Creating Biofidelic Phantom Anatomies of the Colorectal Region for Innovations in Colorectal Surgery

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The aim of this research was to develop a replicated colorectal region for use in laparoscopic instrument innovation. Testing of both surgical skills and laparoscopic surgical instruments takes place in a controlled lab setting. Cadaverous tissue or laparoscopic simulators are the tools of choice for skill testing. However, in the instance of colorectal surgery, porcine intestines remain the gold standard for laparoscopic testing (Lamata et al. 2004). There exists data in current literature which discuss the use of anatomical simulators (also known as simulator boxes) for both researching surgical methods, and testing laparoscopic instruments. There is little focus in the literature on the materials used to create surrogate environments which mimic those of the real world. Simulator boxes exist, and are of high fidelity, but can be quite cumbersome, with some being left in storage areas indefinitely, with some remaining inaccessible for many centers around the world. There are also many peripheral devices which need to accompany these simulators, such as laparoscopes and external monitoring equipment for recording and review. As they are highly specialized pieces of research equipment, in the majority of cases, they are not designed to be portable or readily reconfigurable. These limitations make high end laparoscopic simulators inappropriate choices for early stage HFE (Human Factors Engineering) studies. The authors propose the creation of a laparoscopic simulator which contains anatomically accurate, 3D printed colorectal sections for use in both surgical training and instrument innovation. The colon is modeled from high quality CT data in DICOM format, using the Material Mimics Innovation Suite (Materialise, 2013). By creating virtual models of the internal anatomical structure of the colorectal region, it allows for a more accurate depiction of the anatomy encountered in a surgical setting. A maximum level of realism is required for a simulator to be effective (Lamata et al. 2004). The future application of this work lies in the validation of the 3D printed anatomy which will lead to innovation of new instruments or approaches to laparoscopic surgery.

INTRODUCTION

Minimally Invasive Surgery is fast becoming the first choice for a large portion of surgical procedures. There is an increasing part of surgical interventions that is now conducted though Minimally Invasive Surgery (MIS) means, such as laparoscopy. Due to this rapid evolution, MIS has become fraught with its own challenges to the process of learning, due to the limited tactile feedback and haptics, as well as transferring a three dimensional environment onto a two dimensional screen (Schostek et al. 2009) (Hagiike et al. 2007). Currently, laparoscopic surgical training is dominated by simulation. The incorporation of simulation models in lieu of a surgical setting allows for trainee surgeons to hone their surgical skills without the need for in situ training or risk to patients. Orientation skills, tissue handling, coping with lack of tactile feedback and hand tremor control techniques are crucial for novice laparoscopic surgeons in order to practice safe and efficient laparoscopic surgery while minimizing risk to the patient (Harrell and Kopps 1998). Training of these skills in a real life setting has become increasingly difficult because of time constraints and issues around planning and
ethical considerations with regard to patient safety. As the operating room is no longer an ideal environment for surgeons to develop their core laparoscopic surgical skills, which would put patients at risk, there is an increasing demand for alternative methods to train surgeons, such as simulators. There is a need for innovation outside of the operating theatre environment as many surgeons now feel inadequately prepared to perform advanced laparoscopic surgical procedures even after they complete residency training (Chandrasekera et al. 2006).

Specialized training is required in order to perform safe and efficient laparoscopic surgical procedures. In order to reach professional status that a surgeon requires, progression through the assessment of theoretical knowledge and operative skills is paramount. Procedural skills vary from one surgical procedure to another, the combinations of which define the surgical craft (Clanton et al.). Previously, these skills were honed by spending countless hours in operating theatres, observing and learning from surgical experts and procedures themselves. This “apprenticeship” training method has since been called into question due to its lengthy and drawn out nature. The educational environment is rapidly changing, which leads to the curtailing of work hours. This in turn leads to a significant reduction in opportunities for surgical residents to train and hone their skills (Nagendran et al. 2013).

Simulation in laparoscopy leads to skill acquisition. It is an innovative method to teach, and offers advantages over other training methods such as opportunities for repeated practice, no risk of harm to actual patients, and availability outside of the operating theatre. Simulation encourages trainees to become more proficient in their skills before practicing on real people (Korndorffer Jr et al. 2005).

Both VRSs and box trainers come with both their advantages and disadvantages. VRSs are expensive, but they keep records of multiple variables and can assess different facets of laparoscopic surgery simultaneously (Salkini et al. 2010). They are not readily portable, and require constant input and maintenance in order to assure their validity. Box trainers are cheap, and use real instruments and tangible target anatomies. However, it is difficult to record performance variables, and box trainers require someone who sufficient surgical expertise to lead the training session and assess trainees (Oropesa et al. 2011).

