinal flexibility which is needed to negotiate the tortuous portions of the colon. In Chapter 5 it was mentioned that each segment should not be more than 44 mm for it to negotiate the bends assuming the connections between segments can bend up to 90°.

The struts of the stents are formed by circular arcs with two 5 mm straight portion at the ends for joining with adjacent struts as shown in Figure 4.5.

Figure 4.5 Schematic drawing of the curve profile of each strut

By subtracting the straight portions, the total length of the curve portion of the stent should be less than 34 mm. Assuming the diameter of the whole stent is 30 mm when unconstrained, so that the stent can still give a 22 mm patent lumen when it is compressed by 8 mm, the maximum distance between adjacent strut will be 11.5 mm. (Obtained using cosine rule.) Consider only the curved portion of only half the strut as shown below. For the segment to be less than 44 mm, the length of this curved portion will have to be less than 34 mm.

Figure 4.6 Schematic drawing of half a strut

Figure 4.7 Sector ABC and triangle ABD from Figure 4.6

From triangle ABD, $\cos \theta = \frac{r - 2.9}{r}$ ----- (4.1)

The total length for the curve portion of half a strut, which is formed by two arcs, should be less than 34 mm. Therefore the length of each arc, which is $\frac{\theta}{360}(2\pi r)$ mm, should be less than 17 mm.

i.e. $\frac{\theta}{360}(2\pi r) \leq 17$ ----- (4.2)

Solving equation (4.1) and (4.2) by interpolation, $\theta = 19.75^\circ$ and $r = 49.34$ mm. Using these calculated dimensions, the design of the stent is sketched using Pro Engineer software as shown below.

Figure 4.8 CAD drawing of stent with calculated geometry

With these dimensions, the length of each segment of the opened stent will be as calculated below:

$$\begin{aligned}\text{Length of curved portion} &= 2 \times 49.34 \times \sin 19.75^\circ \text{ mm} \\ &= 33.33 \text{ mm}\end{aligned}$$

$$\begin{aligned}\text{Length of 5 mm straight portion at each end} &= 2 \times 5 \\ &= 10 \text{ mm}\end{aligned}$$

$$\text{Length of open stent} = 43.33 \text{ mm}$$

However it is the norm to refer to the stent in its opened state when choosing a stent. Therefore, the length of an open stent should be a rounded number which is easy to refer. The length of the opened stent is thus rounded off to 40 mm. Calculations are again performed to check if the collapsed stent is within the 44 mm restriction for the stent to negotiate the tightest bends in the colon.

Figure 4.9 Schematic drawing for calculating length of collapsed stent

$$\begin{aligned}\text{Length of BD} &= \frac{1}{2} (40 - 2 \times 5) \text{ mm} \\ &= 15 \text{ mm}\end{aligned}$$

$$\begin{aligned}\text{Angle BCD} &= \tan^{-1} \left(\frac{15}{2.9} \right) \\ &= 79.1^\circ\end{aligned}$$

$$\begin{aligned}\text{Angle ABC} &= \text{Angle BCD (Triangle ABC is isosceles)} \\ &= 79.1^\circ\end{aligned}$$

$$\begin{aligned}\therefore \theta &= 180^\circ - 2 \times 79.1^\circ \\ &= 21.8^\circ\end{aligned}$$

$$\begin{aligned}\text{and } r &= \frac{15}{\sin 21.8^\circ} \\ &= 40.2 \text{ mm}\end{aligned}$$

$$\begin{aligned}\text{Length of Arc BC} &= \frac{\theta}{360}(2\pi r) \\ &= 15.3 \text{ mm}\end{aligned}$$

$$\begin{aligned}\therefore \text{Length of collapsed stent} &= 2 \times 15.3 + 2 \times 5 \\ &= 40.6 \text{ mm} \leq 44 \text{ mm}\end{aligned}$$

4.1.4 MATERIAL SELECTION

With the dimensions of the design, a search was conducted to find a suitable plastic to make the stent. The plastic chosen would need to be strong, flexible and biocompatible. To check the strength that is required by the material, a simplified model is analyzed.

Figure 4.10 Pressure acting on thin wall cylinder

The analysis starts with a thin-wall cylinder of length l , outer radius r and wall thickness t subjected to even loading around it as in Figure 4.10. This pressure, p represents the forces from the tumor acting on the stent. Consider half the cylinder, by performing integration the total resisting force of $2P$ in one direction caused by the external pressure acting on the cylindrical segment is

$$2P = pA_d = p(2lr) \text{ -----} \quad (4.4)$$

where, A_d is the projected area of the cylindrical segment onto the diametral plane and $A_d = 2lr$.

All these forces would be acting on two are of 2.5 mm x 5 mm areas in the stent. Which means the force acting on each end of the strut is lrp .

Figure 4.11 Forces acting on half a cylinder transformed to force acting on ends of strut

The forces and loading condition of each strut were then considered. The cross-section of the stent was converted from a circle to a 16 sided polygon as shown in Figure 4.12.

Figure 4.12 Conversion of sound cross section to 16-sided polygon

Using unit-load method [98], an analysis of the deflection of each strut was examined. The deformation at the straight portion was assumed to be insignificant as they were only designed to hold adjacent strut together and not to absorb any load. Figure 4.13 shows the loading conditions that each strut will undergo.

Figure 4.13 Curve portion of strut that was used to analyze deflection

When loaded, strut ABC will straighten to absorb forces and as point A and B are at the symmetry with adjacent struts, they undergo zero rotation. Letting the position of point A be the reference, unit load method will be used to find the displacement of point B with respect to point A. The above diagram can be translated to the one in Figure 4.14 with displacement in the horizontal direction ignored.

Figure 4.14 Working diagram for finding strut deflection

The known displacements in this model are:

- $\Delta V_A = 0, \Delta H_A = 0$ (i.e. no vertical and horizontal displacement of point A)
- $\Delta \theta_A = \Delta \theta_B = 0$ (i.e. no rotation at both point A and point B)

The system is two degree indeterminate and was broken down into two parts. In the first part, the moment constraining rotation at point B was deemed redundant. The moment at any point along the structure in Fig 4.15 can be written as:

For part BC, $M_1 = FR \sin \alpha$

For part AC, $M_2 = FR \sin \Phi + FR \sin \alpha$

Figure 4.15 Primary structure for finding strut deflection without constraint at B

The vertical displacement at point B of the primary structure can be determined by apply a vertical unit load at point B as shown in Figure 4.16, which gives

$$m_1 = R \sin \alpha \quad \text{for part BC}$$

$$m_2 = R \sin \Phi + R \sin \alpha \quad \text{for part AC}$$

Figure 4.16 Vertical unit load applied to primary structure

Vertical displacement of point B in primary structure, ΔV_{B1}

$$\begin{aligned} \Delta V_{B1} &= \int_0^l \frac{Mm}{EI} dx \\ &= \frac{FR^2}{EI} \int_0^\Phi \sin^2 \alpha + (\sin \Phi + \sin \alpha)^2 d\alpha \\ &= \frac{FR^2}{EI} \int_0^\Phi 2 \sin^2 \alpha + \sin \Phi \sin \alpha + \sin^2 \Phi d\alpha \end{aligned}$$

$$= \frac{FR^2}{EI} \left[\alpha + \frac{1}{2} \sin 2\alpha - \sin \Phi \cos \alpha + \alpha \sin^2 \Phi \right]_0^\Phi$$

$$\Delta V_{B1} = \frac{FR^2 \Phi}{EI} [1 + \sin^2 \Phi] \text{----- (4.5)}$$

To get the rotation at point B of the primary structure, a unit moment was applied at point B and $m_1 = m_2 = -1$ as shown in Figure 4.17.

Figure 4.17 Unit moment applied to primary structure

$$\Delta \theta_{B1} = -\frac{FR}{EI} \int_0^\Phi 2 \sin \alpha + \sin \Phi d\alpha$$

$$= -\frac{FR}{EI} [-2 \cos \alpha + \alpha \sin \Phi]_0^\Phi$$

$$\Delta \theta_{B1} = \frac{FR}{EI} [2 \cos \Phi - \Phi \sin \Phi - 2] \text{----- (4.6)}$$

After getting the displacement values for the primary structure, the secondary structure with the force for the adjacent strut ignored, as shown in Figure 4.18, was examined. The moment at any point along this structure can be written as:

$$M = -M_B$$

Figure 4.18 Secondary structure

To get the rotation at point B of the primary structure, a unit moment was applied at point B and $m = -1$, shown in Figure 4.19.

