Interaction Techniques for Immersive CT Colonography: A Professional Assessment

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Abstract. CT Colonography (CTC) is considered the leading imaging technique for colorectal cancer (CRC) screening. However, conventional CTC systems rely on clumsy 2D input devices and stationary flat displays that make it hard to perceive the colon structure in 3D. To visualize such anatomically complex data, the immersion and freedom of movement afforded by Virtual Reality (VR) systems bear the promise to assist clinicians to improve 3D reading, hence, enabling more expedite diagnoses. To this end, we propose iCOLONIC, a set of interaction techniques using VR to perform CTC reading. iCOLONIC combines immersive Fly-Through navigation with positional tracking, multi-scale representations and mini-maps to guide radiologists and surgeons while navigating throughout the colon. Contrary to stationary VR solutions, iCOLONIC allows users to freely walk within a work space to analyze both local and global 3D features. To assess whether our non-stationary VR approach can assist clinicians in improving 3D colon reading and 3D perception, we conducted a user study with three senior radiologists, three senior general surgeons and one neuroradiology intern. Results from formal evaluation sessions demonstrate iCOLONIC's usability and feasibility as the proposed interaction techniques were seen to improve spatial awareness and promote a more fluent navigation. Moreover, participants remarked that our approach shows great potential to speed up the screening process.

1 Introduction

CRC is the second leading cause of cancer-related death in the western world, with an estimated 1.4 million new cases every year worldwide, half of which end in death [1]. Screening procedures are the most important preventive methods. Although optical colonoscopy is the preferred screening examination [2], CTC

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offers a significantly reduced number of side effects [2,7] as well as a less invasive alternative (e.g., does not require bowel cleansing nor general anesthesia). The CTC also has the advantage of generating subject-specific 3D colon models. Within these models, standard CTC navigation is performed via Fly-Through visualization [3], which simulates conventional optical colonoscopy as the camera follows antegrade (rectum→cecum) or retrograde (cecum→rectum) paths.

From a geometric point of view, a 3D colon model is a complex structure with several inflections and numerous haustral folds. This makes 3D colon navigation a difficult task *per se* and an even more exacerbated task when performed using conventional workstations: the radiologist is seated at a desk in front of a stationary flat display and interacting with complex radiological data using mouse and keyboard interfaces. However, using a 2D display to analyze 3D structures can lead to missing critical 3D information and time consuming screening procedures, hence, resulting in incomplete or lower number of CTC reports [6]. Moreover, conventional systems negatively affect productivity by providing insufficient space and reduced number of monitors [10].

VR appears as an interesting paradigm for CTC navigation since it has been reported that immersion benefits scientific data set analysis [5]. Moreover, previous studies explore the potential of VR in radiologic settings [4,6,8,12] demonstrating that VR solves several ambient lighting issues, forces users to adopt an ergonomically correct posture, and promotes a far more superior camera control when compared to conventional mouse and keyboard based interfaces. Immersion also promotes a greater visual bandwidth and improves 3D perception. Consequently, immersion can improve the colon anatomy reading and spatial understanding of lesions, such as occult polyps that typically hide behind haustra or folds, leading to faster screening practices and improved lesion counting.

Previous studies considered the application of VR technologies to CTC. Mirhosseini et al. [6] used a *Cave Automatic Virtual Environment* to project the gastrointestinal walls onto the display's physical walls. Although its use lead to improvements in medical diagnostics (examination time and accuracy), such displays are unpractical in real clinical settings when compared to head mounted displays (HMDs). On the other hand, Randall et al. [8] resorted on a HMD (i.e., Oculus Rift) to examine the immersiveness of VR to analyze and interpret CTC content. However, the work lacked positional tracking, did not allow users to signalize lesions, was devoid of navigational signs apart from not exploring different navigation techniques. Even with a HMD, the interaction did not allow more interesting movements such as walking inside the colon or adopting postures to control users' point of view towards the anatomical content.

In this work, we present iCOLONIC, a set of interaction techniques for navigating inside and outside the colon. The main objective of this work is to explore how non-stationary VR can help navigation and readability of 3D colon models in CTC. We contribute with novel interaction techniques for immersive CTC navigation, which provide freedom of movement while standing and moving in the work space, but also greater camera control in comparison to conventional systems. Furthermore, we performed a user study to better understand how specialists respond to these interaction techniques.