Box trainers usually consist of a means of containing physical objects such as artificial anatomies, which are positioned for surgery. Trainees can then practice various skills and elements of surgical procedure tasks such as camera navigation, anatomical navigation, and hand-eye coordination. A great variety of physical objects can be placed in the box, depending on the type of training. Novice surgical trainees start practicing navigation and hand-eye coordination by positioning and maneuvering small objects such as beans. More advanced trainees perform actual procedures on either synthetic or organic organs/tissues. The organic tissues can either be living or cadaveric (Newmark et al. 2007). External props such as lights and medical appliances can be used to mimic an operating theatre environment as closely as possible. Trainees can use standard laparoscopic instruments during training and can practice on physical structures that mimic that of human anatomy. This allows trainees to gain experience and develop skills in understanding haptic feedback. Because of this, there has become a need to investigate ergonomic training methods (Diesen et al. 2011). In spite of this, there are several studies which show that VRS training methods have contributed to the reduction in the time and expense in both training and psychomotor skill acquisition, in operating theatres. Simulation is growing in popularity among those who train laparoscopic skills (Taffinder et al. 1998). However, there is still no consensus which determines which simulation method is superior, and which teaching methods should be used.
factors associated with the simulation environment and box trainer, with the aim of improving existing modalities (Xiao et al. 2012). It is common that most simulation environments are suboptimal from a human factors point of view. For example, table heights may not be adjusted, monitors cannot be properly adjusted, and proper staff are not readily available to assist. Moreover, the area inside the box trainer as well as the target area of focus cannot assure a certain range of intra-corporal/extra-corporal instrument length ratio, and the optical axis-to-target view angle is often not constant between surgeries, leading to further suboptimal environmental issues (Kroeze et al. 2009).

A physical model of the colorectal region and surrounding organs can act as a suitable surrogate environment to assess both laparoscopic surgical skills and laparoscopic instrument design. The creation of a permanent anatomical environment which can be used to assess the tissues surrounding the colon could lead to innovation in the creation of laparoscopic instruments which are designed to assist in operations such as colectomies or resections. Moreover, using patient specific scan data to model anatomy allows for trainee surgeons to practice skill acquisition techniques using recreations of actual anatomies from real life cases. There are many advantages to using 3D printed colorectal anatomies for surgical skill acquisition. It is a cheap, accurate method of honing skills without there being any risk to a patient. The structure of the printed anatomy would be a three dimensional facsimile of the CT/MRI data used to create it, which would reflect the specific case on which the trainee could practice. The aim of this research was to develop and facilitate the creation of a 3D printed colorectal region, using patient-specific CT scan data, in order to encourage laparoscopic instrument innovation.

**METHOD**

**Recreating Anatomical Structures Virtually**

The colorectal region of a normal anatomical structure was created virtually using the Materialise Mimics Innovation Suite (Materialise, 2013). The colon was modeled from high quality CT data in DICOM format. This allowed for a true-to-life representation of the colon to be created with primary data, rather than the construction of a virtual colon using secondary information and interpretation. The rough model created in Mimics was then taken into Mimics 3-Matic (Materialise, 2013). Post processing techniques were then applied which smoothed and prepared the model for printing. Mating components were attached to the duodenal and rectal sides to allow for successful integration into a box trainer environment. The colon model could then also exist on its own in a rig for illustrative or educational purposes.

Anonymous CT Scan Data was used to conduct this study. After assessing each scan, it was decided that the higher quality scans best suited. The following assessment criteria were used (Table 1):

<table>
<thead>
<tr>
<th>Table 1. Criteria for CT Scan Data</th>
<th>Acceptable Tolerances</th>
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</thead>
<tbody>
<tr>
<td>Anatomical Selection</td>
<td>Abdomen/Pelvis</td>
</tr>
<tr>
<td>File Format</td>
<td>DICOM</td>
</tr>
<tr>
<td>Scan Type</td>
<td>Helical Full</td>
</tr>
<tr>
<td>Scanning Method</td>
<td>High Res CT</td>
</tr>
<tr>
<td>Slice thickness (mm)</td>
<td>≤ 5</td>
</tr>
<tr>
<td>Pitch/Table Speed</td>
<td>n/a</td>
</tr>
<tr>
<td>Scan Field of View</td>
<td>Large Body</td>
</tr>
<tr>
<td>Anatomical Condition</td>
<td>Normal in Colorectal Region</td>
</tr>
<tr>
<td>Weight of Patient</td>
<td>Normal to Obese</td>
</tr>
<tr>
<td>mA Values</td>
<td>Based on Cover Area and Size of Patient</td>
</tr>
</tbody>
</table>

Six different approaches were used to create the colon virtually:

*Create solid anatomical block and cut out parts that are not required:* This visualization method involved the segmenting of the colon through the use of Boolean subtraction. This method was employed in lieu of inverting the CT data due to difficulties in tissue delineation. A solid block of material was created virtually, and then each irrelevant tissue and cavity was subsequently erased from the block. The end result was...
suspected to be an encased colon that is virtually identical to a real one (Figure 1).