Figure 4.19 Unit moment applied to secondary structure

$$\Delta\theta_{B2} = \frac{2}{EI} \int_0^{\Phi} M_B d\alpha$$

$$\Delta\theta_{B2} = \frac{2}{EI} [M_B \Phi] \text{-----} (4.7)$$

$$\Delta\theta_B = \Delta\theta_{B1} + \Delta\theta_{B2} = 0$$

$$\therefore \frac{2}{EI} [M_B \Phi] = -\frac{FR}{EI} [2\cos\Phi - \Phi\sin\Phi - 2]$$

$$M_B = \frac{FR}{2\Phi} [2 - 2\cos\Phi + \Phi\sin\Phi] \text{-----} (4.8)$$

A vertical load at point B was used to find the vertical displacement of point B in this secondary structure, ΔV_{B2} .

$$\begin{aligned} m_1 &= R \sin \alpha && \text{for part BC} \\ m_2 &= R \sin \Phi + R \sin \alpha && \text{for part AC} \end{aligned}$$

Figure 4.20 Vertical unit load applied to secondary structure

$$\begin{aligned} \Delta V_{B2} &= -\frac{RM_B}{EI} \int_0^\Phi \sin \alpha + \sin \Phi + \sin \alpha \, d\alpha \\ &= -\frac{RM_B}{EI} [-2 \cos \alpha + \alpha \sin \Phi]_0^\Phi \\ &= \frac{RM_B}{EI} [2 \cos \Phi - \Phi \sin \Phi - 2] \text{-----} (4.9) \end{aligned}$$

Substitute in Equation (4.8),

$$\begin{aligned} \Delta V_{B2} &= \frac{R}{EI} \frac{FR}{2\Phi} [2 - 2 \cos \Phi + \Phi \sin \Phi] [2 \cos \Phi - \Phi \sin \Phi - 2] \\ &= -\frac{FR^2}{2EI\Phi} [2 - 2 \cos \Phi + \Phi \sin \Phi]^2 \\ \Delta V_B &= \Delta V_{B1} + \Delta V_{B2} \\ &= \frac{FR^2\Phi}{EI} [1 + \sin^2 \Phi] - \frac{FR^2}{2EI\Phi} [2 - 2 \cos \Phi + \Phi \sin \Phi]^2 \text{-----} (4.9) \end{aligned}$$

For the design of this stent, $R = 49.3 \text{ mm}$ and $\Phi = 19.5^\circ = 0.35 \text{ radian}$.

The cross section of the strut is a circular sector. Thus,

$$I = \frac{r^4}{4}(\theta - \sin \theta \cos \theta) = 0.382 \text{ mm}^4$$

where $r = 2.5 \text{ mm}$ and $\theta = 22.5^\circ = \frac{\pi}{8} \text{ radian}$

The 26 mm Choostent, had been successfully used to treat colorectal obstruction, was used as a comparison. According to Sung et al [99], about 1.47 N of force is required to reduce the circumference of a 10 mm long segment of the stent by 25%. Therefore, for a 40 mm segment, the force required is likely to be 5.89 N. When the circumference was reduced by 25%, the new diameter of the stent would be 19.5 mm.

The new stent has a diameter of 30 mm and when the diameter is reduced to 19.5 mm, the deflection in one strut will be 2.03 mm. Therefore, for the strength of the new stent to match that of the Choostent, the deflection in the strut should be less than 2.03 mm when loaded with a 5.89 N of force. From equation 4.9,

$$\begin{aligned} \Delta V_B &= \frac{FR^2\Phi}{EI} [1 + \sin^2 \Phi] - \frac{FR^2}{2EI\Phi} [2 - 2\cos \Phi + \Phi \sin \Phi]^2 \\ &= \frac{FR^2}{EI} \left\{ \Phi [1 + \sin^2 \Phi] - \frac{1}{2\Phi} [2 - 2\cos \Phi + \Phi \sin \Phi]^2 \right\} \text{----- (4.10)} \end{aligned}$$

$$\therefore E = \frac{FR^2}{I\Delta V_B} \left\{ \Phi [1 + \sin^2 \Phi] - \frac{1}{2\Phi} [2 - 2\cos \Phi + \Phi \sin \Phi]^2 \right\} \text{----- (4.11)}$$

By substituting in all the known values, $E = 1265.54 \text{ MPa}$. This value of the Young's modulus will be used as a guide during the selection of material.

A search of biocompatible PU material was done. The polyurethane had to be ISO 10993 certified. Ideally, this material should be strong yet flexible and of light color. It should also be able to withstand temperature up to 150°C for the purpose of sterilization. It should also be available in the form of a 2-part liquid resin. The reason why polyurethane was selected is that the plastic is available in a wide range of properties, color and are sometimes in the form of a 2-part liquid resin

3 brands of ISO 10993 certified polyurethanes were found. The manufacturers for these polymers were Thermedics Inc., DOW Plastics and CardioTech Inc. All the manufacturers have polyurethane that were used to make stents or used in stent-related application. The Tecoflex range from Thermedics Inc. is used to make ureteral Double-J stents from Devon Innovation. Polyurethane from DOW plastics were used to make a type of trachea stent that was found in a patent article. This stent had been tested in dogs with no adverse reaction reported. The ChronoFlex series of polyurethane from CardioTech had been used to make stent grafting in the blood vessels.

However, the author was unable to find any polyurethane liquid mixture that is biocompatible and FDA approved. All the certified bio-polyurethane resins are sold in pellet form for injection molding. It was decided to get a sample of one of these resins to try by making some modification to the fabrication method. A possible way is melt the polymer pellets and injecting it manually into the mould. According to literature, silicone is able to withstand temperatures up to 250°C. Therefore, the final chosen polymer should have a melting temperature less than 250°C. The polymer chosen for further examination was the Tecoflex EG-72D-B40 from Thermedics Incorporated (USA). Specifications of this polymer can be found in Appendix A.

The polymer is ISO 10993 certified for use for making as implants and is also radio opaque as it is doped with barium. It also has a high ultimate elongation of 190% which means that it will not break easily and cause perforation. As compared with biocompatible PUs from other manufacturer, this one has the lowest melting point and

may be suitable especially that the prototype samples would have to be made cheaply. Silicone can be heated to about 250°C and it was believed that injecting the melted resin into a silicone mould would be possible.

4.2 FABRICATION & BENCH-TOP TESTING

4.2.1 1ST ITERATION

4.2.1.1 FABRICATION OF STENT SAMPLES

Prior to the arrival of the biocompatible polyurethane, prototypes of the new stents were made using MCP PU 6020 which was available in the laboratory where the research was carried out. This material has properties closed to that of the chosen material. Characteristics of this material can be found in Appendix B of this report.

Using patterns made from SLS and coated with a layer of lacquer, stent samples were made with PU 6020. Although a few samples of the stent were produced, the fabrication of the samples faced several problems.

SLS is a powder-based RP process and the resulted parts have rough surfaces. After the RP parts are produced, it was necessary to clean the part. These were done with a compressed air gun and brushing the parts with a toothbrush. Due to the porosity in the part, it was necessary to coat it with lacquer before it can be used for mould making. However, most of the lacquer applied will be absorbed by the RP part and many layers will need to be applied. It was also difficult to lacquer some corners of pattern without affecting much of the accuracy of the part.

The rough surfaces of the SLS parts are also spoiling the silicone mould. Quite often, some silicone adheres to the parts/pattern and is torn off from the mould during removal of the part/pattern as shown in Figure 4.21 and 4.22.

Figure 4.21 Damaged silicone mould

Figure 4.22 Damaged SLS pattern

Another problem faced was warping of the SLS parts as shown in Figure 4.3. Possible reasons for the warping include the orientation that the part was built, the calibration of the RP machine and placement of the part on the part bed, which can affect the cooling of the part. The current SLS patterns were built with the stent lying down to save on materials and positioned at the edges of the part bed. The machine may not have been calibrated properly before the build and had been building parts using other materials.

The core inserts used in the mould were straight tubes, but due to the warping of the SLS pattern, they do not fit the mould properly. This results in flashes as thick as 0.5 mm at parts of the casted sample. A lot of time was necessary to remove these flashes and they also add thickness to the stents filaments. The extra thickness affects the collapsibility of the stent.

To reduce the amount of flash, core insert that will fit the mould properly would be needed. Foundry wax was used to create these inserts. A picture of such an inert can be seen in Figure 4.23. This was done by pouring melted wax into the mould assembled with out the core inserted and shaping the resulted casting by removing the excess wax after the wax had harden. However this did not help much due to the shrinkage of the wax insert during hardening.

Figure 4.23 Warping of the SLS pattern is visible in this picture.

Wax core insert made is on the right of the picture.

