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Three-Dimensional vs Two-Dimensional Minimally Invasive Surgery
A comparison of the visual work load and surgical outcomes

By

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Declaration

I hereby declare that, the contents and organization of this dissertation constitute my own original work and does not compromise in any way the rights of third parties, including those relating to the security of personal data.

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2018

* This dissertation is presented in partial fulfillment of the requirements for **Ph.D. degree** in the Graduate School of Politecnico di Torino (ScuDo).

I would like to dedicate this thesis to my Sara, Tommy and Ricky
“ siete il mio castello e nessuno può entrare”

Acknowledgment

And I would like to acknowledge the precious support of my parents and all my real friends.

Abstract

BACKGROUND

Three-dimensional (3D) imaging, a recent technical innovation in laparoscopic surgery, has been introduced to enhance depth perception and facilitate operations. The clear benefit of the 3D laparoscopy has never been tested. Some concerns emerged regarding the possible negative effects over the visual system in those surgeons who performed 3D surgery every day. 3D laparoscopy has been validated both in "in-vitro" and "in-vivo" (clinical) settings. All survey done in laparoscopic simulator comparing surgical exercise (suturing, peg transfer, cutting) performed with 2D or 3D system reported better results in the second group, regardless the surgeon experience. Less data is disposable in the clinical setting, but with same conclusions.
The use of 3D technology needs passive or active polarized glasses. Optometric tests, objective exams (RMN or EEG) and subjective questionnaires have been widely used to evaluate the alterations in the visual system utilizing the 3D technology. Each test concluded that 3D technology causes alteration in the EEG waves, but how long these alterations last is still unknown.

AIM

The aim of this study was to evaluate the possible benefit of using the 3D technology in terms of surgical outcomes (study 1) and to evaluate the alterations over the visual system operating in 3D laparoscopy (study 2).

MATERIALS AND METHODS

The study was a single-center prospective observational clinical trial, divided in two sub-study with a single patients-population. Participants included patients aged 18 years old and above, eligible for colorectal resections for neoplastic or inflammatory diseases. Four experienced surgeons in colorectal and laparoscopic

surgery participated in the study. Each surgeon followed the standard laparoscopic surgical rules performing the different type of colorectal resection, regardless the study subgroup. Data were collected at the pre-operative clinic, during surgery, during the hospitalizations and at the short term follow-up (30^{th} days).

For each study, there was a primary endpoint:

1. Primary endpoint for Study 1: incidence of Clavien grade 3, 4 and 5 post-surgical complications in patients undergone 3D colorectal resection;
2. Primary endpoint for Study 2: to grade the visual work load of surgeons operating with 3D screens and glasses.

At the end of each procedure (2D or 3D) the first surgeon had to fill in two different subjective questionnaire (the NASA task load index questionnaire and the Simulator Sickness questionnaire) to grade the visual sickness felt during the operation.

RESULTS

From January 2015 to September 2017, 313 patients were enrolled in the study: 82 in the 2D group, 231 in the 3D group.

STUDY 1: Colorectal cancer was the main indication for surgery (n 235, 75.1%), followed by colonic diverticulosis, benign polyposis and inflammatory bowel diseases (IBD), respectively 43 (13.8 %), 25 (7.9 %) and 10 (3.2 %). Age, sex, ASA score were comparable between the two groups. The median operative time showed no statistically significant difference between the 3D and 2D groups (p 0.611). Less drains were positioned at the end of the 3D operations comparing with 2D procedures (p 0.013). The stapled anastomosis was the most frequent performed over other techniques. The other intra-operative findings showed no significant difference between the two study groups. The median hospitalization and the reoperation rate showed no difference between the two groups.

STUDY 2: The statistical analysis done over all 313 cases divided in 2D and 3D did not reveled significant difference of the visual work scored by the NASA TLX. Data emerging from the SSQ questionnaire reveled no case of moderate or severe symptoms in both groups.

CONCLUSIONS

3D laparoscopic surgery had the same postoperative results of the 2D standard laparoscopy. The more frequent intra-abdominal anastomosis in the 3D group might suggest a more safeness felt by the surgeon using the new technology. The

NASA TLX and the SSQ questionnaire did not reveled significant difference of the visual work between 2D and 3D vision.

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Chapter 1

3-Dimensional Technology

1.1 Introduction

Since the first laparoscopic cholecystectomy performed in the late 80', many technological improvements were introduced in surgery to help surgeons during operations. The visual system in minimally-invasive surgery play a crucial role in this field.

The term three-dimensional minimally-invasive surgery (3D-MS) describes a medical term based on the application of the three-dimensional vision in the laparoscopic, endoscopic or robotic surgery. This technology has been first introduced in military and cinematographic field more than 20 years ago and only in the last decade was stably introduced in the medical practice.