Create abdominal cavity and construct the colon from the outside inward: Similar to the first method, the creation of the cavity facilitated the visualization of the colon as it acted as a guide for positioning and thresholding. The walls of the abdominal cavity were created first and this served as a foundation on which to build the colon proper (Figure 2).

Threshold soft tissues and erase irrelevant areas: Unlike the previous two attempts, this method did not require tissues to be identified. All tissues in the area were visualized and created virtually, and the irrelevant tissues were then erased. It was found that this method created a rather cluttered 3D space in which to work. (Figure 3).

Manually create each slice of colon and create 3D models: Rather than segmenting specific tissues and inheriting the difficulties therein, an approach which involved the masking of each slice manually was devised. This method allowed for the relevant tissues to be segmented without the need for there to be significant differences in the consistency between relevant and irrelevant areas (Figure 4).

Create multiple sections of colon cavities and join the spaces between them: A different scan was used for this method which did not feature an insufflated colon. However it led to inaccuracies due to the perceived joining of tissues where it did not occur. The end result of this method was a collection of broken “chunks” that resembled that of a colon (Figure 5).

Segment insufflated colon cavities and build up tissue: Through the use of cavity visualization techniques, and CT scan data which lent itself to the process, this method accurately visualized the inside of an insufflated colon. Although no tissues were visualized, the accuracy of the pathway remained intact. Tissues were then built around the cavity in order to form a solid shape for 3D printing. The area gained from insufflation compensated for the bidirectional thickening of the colon walls when creating the solid body. Although the accuracy of the outer walls is not true-to-life, the internal structure is an exact replication of that presented in the scan data and as such, this method was deemed most appropriate (Figure 6).

Recreating Anatomical Structures

By creating virtual models of the internal anatomical structure of the colorectal region, it allows for a more accurate depiction of the anatomy encountered in a surgical setting. A maximum level of realism is required for a simulator to be effective (Lamata et al. 2004). The scope of this research encompassed that of the inner pathway of the colon. Because of this, the shape and consistency of the outside was not modeled as accurately.
The method which facilitated the creation of the colorectal model in a virtual space did not take into account model adherence or stabilization components for when the printed model is placed in a simulation environment. Post processing work was needed using companion software in order to tailor the model, making it more suitable for 3D printing. Mating components were attached to the duodenal and rectal sides to allow for successful integration into a box trainer environment. The colon model could then also exist on its own in a rig for illustrative or educational purposes (Figure 7). To facilitate this, the beginning and end of the model were shortened (Figure 8). However, this was mainly due to issues with the scan data.

**DISCUSSION**

One of the main focuses of this research was to maintain accuracy of the colon in terms of both tissue allocation and transit route. Difficulty arose in determining which tissues belonged to which anatomical entity. Because of this difficulty, it was decided that the colon cavity would be modeled first, and then the tissues would be constructed around it. This allowed for accuracy of the internal pathways to be maintained. There was also difficulty in segmenting key tissues of the colon itself due to the resolution of the scan.

The future development of simulators could bring in external measurement tools to further assess the skill development of trainees. Instruments which monitor the motions of trainee surgeons’ hands and the instruments they use while performing laparoscopic surgical procedures in a live setting could provide safer, more efficient surgical practice as well as improved patient safety, by indicating potential adverse events before they occur (Debes et al. 2012). The development of an accurate colorectal model that is fabricated in separate components could allow for resections to occur in a more realistic simulation space. The work to replicate atomically accurate colorectal regions of the human body is ongoing. The authors propose performing the same task on CT EVAR scans. This could allow for more accurate construction of the colon and surrounding tissues.
CONCLUSIONS

Currently, laparoscopic surgical skills are honed by surgeons through use of box trainers, virtual reality simulators, self-directed practice, and mental training, although some methods are used far more than others (Mulla et al. 2012). There is a need for greater innovation for laparoscopic surgical skill acquisition methods, and a need to develop novel methods of assessing these skills over time, and to take into account additional factors such as skill decay (Stefanidis et al. 2005). By creating a more realistic representation of a colon in a simulation environment, the degree of realism would be increased allowing for enhanced skill acquisition and reinforcement, and reducing skill decay. Surgical simulators, both virtual reality and box trainers, are already a very important part of surgical training. Real cases could be studied using patient specific anatomy. There are also different facets of training which much occur in order to ensure surgical competency, such as psychomotor testing. However, newer training methods are needed in order to maintain a sense of realism, surgical efficiency, safety and high quality standards (Hull et al. 2010).

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REFERENCES