4.2.1.2 RESULTANT STENT

Nevertheless, a few good samples of the stents were fabricated as shown in Figure 4.24. The test samples fabricated are able to collapse to a diameter of 7 mm, which is 2 mm more than the targeted collapsed diameter, but this diameter is still better than some of the current metallic colonic stents. The extra 2 mm in the collapsed diameter of the stent is largely due to the extra thickness of the stent filament due to the flashes. Other than that, the sample seems to function properly.

Figure 4.24 The new polymeric colonic stent in its (a) expanded and (b) collapsed state (pre-deployment state)

4.2.2 2ND ITERATION

To overcome the problems in the fabrication of the new stents, CAD data to the stent model was given to a vendor to get a new pattern made by SLA. Previous works [95] have shown that SLA gives better finishing and accuracy than SLS. Therefore, the new SL pattern would have better surface finishing than the SLS ones and the warping problem encountered while using the SLS could be solved.

4.2.2.1 FABRICATION

With the new SL pattern, it was easier to remove the pattern from the silicone mould and the pattern did not break during this stage of the fabrication process. There was also no visible warping in the part. Measurements at different parts of the pattern with vernier calipers also fail to show inaccuracies above 0.1 mm in dimensions.

Previously, the chances of the silicone mould tearing were high. In every attempt, some parts of the mould would be stuck to the pattern or the part and these would be torn off during the de-molding process and patching of the defects had to be done almost every time. With the pattern made from SLA, such occurrences were much fewer owing to the much better surface finishing. None of the mould made with the new pattern have significant tearing during the removal of the pattern and most lasted at least 20 casts before damages to the mould starts to occur largely due to the degradation of the mould material.

Owing to higher accuracy of the new pattern, flashes in the parts produced were much thinner than the previous attempts with SLS patterns. These flashes were lesser than 0.3 mm thick as compared with over 0.7 mm previously. Thus, the flashes in the new parts were much easier to remove and parts produced were also more accurate.

It was also observed that the liquid polymer resin also flows more readily in the new moulds and this was likely to be an effect to the smoother walls of the cavity.

4.2.2.1 RESULTANTS STENTS

The stents produced could easily be collapsed without breaking or yielding of the material. This was unlike the earlier ones which had to be closed carefully to avoid breaking the struts. The stents collapsibility was also improved. The collapsed stents measured only 6 mm in diameter thanks to the improved accuracy of the parts produced. However, the new stents is lacking in strength. The new stents although collapsible, were significantly weaker than its predecessors. When loaded with the required 0.6 N of load, the stent is fully collapsed.

A review of the design was done to find the cause resulting in this lack of strength. It was found that this was a problem that resulted from a calculation in the Young's Modulus required by the material. This calculation error was caused by an error in the

value of one of the constants. The actual value of the Young's modulus should have been 10018 MPa instead of the 1265.54 MPa calculated.

Therefore, the new stent should be fabricated with a polymer that has a Young's modulus of at least 8 times that of the material used. However, such polymers would be very brittle if available and therefore the resultant stent may break when collapsed. Such a hard material can also pose problems in the fabrication process as it would make the removal of the runners, venting and flashes even more difficult. Furthermore, a flaw was also observed in the design. It was learnt from the fabricated samples that the stent was weak between segments. Thus, a modification to the design of the stent would be preferred over the use of a harder polymer.

4.2.3 3RD ITERATION

4.2.3.1 CHANGE IN DESIGN

A modification to the stent design was adopted. The aim of this modification in the design was to reduce the Young's modulus of the requirement and to solve the problem of the lack of strength at the connections between adjacent segments of stents.

The new design was formed by joining 2 segments of the stent end to end. Figure 4.25 shows the design of the modified stent. The length of each modular segment stayed fixed at 40 mm and as a result of this, the struts would be more curved. The struts of this new stent would undergo more deformation than the previous design when fully collapsed. The same calculations used to derive the required Young's modulus of the stent were repeated for this new design.

Figure 4.25 Design of modified stent

Each segment of the new stent would have straight portion of 5 mm at its ends and of 10 mm at its center for joining adjacent struts. The straight portions at the ends also allow features to join the segments together to be added. This is shown in Figure 4.26.

Figure 4.26 Strut profile of modified stent

Results from the calculations performed, indicated that the new stent design would have a length of 40.5 mm when fully collapsed and a material with a Young's modulus of 1060 MPa would be needed.

SLS prototypes of the stent patterns were built. These RP stent patterns were used to create molds to produce samples for testing. Although SLS had been tried and were deemed to be unsuitable in previous attempts, the process was again used as it was available in-house. This was an attempt to cut cost. To try to overcome the problems caused by the roughness of parts produced by SLS, the models were made slightly larger for the rough outer surface to be grinded off. The grinding was done manually with a small hand drill with routing tool bit. The mould patterns obtained by this process were generally much smoother than those used in the early parts of the project. However by manually grinding of materials, the accuracy of the parts and consistency in surface finishes were compromised and also the process was tedious. This compromise was deemed to be unimportant as the patterns were only used to prepare prototypes to get a feel of the proposed stent.

The polished patterns were used to make silicone mould to fabricate the stent prototypes. Tearing of the silicone was not significant, but the removed patterns were always broken and not reusable.

Based on calculated results, the Young's modulus for the material required for this stent design was 1060 MPa. The two materials with Young's modulus closest to this value and available in the institute were MCP's PU 6020 polyurethane with $E=1295$ MPa and PU 8040 polyurethane with $E=942$ MPa. Both materials were tried to make the test samples.

The samples made from PU 6020 felt strong but they failed to collapse fully. Thus PU 6020 would have to be ruled out. The PU 8040 samples on the other hand were softer, but fully collapsible. Bench-top testing was conducted on the samples made from the PU 8040. Results of the test are shown in Figure 4.7. From the results, it was clear that the strength of this stent is insufficient when compared with the target set. However, this was expected, as calculated results using equation 4.10 showed likewise.

Figure 4.27 Results on distending strength of stent samples

$$\Delta V_B = \frac{FR^2}{EI} \left\{ \Phi [1 + \sin^2 \Phi] - \frac{1}{2\Phi} [2 - 2\cos \Phi + \Phi \sin \Phi]^2 \right\} \text{----- (4.10)}$$

However, it was close to what was wanted. The design was studied using Finite Element Analysis. Using ANSYS, a static large deformation analysis was performed. A pressure of 0.0024 MPa was applied on the exterior surface of the stent. This pressure is equivalent to that experienced by the Choostent when compressed to a diameter of 19.5 mm.

Two levels of meshing at 44432 and 46912 elements were tried and both yielded close results. From the element plots of finite element analysis, as shown below, it was noticed that the areas nearer to the joints of the stent underwent most stress and strain when loaded. The middle of the struts underwent little deformation. Therefore, it was decided to change the profile of the struts from circular to elliptic to transfer more of the deformation to the middle.

Figure 4.28 FEA element plot of stress at a joint

Instead of having the strut in the shape of circular struts, the profile was modified to elliptic as illustrated in Figure 4.29. This would length the collapsed stent by 2.1mm but even with increase it will still be shorter than the maximum allowable length of 44mm. A simple FEA simulation was also carried out to ensure that there would be no yielding of the material when the stent is fully collapsed.

Figure 4.29 Modification to profile of strut

Using SLA, a RP pattern of the new design was built. The stent produced felt strong and the surface finishing was good. It was also able to fully collapse without breaking. The stent produced were put through the same bench-top test and the results are as shown below.

Table 4.1 Strength of Polymer Stent prototypes

Load (N)	Lumen Diameter (mm)				
	Sample 1	Sample 2	Sample 3	Sample 4	Average
0	30	30	30	30	30.0
1	29	29	29	30	29.3
2	28	28.5	28	29	28.4
3	27	27	27	27	27.0
4	26	25.5	26	26	25.9
5	25	24	24	25	24.5
6	23	19	23	21	21.5
7	20	17	20	19	19.0
8	17	11.5	18	16	15.6
9	16	9	14	15	13.5
10	12	8	11	13	11.0
11	11	7	8	12	9.5
12	10	6	7	11	8.5
13	9	6	6	10	7.8
14	7	5	5	8	6.3
15	4	4.5	4	5	4.4

Table 4.2 Strength of Choostent from literature

Load (N) per 40 mm	Lumen Diameter (mm)
0	26
5.886	19.5

Figure 4.30 Strength of polymer stent vs. strength of Choostent

Therefore the new stent met the target strength-wise. There was however a drawback. The material used was slow in recovering to its original shape. Upon release, the new stent only opens up about 15 mm. For the stent to recover to 90% of its fully deployed diameter (27mm), it would take about one and a half days. To aid the stent's recovery to its original form, it balloon may be needed to be incorporated into the catheter.