2 Immersive CT Colonography System

A VR system called iCOLONIC (Immersive CT Colonography Navigation Interaction Techniques) was developed to navigate both exo- and endoluminal spaces of a virtual 3D colon. Several tools were developed to assist 3D immersive navigation and to perform radiologic measurements. All the code was developed in C# using the SteamVR Plugin and Unity game engine (version 5.5.1f1).

2.1 Apparatus

Our setup relies on the off-the-shelf solution embodied by HTC Vive (Fig. 1). It consists of a binocular Head-Mounted Display, two game controllers and a Lighthouse Tracking System composed by two cameras with emitting pulsed IR lasers that track all 6 degrees-of-freedom of head and handheld gear. The tracking system generates an acquisition volume that enables users to move freely within a $4.5 \times 4.5 \times 2.5\ m^3$ space. User tests were performed on an Asus ROG G752VS Laptop with an Intel® Core™ i7-6820 HK Processor, 64 GB RAM and NVIDIA GeForce GTX1070. iCOLONIC runs at 60 frames per second.

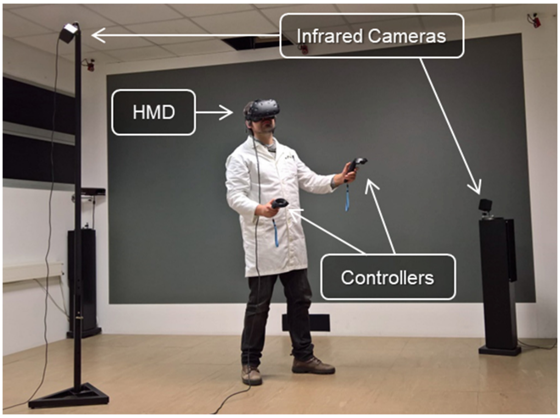

Fig. 1. Virtual Reality setup of the iCOLONIC interactive system.

2.2 3D Data

A single CTC data set from *The Cancer Imaging Archive* [11] was considered (subject ID *CTC-3105759107*), which had almost no liquid, acquired in a supine position, presented large (>10 mm) and quite visible polyps along with several

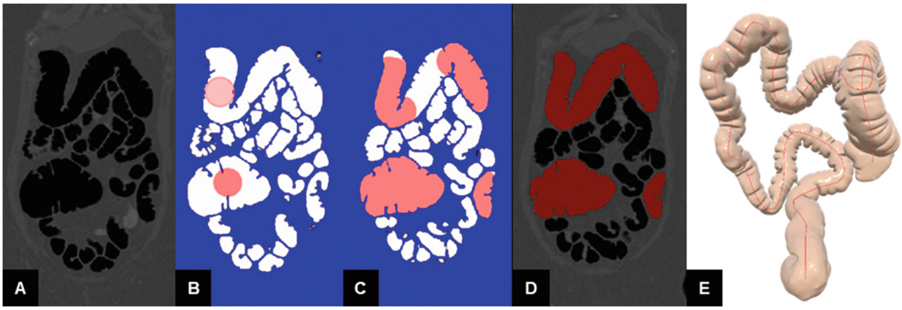

Fig. 2. 3D colon reconstruction: (A) original CTC image; (B) global threshold image with two active contours (red); (C) active contour model progression; (D) segmented colon overlapped with CTC image; (E) reconstructed 3D model with centerline [14]. (Color figure online)

diverticula. The 3D model was reconstructed using the image-based geometric modelling pipeline that is composed by freeware tools [9] (Fig. 2).

The high contrast between luminal space (air: black) and colon luminal surface (colon wall: light grey) facilitates 3D reconstruction (Fig. 2(A)). Firstly, the 3D colon structure is segmented using the active contours method based on region competition (Fig. 2(B-D)), which depends on the intensity values estimated via a simple global threshold filter (ITK-SNAP 3.6). Secondly, a 3-D surface mesh of the segmented data is generated using marching cubes. Thirdly, undesired mesh artifacts were attenuated through a cycle of smoothing and decimating operations (ParaView 5.3.0) and exported into a *.ply (ASCII) file. Finally, the mesh file was converted to *.obj (Blender 2.78) and imported into Unity (version 5.5.1f1). To compute the 3D centerline of the colon mesh, we used the algorithm proposed by Tagliasacchi et al. [14] which solves the 3D mesh skeletonization problem by resorting on mean curvature flow (Fig. 2(E)).