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5.1 INTRODUCTION

In order for the new stent to be usable, a catheter is required to deploy it at the stenotic site. Currently the catheters are sold together with the stents inserted. These catheters are meant for one time use only. Once deployed, it would be very difficult to refit the stent in them. As such, once deployed a stent-catheter system is expended irregardless on whether it was properly deployed or just used for training and as mentioned, these devices are costly.

Current deployment techniques for self-expandable stents are generally about the same. These usually involve a pusher and a sheath. The catheter is usually first inserted across the obstructing lesion with the aid of a guide wire. Thereafter, the stent will be deployed by either withdrawing the sheath or pushing the stent out of the sheath. This method can also be used for the new stents, however due to the slow recovery to their expanded form, a balloon would also had to be incorporated into the catheter. In view of this and the cost issue, a new cost-efficient catheter would have to be designed and fabricated for this project.

5.2 CONCEPTUAL DESIGN

Concept 1

Figure 5.1 Concept 1 (1) Catheter approached tumor, (2) Catheter passed through tumor, (3) Sleeve of catheter retracted, (4) Balloon inflated to help open stent, (5) Catheter retracted leaving stent at stricture.

This design is a modification of current colonic stent catheters. Like current colonic stent catheters, this catheter would have a slender pilot head for it to slide through the tiny tumor opening, a sleeve to keep the stent collapsed, and a pusher to keep the stent in place when the sleeve is retracted. Due to the slow recovery rate of the polymer stent to be used, a balloon is incorporated into the design. The stent would be compress over the

deflated balloon. After the stent is in place and the sleeve retracted, this balloon would be inflated to force open the stent. Figure 5.1 illustrates the working of the design.

Concept 2

Figure 5.2 Concept 2

For this design the stent is constrained in its closed form by a collar. Like Concept 1, the stent has a deflated balloon is through a center. The difference in this design is that there is no sleeve involve. The stent is position through the tumor as per normal. To deploy the stent, fluids will be pumped into the balloon to inflate it. This forces the collar to break and the stent will be expanded. The balloon will then be deflated and the catheter removed. The remains of the collar and the stent will be left inside the colon.

Concept 3

Figure 5.3 Locking of stent

Figure 5.4 Deployment of stent (1) Stent locked in closed form, (2) Pin retracted to release stent, (3) Balloon inflated to help open stent.

In Concept 3, short pieces of strings with tiny rings on their ends are used to maintain the stent in its closed state during delivery. The strings are to be wrapped around the collapsed stent and a pin would be passed through the two loops, thus locking the stent in its closed form as shown in Figure 5.3. During deployment, the pin would be retracted to unlock the stent and a balloon at the center of the stent would then be inflated to aid the expansion of the stent.

5.3 SELECTION OF DESIGN

Concept 1 is a proven design except for the addition of the balloon to aid the stents expansion. This is a safe option with the highest likelihood of success. In addition, it should also be easy to make and is therefore worth trying.

Concept 2 also seems plausible. The concept is simple and should also be easy to make. A foreseeable obstacle to the realization of this catheter maybe in finding a suitable material for the collar. This collar has to be strong enough to keep the stent closed yet be able to break easily when fluids are pumped into the balloon.

Concept 3 should also work and should also be easy to fabricate. However the pin used to lock the stent maybe dangerous. This pin has to be thin in order to fit into the small rings and therefore may perforate the colon walls.

In view of the above reasons, the first two concepts were tried out.

5.4 FABRICATION AND TESTING OF CATHETERS

Concept 2 was first tried, however with little success. Several types of plastic sheets were tried, but they were either too weak or too strong. Attempts to use plastic sheets

with adhesives to form the collar were also met with limited success. As such, the concept was abandoned for the safer Concept 1.

The sleeve for Concept 1 was made with plastic sheets from plastic bags. The prototype worked with little problem.

Figure 5.5 Stent Catheter

5.5 ATTACHMENT OF CATHETER TO COLONOSCOPE

Due to the small size of colonoscopes' working channels, the stent-catheter system would not be able to deploy through them. Thus, an external working channel would be required to guide the catheter to the head of the colonoscope. This working channel will "piggyback" on the colonoscope and enter the bowel together with the scope. The addition would have two components, namely:

- The sleeve
- The attachment

It was not advisable to have the catheter enter the colon after the colonoscope without the external channel covering and guiding it, as the pointed pilot head of the catheter may puncture the colon wall. Moreover, this would happen without the colonoscopist knowledge, as any damage to the colon caused by the catheter would occur out of his/her site. Therefore if it were to happen, the operator would continue to push in the device and as a result causing further damages.

Figure 5.6 Direct connection of catheter to colonoscope

It was also not feasible to just attach the catheter directly onto the colonoscope as shown in Figure 5.6. This is because all colonoscopes have their fixed focal length. The colonoscopist would not be able to see the stricture if the scope's head was moved to the edge of the tumor as illustrated in Figure 5.7. Having the pilot head of the catheter fixed in front of the scope was also unsuitable, as it would hinder the view and the surgeon may also not see it especially at the bends. Due to the second reason, there would also be a chance of puncturing the colon.

Figure 5.7 Problem when catheter is fixed on colonoscope

Although the author had not managed to find any external working channels in the market, the project's consultant surgeon had. According to him, it was just a simple tube with rubber bands attached to the tube's outer surface for attachment onto the colonoscope. It was far from desirable, as it was not securely fixed to the colonoscope.

The creation of this module of the system was very much of trial and error. The first one was to attach a U-shaped clip at the head of the colonoscope, as shown in Figure 5.8. The catheter was inserted through the clip and the catheter would enter the colon together with the colonoscope. When the stenotic site was approached, the catheter would be pushed forward through the stricture and triggered to release the stent.

Figure 5.8 Clip to attach catheter to colonoscope

This model however had its problems. Firstly, unless the catheter was pushed into the colon at the same speed as the colonoscope, there was a high chance that the catheter would move forward or backwards with respect to the head of the colonoscope. If the latter were to happen, the movement of the catheter may no longer be guided by the scope if the pilot head of the catheter had dislodged from the constraining clip. Another problem was the sharp corners of the clip. This was raised by the surgeon who was concerned that the square corners of the clip would scratch the colon walls. What was more, the clip was not securely fixed on the catheter and small amounts of sliding were still possible.

A second model was made. This model consists of two long tubes. The two tubes were joined along their length to form a figure-of-8 cross-section. One of the tubes was made from plastic sheet. The material was chosen because it was soft, cheap, smooth and easy to join by heating. Its softness and smoothness would eliminate almost any chance of

damage to the colon. The smoothness would also allow the catheter to slide along it easily. This tube would be for the catheter to slide through after the colonoscope carrying it had reached the site of stricture. The other tube was made from rubber. Like the one seen by the consultant surgeon on the market, rubber would be used to attach the external channel to the scope, but unlike it the rubber sleeve would cover the entire length of the scope and thereby offering a more secure grip onto the scope. This rubber sleeve was formed by sewing two edges along the length of a constrictive bandage together. The formed sleeve was then sewed onto to the plastic sheet sleeve to form the figure-of-8 cross-section as illustrated in Figure 5.9.

Figure 5.9 Figure-of-8 cross-section of sleeve

The model was tried but fitting the entire length of the colonoscope through the rubber sleeve was to be very difficult. Therefore a modification was made and the rubber sleeve was replaced by a plastic one similar to the one for the catheter. Its movement was to be constrained by ropes tied at regular interval. This was tested on 20 mm diameter water hose which was used to simulate the colon. Sadly, it was unsuccessful as plication of the sleeve occurred when it was passing through the hose, as it did not have a firm grip on the colonoscope due to the smoothness of the material. The kinking of the plastic sheets also interferes with the maneuvering of the colonoscope. Therefore, it was again replace with another material - this time with cloth.

Figure 5.10 Sleeve made from cloth

The system worked well when it was tested on a 2 feet (approx. 600mm) long curved hose. There was no problem deploying the stent at the end of the hose and the addition of the cloth sleeve did not pose too much of a hindrance to the maneuverability of the colonoscope. However, problems arose when the same test was repeated on a longer hose (1.5 m long). Problem was encountered in pushing the catheter through the external sleeve. The sleeve was in a normally closed state and some parts of it are crumpled as the colonoscope enters the water hose. This hindered the movement of the catheter through it. Although the catheter did manage to reach the other end of the sleeve eventually, much effort required to do it. Also after getting the head of catheter to the site of the simulated obstruction with much difficulty, it was another challenge trying to maneuver the catheter to through the stricture. These problems may even be compounded if it was tried in a real colon by the peristaltic reaction of the colon. It was

therefore decided that the channel for the catheter should be normally open to provide an easier passage for the catheter to pass through and also resist against the squeezing from the colon wall. For this, a common water hose was used for a start.

To attach the hose onto the colonoscope, a heat shrink was used. The idea was tried out and it worked very well. The heat shrink was able to hold the tube onto the colonoscope very firmly. In addition, the idea was simple and the parts were all readily available in the market.

Figure 5.11 Final attachment method

The attachment to the colonoscope was only done to the head of the scope to reduce the amount of interference on the maneuverability of the colonoscope caused by the stiffness of the tube used. As such, only about 5 cm of heat shrink was used, but it was enough to secure the hose in place.

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6.1 INTRODUCTION

The tumor-length measuring device was designed to allow the physician to determine the length of the stricture with out the need for fluoroscopic apparatus. This not only cuts down cost, but also avoids harmful exposure to the radiation on the medical staff and patient as it is known that radiation can be harmful mutagens.

The device would utilize normally-opened switches to act as sensors. The switches would be connected to a power source and a light-emitting diode which would act as the indicator as shown.

Figure 6.1 Basic layout of device

6.2 DESIGN OF THE DEVICE

The head of the new device should be slender enough to fit into the instrument channel of the colonoscope. Upon seeing the obstruction through the colonoscope, the colonoscopist could insert the device through the instrument channel to the occlusion. When inserted through a fully occluded colon, these switches would be closed and thereby indicating the presences of a full occlusion. The operator would then continue to push the device further into the obstruction until the indicator light had gone off. This would happen when the switch had been pushed past the stricture. Using the color

coding on the device, the colonoscopist would read off the stricture's length from the view obtained by the colonoscope. Figure 6.2 illustrates the working of the device.

Figure 6.2 Illustration of the working of the new device

The shape of the tumor obstructing the colon can be irregular and there are chances that there may be gaps within the obstruction. Such gaps may fool the device that it had fully passed the stricture as illustrated below.

Figure 6.3 Possible failure caused by gap within tumor

To overcome this problem, the device will have three switches that are placed along the head of the device as shown in Figure 6.4. As long as one of the switches was closed, the indicator would be on. This indicates that at least one of the switches was still within the obstructed region. Only when all three switches had passed the stricture will the indicator go off. Measurement of the stricture's length will start from the last switch.

Figure 6.4 Proposed solution

The switches would also be placed facing different directions approximately 120° apart as shown in Figure 6.5. This would prevent all the switches from being opened in case the opening of the stricture is along a plane.

Figure 6.5 Positioning of switches from the front

Figure 6.6 shows the schematic circuit diagram of the simple device with a buzzer added. The addition of the buzzer would allow the colonoscopist to concentrate on maneuvering the device rather than having to look at the LED and the images from the colonoscope at the same time.

Figure 6.6 Schematic circuit diagram of device

For the measuring head of the device to fit into the working channel of the colonoscope, the diameter of its cross-section would have to be below 3 mm. Due to this constraint on the slenderness of the cross-section, the switches were to be made as simple as possible. The thinnest electrical wires that are readily available were 0.7 mm in diameter. The

thickest portion of the head of the device would be at the third switch because it would consist of the third switch and three wires. All these would have to fit into a diameter of less than 3 mm in diameter.

The design of the switches on the measuring head was kept simple to minimize their size. The switches were formed by folding the wires and using pieces of aluminum foil wrapped around the wires as the contact of the switches. Figure 6.7 illustrates the design.

Figure 6.7 Design of switch

The insulated wires were bent in the U-shape form enable the switch to be open when pressure is removed. The rubber insulation helped in returning the wire to its intended shape. This profile was arrived at by trial and error.

It is a common practice for the surgeon to pass a guide wire through the obstruction. This wire is used to estimate the length of the lesion under fluoroscopy and to serve a guiding rail for instruments passing through the region to ride on. To enable the wires and switches to be passed through the obstruction under the guidance of a guide wire, features were made to the pilot head of the wires. The feature was adopted from fishing rods. It would allow the guide wire to be inserted through the pilot head of the device and there by ride on the guide wire when passing through the stricture. The feature is as shown in Figure 6.8. In this prototype, it was made from the rubber insulation from a normal electrical wire.

Figure 6.8 Pilot head to allow passing of guide wire

The environment inside the colon is wet. The liquids in the colon may be conductive and can cause the circuit to be closed. To overcome this, a plastic-cover was made. This cover was meant to prevent the liquids from reaching the switches. The effectiveness of this cover was tested out in immersing the covered switches into water and passing then through a tube with an obstruction created using sponge. There was no problem encountered during this test.

Figure 6.9 Final sensing head of device

The rest of the components were assembled inside a computer mouse cable organizer from the market. The wire can therefore be rolled into the casing for easy storage. The finished product is showed below.

Figure 6.10 Finished device

**ANIMAL TESTING, RESULTS
OVERVIEW & DISCUSSION**

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7.1 ANIMAL TESTING

An animal trial was conducted with the help of surgeons from the National University Hospital, Singapore. In this trial, a sedated adult pig was used, as the diameter of the animal's colon is close to that of an adult human. To form the stricture, a portion of the pig's colon was removed and sewed to form a waist. The procedure is as shown in Figure 7.1.

Figure 7.1 Formation of waist in colon

The external working channel attachment of the catheter was attached into the colonoscope with a heat shrink and was inserted through the pigs rectum to the artificial stricture made. Problems were however encountered while maneuvering the colonoscope to the stricture. This was caused by the leakage of air through the channel attachment of the system. The air is required to inflate the colon to open up the colon for visual inspection through the scope. To overcome the leakage, the external opening of the attachment was temporarily covered and thereby allowing the scope to reach the stricture.

An 80mm long segment of the new stent was cut from one which was 160mm long. This stent was fitted into the catheter. They were then passed into the attached working

channel and guided through the obstruction. Unfortunately, the sleeve was able to retract. Despite numerous bench top testing before, the sleeve snapped when it was applied to the colon. This was mainly due to the moisture in the colon. Although the material used was the smoothest amongst the materials tried, it was not the case when it is wet. The moisture had caused the soft sleeve of the catheter to stick to the stent and the pusher and thus making it impossible for it to be pulled back. Due to this, the catheter had failed, but the stent would still be inserted by other means.

The sleeve of the failed catheter was cut off. Thereafter, the remaining parts and the stent were inserted through an opening that was made near the stricture. Unfortunately, the balloon that was meant aid the stent the stent expand was punctured while removing the sleeve. To help the stent open up, fingers stuck into the colon through the opening to open up the stent. An opening about 20 mm was attained with the stent which is sufficient for effective irrigation of blocked colon. However it was also noted that the stent tends to slide in the colon easily.

Figure 7.2 Prototype stent in pig's colon

The tumor length measuring device was not tested, as there was not enough time to test it during the trials. However, the projects consultant surgeon had expressed his satisfaction for it.

7.2 SUMMARY OF RESULTS

A polymer stent with strength comparable with some commercial colonic stents was developed. Results from bench top test showed that the new stent can offer a lumen of 21.5mm when subjected to a load of 6 N as compare with 19.5mm when a commercial Choostent of similar length was subjected to 5.89 N. The new stent can be compressed to a diameter of 7 mm from an unloaded diameter to 30mm. The length of the stent can also be customized by joining modular segment together.

A catheter for the new stent was developed. The catheter is a modification of current colonic stent catheter with the addition of a balloon to speed up the expansion of the stent. To allow sliding of the catheter along the colonoscope, an external working channel was made and can be attached to the scope using a heat shrink.

Also developed in this project, was a stricture length measuring device. This simple device was to remove the need fluoroscopy in determining the length of the stent to be used. The prototype of the device was able to perform satisfactory during bench top testing.

Animal testing conducted on a pig, provide some valuable insight into the performance of the package. The colonoscope with the external working channel attachment on it was able to enter the colon at the same time. The heat shrink used to attach the channel onto the scope was able to hold the two parts together firmly.

It was also demonstrated during the trials that the length of the stent can be quickly customized with the modular design of the stent. This was done when a 160mm long

stent was cut down to 80mm for use in the pig. The catheter made to deliver the stent was also able to slide through the stricture without much problem too. After implantation, a lumen of about 20mm was obtained which was enough for effective decompression of the colon.

On the other hand, the animal trial also revealed several short comings of the products. For the external working channel, one problem lies with the leakage of air. Air is pumped into the colon during colonoscopic procedures to open up the colon. This leakage of air cause the colon to stay collapsed and made it difficult to see through the colonoscope.

The catheter for the stent faired badly in the trial. Under dry conditions, the catheter was able to work without much problem, but in the wet colon, the plastic sheets used to make the sleeve would stick onto the stent and the pusher of the catheter. As a result, it was not possible to retract it. Attempts to pull back the sleeve ended up breaking it.