2.3 Interaction Design

From an anatomical point of view, the colon is a complex structure where lesions, anatomical deviations and/or conditions can occur on either sides of the luminal surface. Therefore, iCOLONIC's interaction techniques allow users to navigate on both spaces and to switch between Exo-Luminal View (*ExoV*) and Endo-Luminal View (*EndoV*) for outer and inner colon navigation, respectively. In *ExoV*, the 3D colon is up scaled to the size of an average adult and is placed floating above the ground (Fig. 3(A-B)). As for *EndoV*, the user is down scaled to fit inside the luminal space and experiences the colon confined from within (Fig. 3(C)).

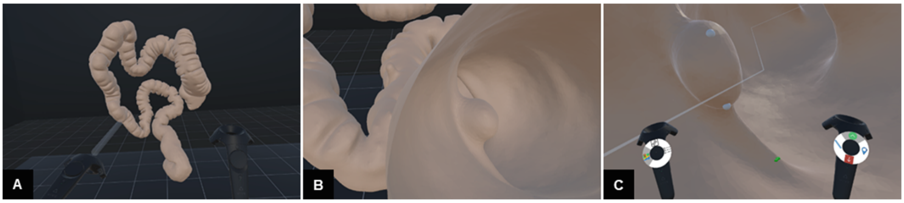

Fig. 3. Representing the colon in different scales and views: **(a)** up scaled colon in *ExoV*; **(b)** clipped view of up scaled colon in *ExoV*; **(c)** down scaled colon in *EndoV*.

The motivation behind *ExoV* came from colonic conditions, such as diverticulosis, that can be better diagnosed when viewed from the outside. To take advantage of the virtual space made available in VR, we consider an up scaled representation so that the user can instantly withdraw the overall geometry and also local landmarks that are now magnified. In *ExoV*, users can freely move around the 3D colon or rotate the model using the non-dominant hand (NDH) controller. Alternatively, users can also stick their heads beyond the colon wall to get a glimpse of the endo-luminal space (Fig. 3(B)). In a less meddlesome fashion, a user can also opt for a target-based travel by selecting a point from outside the colon with the NDH controller to be transported to the closest point on the centerline (Fig. 4), hence, the user is down scaled into the endo-luminal space where the view immediately switches to *EndoV* similarly to the *World In Miniature* metaphor [13].

Following conventional CTC practices, endo-luminal navigation can also be performed in a more orderly fashion, where the user begins navigating from the rectum towards the cecum and *vice versa*. In *EndoV*, the user is placed inside the colon and travels via Fly-Through navigation techniques [8] at a self-controlled smooth pace. Inside the colon lumen, navigation follows the path defined by the colon's centerline. By default, the user is anchored to the centerline to avoid unwanted intersections against the colon walls or, *in extremis*, to avoid exiting the luminal surface. Users can freely move their heads and/or body to look around and behind the virtual colonic scenery. However, users can opt to abandon the centerline by physically walking towards the colon wall and reach the lumen limits to better examine local features. After exploring the colon wall, users can reposition themselves by moving back towards the centerline. To assist navigation, two arrows pointing in opposite directions are placed in front of (green: antegrade) and behind (red: retrograde) the user accompanying the centerline.

iCOLONIC provides navigational and diagnostic tools (only in *EndoV*) that are managed through two HTC Vive controllers (Fig. 4(A)). A menu appears every time the touchpad is touched and tools are activated by pressing the corresponding widget button. The dominant hand (DH) controller handles up- and down-stream navigation as well as tagging and measurement tasks, while the

NDH controller showcases either CTC slices (axial, sagittal, coronal) (Fig. 4(B)), a list of tagged lesions with dimension and C-Rad type information (Fig. 4(C)) or a colon mini-map with current location and lesions tags (Fig. 4(D)).

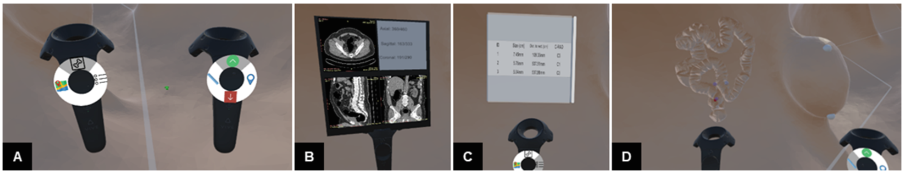

Fig. 4. iCOLONIC tools: **(A)** circular touchpad menus; **(B)** CTC slices of the user's location inside the colon; **(C)** polyp list of tagged lesions with size and C-Rad type; **(D)** colon mini-map with location and tagged lesions.