As for the stent, despite it being able to support the narrowed colon wall, the new stent did not have much grip on the walls.

7.3 DISCUSSION

From the results of this project, the idea of having a polymeric colonic stent can be deemed possible. However there are still much room for improvement before the device can be ready for clinical use.

The stent has passed the test in terms of its strength, collapsibility, longitudinal flexibility and ease of length customization. However, its ability in resisting migration is doubtful. Although meshed profile stents are known to resist migration by having partial granulation of the lumen walls through the mesh, the stent implanted in the pig was able to slide easily after deployment. One possible explanation for this may be the thicker

struts which are less effective in cutting into the colon walls. Only small amount of the colon tissue went through the mesh in this case. Another possible explanation may be the inaccuracy of the tumor model. The method of creating a waist to simulate the obstruction is a quick but untested method. The stricture created in the trial may be smoother than actual ones. The stricture was straight and smooth which was unlike real tumors which are irregular. This may explain the small amount of tissue penetration through the mesh of the stent that was observed.

To improve the anti-migration ability of the stents, the next evolution of stent should have sharp outer surface and ends to cut into the colon wall and thereby anchoring it into position. Sharp features were avoided during the design of the stent to avoid perforation of the colon, however from this experience, such features are a must to help keep the stent in place. Thus it could explain why the ends filaments of the Wallstents are left exposed even though it can perforate the colon. The filament ends pierce into the colon to anchor the device in place.

Although the current stent is still unusable in a real colonic obstruction due to its inability to anchor itself to the colon wall, it does show potential that it could be a more economical alternative than the current commercial colon stents.

A polyurethane urethral stent can cost as little as US\$100 [90] and in terms of its volume, it does not defer much to that of the one segment of the derived colon stent. Assuming that the cost of the polyurethane used are the same, the new stent could cost just slightly more than that of the urethral stent due to its more complex shape.

Based on feedback from the project's surgeon, the most commonly used colon stent used is about 60mm long. Thus two segments of the new stents would be required for most cases. Assuming that the cost of each of these stent segment to be US\$125 (25% more due to the more complex shape), 2 segments of this polymer stent would cost just US\$250.

Currently all commercial colonic stents are metallic. Based on feedback from the project's surgeon, each stent costs about S\$2500 (approx. US\$1500). Therefore the new stent could represent an 83% saving.

The catheter seemed simple and made use of techniques that had been tested before. However, despite successful trial outside the animal, it failed to work when it was used in an actual colon. This has much to do with the fluids that are inside the colon. When the plastic sleeve of the catheter got wet, it adhered to the other components. Thus it was not possible to retract as planned. Therefore, for the catheter to work, the material used to make the sleeves had to be changed. The testing of the catheter also had to be conducted in a wet environment. A stiffer sleeve like the one used to make the external working channel could be the answer as the catheter was able to slide through the channel without difficulty.

As for the external working channel, the current hose used for the external working channel interferes with the maneuverability of the colonoscope. There for a smaller and more flexible tube will have to be used. The wall thickness of this new tube will have to be thinner. A possible replacement could be PTFE tubes as they have thinner walls. They were considered, but they were more costly and less ready available than the water hose. 5m of the PTFE tube of the required internal diameter would cost over S\$100 whereas a similar length water hose cost only about S\$10. For testing purposes, the cheaper alternatives was used to confirm the workability of the idea before investing in the better but more expensive tubes. Alternatively, tailor made long springs could be use as the sleeve. This should give us a strong and yet flexible sleeve, but at added cost.

The catheter and external working channel were developed to deploy the new stent, because the new stent is not able to use current commercial ones. The design of the catheter is similar to that of current colon stent catheter. The main difference is in the

additional balloon to help expand the stent to the required diameter. If improvement in the stent material is achieved to enable the stent to return to its expanded form quickly without the aid of the balloon, it maybe possible to use current available catheters in the market which had been clinically tested before.

Although the tumor length measurement device was not tested in the animal due to time constraint during the trials, it was tested in wet conditions as the possible failure that would be caused by electrical conductivity of the fluids was foreseen.

With this device, fluoroscopic guidance could be deemed to be redundant and the physician would not have to expose themselves to harmful radiation. The fabrication of this tumor length measurement device was less than S\$20. Hence, it could even be cheaper than the current practice of using fluoroscopy to determine the stricture length.

8

CONCLUSIONS

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8.1 CONCLUSION

The results of this project suggest that it is possible to create a polymeric colonic stent system for use in the colon. The colon stent developed was able to fulfill most of the requirements of a colonic stent. Its stiffness is comparable to that of some commercial colon stents and therefore able to support a lumen for effective decompression of the colon. It was also able to collapse to a diameter comparable to some metallic colonic stents which is much more than current polymer stents. The modular design of the stent allows the length of stent to be changed quickly by adding or removing modular segment. The flexible joints between these segments also give the stent flexibility along its length in both its open and collapsed form. However, the stent's anti-migration ability is still needs to be improved.

The catheter of the stent, however, was less successful. Despite successful bench top testing, the effects caused by the wetness inside the colon were not predicted. The external working channel, for the catheter to pass through, faired much better. The catheter was able pass through it without difficulty and the attachment to the colonoscope was excellent. There is room for improvements, such as its flexibility and its wall thickness. These could be done by using better but more sophisticated tubes for the channel. Another improvement to the channel would be to add a seal at its entrance to prevent the leakage of air.

For the third part of the system, the tumor length measurement device was not tested in a real animal, but bench top test results were satisfactory.

Overall the project provided the first step to further developments of such a system. With the knowledge and experience gained from this exercise, a polymeric colonic stent system could be developed to benefit the many patients that would suffer from colorectal obstruction.

A couple of publications were published with regards to this work. Their titles can be found in Appendix C.

8.2 RECOMMENDATION FOR FUTURE WORK

This project laid the foundation work for further development for a polymer colonic stent. Further works are required for the stent to be suitable for clinical use. Below is a list of recommendation of further development works.

- 1) Make improvement to the design of the stent. The improvements can be made to the different aspects of the stent.
 - a) Stiffness - Although the current stent already has ample stiffness, it would be always be better to allow the stent to support higher loads. This would allow it to be used in situations where the tumors are stiffer than usual.
 - b) Anti-migration - The anchoring ability of the current prototypes are just not good enough. Sharp features that may injure the tissue were avoided in the design, but from the experience of this exercise, it was learnt that such features are necessary for the stent to stay in place even though the wall of the implant was meshed.
 - c) Better shape recovery – The current prototypes are slow in recovering to their normal form. A balloon had been added to speed up the shape recovering process. It would be good if the stent can spring back to shape more readily. Such improvement can be made by trying our new materials and the geometry of the struts.
- 2) The catheter made in this project had failed. Further work on it would therefore be needed. A change in the material of the sleeve should be able to solve the problem.

- 3) The external working channel of the system can be improved by changing the tube to a more flexible one with thinner walls as suggested before at the expense of higher cost. A seal at the proximal opening of the tube would also have to be added to reduce air leakage.
- 4) More animal testing of new designs and newer components of the package.

REFERENCES

References

1. "Simple test kit for cancer to hit the shelves soon" The Straits Times, 20 Feb 2002. (Singapore)
2. "Colorectal cancer is curable – Test yourself" Streets, 20 Feb 2002. (Singapore)
3. "How Cancer Kills", Cancer-therapy.net
(<http://www.cancer-therapy.net/how%20cancer%20kills.htm>)
4. RG McKinnell, RE Parchment, AO Perantoni and GB Pierce "The Biological Basis of Cancer" Cambridge University Press (1998) pp 33
5. "Medical Alphabet" Mediacorp Singapore, 2001.
6. M Lahmah, P Mathur, B McKeown, H Blake and RI Swift, "The use of rectosigmoid stents in the management of acute large bowel obstruction." J.R. Coll. Surg. Edinb. (1998) Vol 43 pp 318-321.
7. T Ahmad and AS Mee, "Expandable metal stents in malignant colorectal obstruction", British Medical Journal (2000) Vol 321 pp 584-585.
8. WR Castaneda, "Use of Metallic Stents for the Treatment of Colorectal Obstruction", 8th Midwest Institute for Interventional Therapy Endovascular Seminar (1999)
(<http://www.miiit.com/METALLICSTENTS.htm>)
9. A Mainar, MADG Ariza, E Tejero, R Tobío, E Alfonso, I Pinto, M Herrera and JA Fernández, "Acute Colorectal Obstruction: Treatment with Self-expandable Metallic Stents before Scheduled Surgery—Results of a Multicenter Study", Radiology. (1999) Vol 210 pp 65-69.
10. TH Baron, "Expandable Metal Stents for the Treatment of Cancerous Obstruction of the Gastrointestinal Tract", The New England Journal of Medicine (2001) Vol 344 pp1681-1687.
11. JP Welch, "Bowel obstruction: differential diagnosis and clinical management", W B Saunders (1990) pp 546.
12. GJC Harris, AJ Senagore, IC Lavery and VW Fazio, "The Management of Neoplastic Colorectal Obstruction with Colonic Endolumenal Stenting Devices", American Journal of Surgery (2001) Vol 181 pp 499-506.

13. MS Mokhashi, "Expandable Stents in the Colon – Review", MUSC Digestive Disease Center (1998).
14. C Montes, JM Romeo, E Tejero, L Rabago, A Marinelli, J Vazquez, R Fernandaz, JL Castro and JL Martinez, "Treatment of left colon neoplastic obstruction by placement of self expandable stents", *Revista Espanola De Enfermedades Digestivas* (2001) Vol 93 pp232-237.
15. MA Mauro, RE Koehler and TH Baron, "Advances in Gastrointestinal Intervention: The Treatment of Gastroduodenal and Colorectal Obstructions with Metallic Stents", *Radiology* (2000) Vol 215 pp 659-669.
16. "Cordis Endovascular" Johnson & Johnson News
17. R Balcon, R Beyar, S Chierchia, I De Scheerder, PG Hugenholtz, F Kiemeneij, B Meier, J Meyer, J P Monassier and W Wijns, "Recommendations on stent manufacture, implantation and utilization" *European Heart Journal*. (1997) Vol 18 pp 1536–1547
18. A Adam, RF Dondelinger and PR Mueller, "Textbook of Metallic Stents" Creative Associates Ltd., Oxford (1997)
19. SR Reuter, "Keeping the blood flowing - stents open clogged arteries" *The Mission* by University of Texas Health Science Center (1998)
20. "Institut für Materialforschung", Forschungszentrum Karlsruhe (<http://hikwww9.fzk.de/imf/>)
21. WB Harkins "An endotracheal metallic prosthesis in the treatment of stenosis of the trachea." *Ann Otol Rhinol Laryngol*, (1952).
22. "Boston Scientific" (<http://www.bostonscientific.com>)
23. C T Bolliger, C Wyser, X Wu, R Hauser, W Studer, P Dalquen, and AP Perruchoud, "Evaluation of a New Self-expandable Silicone Stent in an Experimental Tracheal Stenosis" *American College of Chest Physicians* (1999) Vol 115(2) pp 496-501.
24. "Rusch" (<http://www.ruesch.de/en/produkte/neuheiten/stents/stents001.php>)
25. SP Hong, SD Young, WS Soo, WC Sung, KL Hyo, HK Seung, MS Young, CP Keun and WC In, "Upper Gastrointestinal Tract Malignant Obstruction:

- Initial Results of Palliation with a Flexible Covered Stent” Radiology. (1999)
Vol 210 pp 865-870.
26. U Siwart, J Puel, V Mirkovitch, F Joffre and L Kappenberger. “Intravascular Stents to Prevent Occlusion and Restenosis after Transluminal Angioplasty” N England J Med (1987) Vol 316 pp 701.
 27. “Devon Innovations Private Limited”
(<http://www.devoncatheters.com/index.htm>)
 28. Francesco Grasso “Greater Baltimore Colorectal Specialists”
(<http://www.colorectalsurgery.org/colscopy.html>)
 29. “Peristalsis”, University of Bath
(<http://www.bath.ac.uk/~enprh/Peristalsis.html>)
 30. “Cancer Reference Information-Detailed guide”, American Cancer Society
(http://www.cancer.org/eprise/main/docroot/cricri_2_3x?dt=10)
 31. T Weston, “Atlas of Anatomy”, Marshall Cavendish Books (2000)
 32. “World Health Report 2001”, World Health Organization. (2001)
 33. “Images of Colon Carcinoma”, Rattler Web Site - Cameron University
(<http://rattler.cameron.edu/colon/images.html>)
 34. “Understanding Treatment Choices for Prostate Cancer”, Federal Consumer Information Center
(http://www.pueblo.gsa.gov/cic_text/health/treat-prost/what-is.htm)
 35. “Early-Care® Products”, Systems Complete
(<http://www.systemscompletellc.com/Products.htm>)
 36. “S-F100 Sigmoidoscope”, EndoSheath.com
(<http://www.endosheath.com/pages/products/sf100>)
 37. “Endoscope Products Colonoscope(Flexible: JFE201AF/JFE-202BF)”,
(http://www.dnacounter.com/dnacounter/dnac_site/endoscope_s/endos_s/colono/colonoscope_1.htm)
 38. “Clinical Radiology- Barium enema” United Bristol Healthcare
(<http://ubht.org.uk/radiology/examinations/barium.htm>)
 39. “3D Virtual Colonoscopy - Sample Images” Visualization Lab
(http://www.cs.sunysb.edu/~vislab/vislab_home.html)

40. "Bowel Obstruction" Intelihealth
(<http://www.intelihealth.com/IH/ih/IH/WSIHW000/9339/25863.html>)
41. J Beardmore, "John's Ulcerative Colitus",
(<http://members.madasafish.com/~beardmore/website%20pages/uc.htm>)
42. MB Nicholl, J Shilyansky and DM Ota, "Current Management of Malignant Large-Bowel Obstruction" Contemporary Surgery (2002) Vol 58 (8) pp 396-400
43. "Percutaneous Cecostomy Insertion", Cecostomy.com
(http://www.cecostomy.com/Health_Care_Providers/cecos_chaitset.htm)
44. S Lelcuk, JM Klausner, A Merhav, J Ratan, Y Skornick and RR Rozin
"Endoscopic decompression of acute colonic obstruction: avoiding staged surgery" Ann Surg (1986) Vol 203 pp 292-4.
45. M Dohmoto "New Method – Endoscopic Implantation of Rectal Atent in Palliative Treatment of Malignant Stenosis" Endosc Dig (1991) Vol 3 pp 1507-1512.
46. P Spinelli, M Dal Fante and A Mancini "Self-expanding Mesh Stent for Endoscopic Palliation of Rectal Obstructing Tumors: A Preliminary Report" Surg Endosc (1992) Vol 35 pp 912-913.
47. "Amitech – Gastro, Colorectal Stent"
(http://www.ami.co.il/html/gastro/in_gastro/stent.htm)
48. LP Diaz, IP Pabon, RF Lobato, and CM Lopez, "Palliative Treatment of Malignant Colorectal Strictures with Metallic Stents", CardioVascular Intervention Radiology (1999) Vol 22 pp 29-36.
49. IW Choo, YS Do, SW Suh, HK Chun, SW Choo, HS Park, SK Kang and SK Kim, "Malignant colorectal obstruction: treatment with a flexible covered stent", Radiology (1998) Vol 206 pp 415-421
50. F Camunez, A Echenagusia, G Simo, F Turegano, J Vazquez and I Barreiro-Meiroa, "Maglignant Colorectal Obstruction Treated by Means of Self-expanding Metallic Stents: Effectiveness before Surgery and in Palliation", Radiology (2000) Vol 216 pp 492-497.
51. MA DeGregorio, A Mainar, E Tejero, R Tobio, E Alfonso, I Pinto, R Fernandez, M Herrera and JA Fernandez, "Acute colorectal obstruction: stent

- placement for palliative treatment—results of a multicenter study”, *Radiology* (1998) Vol 209 pp 117-120
52. CA Binkert, H Ledermann, R Jost, P Saurenmann, M Decurtins and CL Zollikofer, “Acute colonic obstruction: clinical aspects and cost-effectiveness of preoperative and palliative treatment with self-expanding metallic stents—a preliminary report”, *Radiology* (1998) Vol 206 pp199-204.
 53. TH Baron, PA Dean, MR Yates, C Canon and RE Koehler, “Expandable metal stents for the treatment of colonic obstruction: techniques and outcomes”, *Gastrointestinal Endoscopy* (1998) Vol 47 pp277-286
 54. K Mishima, S Sawada, N Tanigawa, Y Okuda, M Kbayashi and T Koyama, “Expandable Metallic Stent Treatment for Malignant Colorectal Strictures”, *CardioVascular and Interventional Radiology* (1999) Vol 22 pp155-158
 55. E Tejero, R Fernandez-Lobato, A Mainar, C Montes, I Pinto, L Fernandez, E Jorge and R Lozano, “Initial results of a new procedure for treatment of malignant obstruction of the left colon”, *Dis Colon Rectum* (1997) Vol 40(4) pp 432-436
 56. CL Canon, TH Baron, DE Morgan, PA Dean and RE Koehler, “Treatment of colonic obstruction with expandable metal stents: radiologic features”, *American Journal of Radiology* (1997) Vol 169-205
 57. KD Rupp, M Dohmoto, R Meffert, A Holzgreve and G Hohlbach, “Cancer of the rectum-palliative endoscopic treatment” *Eur J Surg Oncol* (1995) Vol 21(6) pp 644-7
 58. Y Saida, Y Sumiyama, J Nagao and M Takase, “Stent endoprosthesis for obstructing colorectal cancers”, *Dis Colon Rectum* (1996) Vol 39 pp 552-555
 59. M Dohmoto, M Hunerbein and PM Schlag, “Application of rectal stents for palliation of obstructing rectosigmoid cancer”, *Surgery Endoscopy* (1997) Vol 11 pp 758-761
 60. T Arnell, MJ Stamos, P Takahashi, S Ojha, G Sze and V Eysselein, “Colonic stents in colorectal obstruction”, *American Surgery* (1998) Vol 64(10) pp 986-988
 61. MH Wholey, EA Levine, H Ferral and W Castaneda-Zuniga, “Initial clinical experience with colonic stent placement”, *American Surgery* (1998) Vol 175 pp 194-197