3 Evaluation with Professionals

We conducted an evaluation with seven medical professionals, two of which were female, ages ranged between 29 and 55 years old. The group included two radiologists with specific training in CTC (each with 3 years of experience), one senior radiologist (10 years of experience), one neuroradiology intern and three general surgeons (1, 8, and 26 years of surgical experience). Four of these professionals regularly examine CTC images, and only one reported previous VR experience. With the exception of the intern, all reported that they read CTC images on a daily basis.

Evaluation sessions comprised four stages: (1) Introduction, (2) Free Experimentation, (3) Questionnaire and (4) Guided Interview. After a thorough demonstration of all available functions and their application, all professionals were asked to test iCOLONIC alone. Participants tested the interaction techniques for 35 min, with 10 min to familiarize themselves with the interface and interaction techniques. The only restriction being they had to experiment each available function at least once. After Free Experimentation participants filled a small profile form along with a questionaire regarding the quality of their experience with the interface and interaction techniques (6-point Likert Scale: 1 - totally disagree; 6 - totally agree). Afterwards, we conducted a semi-structured interview where participants gave insights about the experience, their preferences and suggested improvements. None of the participants reported discomfort, dizziness or fatigue.

(Table 1) reports the participants opinions regarding usefulness and performance of the proposed interaction techniques and tools. In general, users considered the navigation interaction techniques easy to execute and to remember. Navigation tools were considered highly useful with adequate feedback although the CTC slices tool was given a slightly lower score compared to mini-map (Table 1). The participants were able to identify several polyps and diverticula, even though none was prompted to do so. Most participants referred that the color contrast could be slightly improved, specially in *EndoV* mode. With the exception of the intern, all participants mentioned that the non-stationary VR environment clearly improved on the tedious and complex movements performed with mouse and keyboard based CTC interfaces. Even though participants had access to the 3D colon surface and images, two radiologists trained in CTC referred that data was missing as they performed screening with both prone and supine models. The senior radiologist and one senior surgeon referred that larger CT slices with arbitrary orientation could help understand the relation between colon conditions (e.g., polyps, diverticula) and the adjacent tissues. Furthermore, participants were unanimous with the need to paint suspicious areas with different colors, a feature yet to be implemented.

Table 1. Questionnaire results regarding user experience and preferences. NV - up- and down-stream navigation; DM - distance measurement; TG - Tagging; MM - colon mini-map; CS - CTC slices; PL - polyp list; TT - target-based travel from *ExoV* to *EndoV*. Median (Interquartile Range).

Was it	NV	DM	TG	MM	CS	PL	TT
Useful	6(1.5)	6(1)	6(1.5)	6(1.5)	5(1.5)	6(1.5)	5(1.5)
Easy to execute	6(1.5)	5(1.5)	6(1.5)	5(1.5)	4(2)	6(1.5)	5(1.5)
Easy to remember	6(1)	6(1.5)	6(1.5)	6(1)	5(1.5)	6(1.5)	6(1.5)

In general, professionals felt immersed and believed that this kind of interactive visualization will become a future standard. In their opinion, the main advantage of our approach is the speed at which radiologists will be able to examine CTC data. In their words, *"conventional CTC is cumbersome and slow"*, besides the fact that the software and hardware used are expensive. Despite the novelty and early enthusiasm, their opinions are encouraging as they uncover the possibility of radiologists and surgeons to adopt non-stationary VR-based approaches as novel diagnostic and surgical planning tools. Finally, participants mentioned that once the missing features were implemented they would be prone to use iCOLONIC in their day-to-day work.

4 Conclusions

In this work, we explore the potential of VR immersion and freedom of movement to assist CTC navigation. Our approach addresses issues intrinsically associated to conventional CTC screening interfaces that are known to limit camera control, 3D perception and visual bandwidth. Results strongly indicate that the combination of immersion, freedom of movement and World In Miniature metaphors is a feasible way to overcome limited camera control and assists the professional to more rapidly detect lesions and other conditions. Furthermore, participants in our evaluation were positively impressed and suggested that the interaction techniques were adequate. However, several features need to be implemented to provide a more complete diagnostic tool, namely inclusion of both prone/supine 3D data, computer-assisted detection and fecal tagging. To clinically validate the interaction techniques, future research will focus on quantifying user fatigue, polyp count effectiveness and screening efficiency using several CTC data sets.

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