62. JF Rey, T Romanczyk and M Greff, "Metal stents for palliation of rectal carcinoma: a preliminary report on 12 patients" *Endoscopy* (1995) Vol 27 pp 501-504
63. M Itabashi, K Hamano, S Kameoka and K Asahina, "Self-expanding stainless steel stent application in rectosigmoid stricture" *Dis Colon Rectum* (1993) Vol 36 pp 508-511
64. E Tejero, A Mainar, L Fernandez, R Tobio and MA DeGregorio, "New procedure for the treatment of colorectal neoplastic obstructions" *Dis Colon Rectum* (1994) Vol 37(11) pp 1158-1159
65. F Turegano-Fuentes, A Echenagusia-Belda, G Simo-Muerza, F Camunez, F Munoz-Jimenez, E Del Valle Hernandez and A Quintans-Rodriguez, "Transanal self-expanding metal stents as an alternative to palliative colostomy in selected patients with malignant obstruction of the left colon", *British Journal of Surgery* (1998) Vol 85(2) pp 232-235
66. JC Palmaz, "Expandable intraluminal graft, and method, and apparatus for implanting an expandable intraluminal graft", US Patent No. 4733665 (1988)
67. "経皮的血管形成術テクニック"
(<http://hippo.med.hirosaki-u.ac.jp/~radio/IVR/index.html>)
68. "頭頸部血管に脳"
(<http://www.geocities.co.jp/HeartLand-Sumire/6231/gfx.htm>)
69. S Jayaraman, "Embodiments of multiple interconnected stents", US Patent No. 5733781 (1998)
70. ML Marin and R Marin, "Intraluminal stent", US Patent No. 5397355 (1995)
71. JS Yadav, "Locking stent", US Patent No. 6083258 (2000)
72. HM Israel and G Pinchasik, "Flexible expandable stent", US Patent No. 5733303 (1998)
73. EP Strecker, "Dilatation catheter", US Patent No. 4922905 (1990)
74. "Intravascular Stent", Central Illinois Radiological Associates, Ltd
(<http://www.peoria-radiology.com/ivstents.htm>)
75. C Gianturco. "Endovascular stent and delivery system", US Patent No. 4800882 (1989)

76. SE Boatman and KD Brummett, "Flexible stent having a pattern formed from a sheet of material", US Patent No. 5632771 (1997)
77. DM Wiktor, "Intravascular radially expandable stent and method of implant", US Patent No. 4886062 (1989)
78. "Invention of the Cardiac Pacemaker - Artificial Hearts – Electrocardiography", Inventor
(<http://inventors.about.com/library/inventors/blcardiac.htm>)
79. RA Hillstead, "Endovascular stent apparatus and method", US Patent No. 4856516 (1989)
80. RA Hillstead, "Endovascular stent and method", US Patent No. 5135536 (1997)
81. A Beck, N Nanko, "Device for the widening of blood vessels", US Patent No. 4877030 (1989)
82. G Derbyshire, "Expandable transluminally implantable tubular prosthesis", US Patent No. 5007926 (1991)
83. MS Williams, "Stent capable of attachment within a body lumen", US Patent No. 5423885 (1995)
84. KW Carpenter, LR Roucher Jr., EJ Jung Jr., EH Wolf and TH Steinke, "Stent", US Patent No. 5735872 (1998)
85. HI Wallsten, "Prosthesis comprising an expansible or contractile tubular body", US Patent No. 4,655,771 (1987)
86. "Peripheral Vascular Disease: Diagnostic & Treatment Procedures", Hall-Garcia Cardiology Associates
(http://www.hgcardio.com/PVDdx/body_pvddx.htm)
87. C Gianturco, "Percutaneous endovascular stent and method for insertion thereof", US Patent No. 4580568 (1986)
88. C Gianturco, "Percutaneous stent assembly", US Patent No. 5282824 (1994)
89. M Maeda, HA Timmermans, BT Uchida and J Rosch, "Spiral stent", US Patent No. 5507767 (1996)

90. "Multicenter Randomized Comparative Trial of the New Spiral Z-Stent Compared to Wallstent: Final Results of the ZOOM Study", American Society for Gastrointestinal Endoscopy (ASGE) Annual Meeting (2001)
91. "Wilson Cook Medical"
(http://www.cookgroup.com/wilson_cook/)
92. D Maass and HI Wallsten, "Device for application in blood vessels or other difficultly accessible locations and its use", US Patent No. 4553545 (1985)
93. CT Dotter, "Transluminally placed expandable graft prosthesis", US Patent No. 4503569 (1985)
94. "Technology status evaluation report – Biliary stents", American Society for Gastrointestinal Endoscopy (1999)
95. CS Lim, PCT Eng, SC Lin, CK Chua and YT Lee", Rapid prototyping and tooling of customized tracheobronchial stents", Int J adv Mfg Technol.
96. CJ Pepine, DR Holmes, PC Block, CE Mullins, JA Brinker, SE Nissen, DB Mark, EJ Topol and DO Willaims, "Coronary Artery Stents", JACC Vol 28(3) pp782-794 (1996).
97. "Selective Laser Sintering", Rapid Prototyping and Solid Freeform Fabrication - The Worldwide Guide
(<http://home.att.net/~castleisland/sls.htm>)
98. Gere and Timoshenko "Mechanics of Materials", Chapman Hall (1994) pp 632 -638.
99. KG Sung, GS Jung, SG Cho, JG Kim, JH Oh, HY Song and ES Kim, "The Efficacy of Metallic Stent Placement in the Treatment of Colorectal Obstruction", Korean J Radiol Vol. 3(2) pp79-86 (2002)

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APPENDIX

Appendix A

The Tecoflex EG-72D-B20 polyurethane resin from Thermedics Incorporated (USA) was selected to make the new colonic stents. The resin is ISO 10993 certified to be biocompatible and is sold in the form of pellets for injection molding. The followings are its properties:

Shore Hardness	82D
Youngs Modulus	1234 MPa
Ultimate Elongation	190%
Melt Index g/10min at 2160g load	3.5 175°C
Mould Shrinkage	0.4%

Appendix B

The 6020 polyurethane resin from MCP HEK-GMBH was used to make preliminary test samples of the new colonic stents. The resin comes in a two parts, 6020A and 6020B. The two part are mixed to form the harden plastic. However, this polyurethane had not been ISO 10993 certified to be biocompatible. Biocompatibility testing and certification would be necessary should it be deemed as the material for the stent. The followings are its properties:

Shore Hardness @ 23°C	70D
Youngs Modulus	1395 MPa
Ultimate Elongation	50%
Mixing Ratio by weight (A:B)	1:1
Pot Life	110 sec
Viscosity @ 25°C	
Part A	200 cPs
Part B	40 cPs
Mould Shrinkage	0.6% - 0.8%
Demoulding Time @ 70°C	45 min

Appendix C

Publications

The following papers regarding this new stent were published:

1. KS Ang, SC Lim, WS Ng, C Tsang and GB Chai, "Rapid Prototyping and Tooling in the Production of Polymeric Meshed-type Colon Stent", International Conference on Advanced Research in Virtual and Rapid Prototyping (2004), pp 645-647.
2. CS Lim, WM Chiang, KS Ang, CK Chua, WS Ng and GB Chai. "Polymer-based Stents Produced by Rapid Prototyping and Tooling", International Journal of Product Development (2004) Vol 1 pp 172-182.

Awards

This project had won a Commendation Award at the Tan Kah Kee Young Inventors Award 2003.