The first medical branch who adapted the 3D-technology was radiology and the 3D ultrasound used in morphological prenatal studies is an example. Lately the CT and RMI scans were implemented by software able to create 3D imaging. Currently the 3D printer is the last innovation used by radiologist in the preoperative planning.

Regarding the laparoscopic surgery, 3D vision was used for the first time at the endo of the 90's with a very poor debut. The first few clinical experience reported bad results mostly because these 3D camera systems had unclear vision with a long reaction time, i.e. long time between the surgeon's movements and their perceptions on the screen. The introduction of recent new technologies like HD

screens and the improvements obtained by the companies on the camera's systems allowed to get through these problems obtaining new 3D camera systems.
The 3D-MS has the peculiarity to add the depth perception at the well know mininvasive surgery. This allow the surgeons to perform the surgical maneuver watching a 3D screen with a virtual three-dimensional space.
At the base of the 3D imaging, there is the capacity of the camera to record two perspectives of the same image. To use the 3D-MS system is finally necessary to wear polarized glasses, thanks to which the surgeon's central neurological vision system can rebuild images coming from the 3D camera. Some concerns emerged about the potential negative effects over the human visual system using this technology.
Many in-vitro (laparoscopic trainer) surveys have recently demonstrated as useful is the 3D-MS to reduce operative time, number of errors and number of attempts performing laparoscopic exercise in expert and young surgeons.
This emerging technology promises to be a great enhancement for mini-invasive surgery, but the real benefit in live surgery and the visual work load using the 3D camera system have not been studied yet. To become an every-day technology in surgery, 3D-MS has to demonstrated to be safe, feseable, reproducible and able to improve significantly the normal clinical work-flow.

1.2 State of the Art

The 3D-MS was introduced in the medical practice at the end of 90's. These first 3D camera systems allowed a three-dimensional vision with blurred images. The sickness felt by the surgeons made the 3D-tachnology unusable mostly in long operations. Moreover, the long reactive time between the surgeon's movements and the screen's images, added to the poor definition of the figures, made very high the risks of intraoperative errors. For these reasons the initial enthusiasm on 3D-laparoscopy left space to great pessimism.
In the first 2000's few companies kept developing this technology, obtaining new version of the old laparoscopic columns. The 2.0 version of 3D-MS solved the old problems, obtaining better results in laparoscopic trainers.
The new 3D laparoscopes offered excellent, magnified, and brilliantly illuminated high-definition images of the surgical field.

1.2.1 Definition, How it works and Devices

The three-dimensional vision allows the feeling of stereopsis of the surgical field. This is obtained thanks to a system composed by 2 parts:

- Imaging capture: camera and laparoscope
- Imaging projection: video and glasses

The technology used to capture a 3D image include a laparoscope, a camera and an image processor. A camera is present at the tip of the laparoscope (chip on the tip) and it is able to capture the image and sends it as an electrical info, through the laparoscope to the image processor (Figure 1). Basically, there are two technologies used to capture the image for 3D vision: single-channel and dual channel. The former extracts two perspectives of one image from a single point of view, splitting the image with a filter, the letter has two cameras at the laparoscope's tip with two different perspectives (Figure 2 and 3).

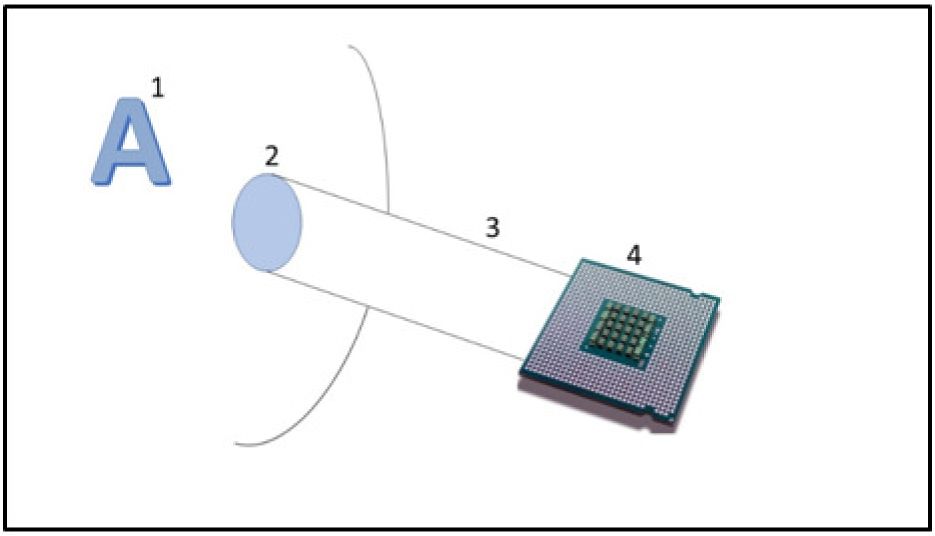


Figure 1: image capture system, 1 image, 2 camera on the tip, 3 laparoscope, 4 processor

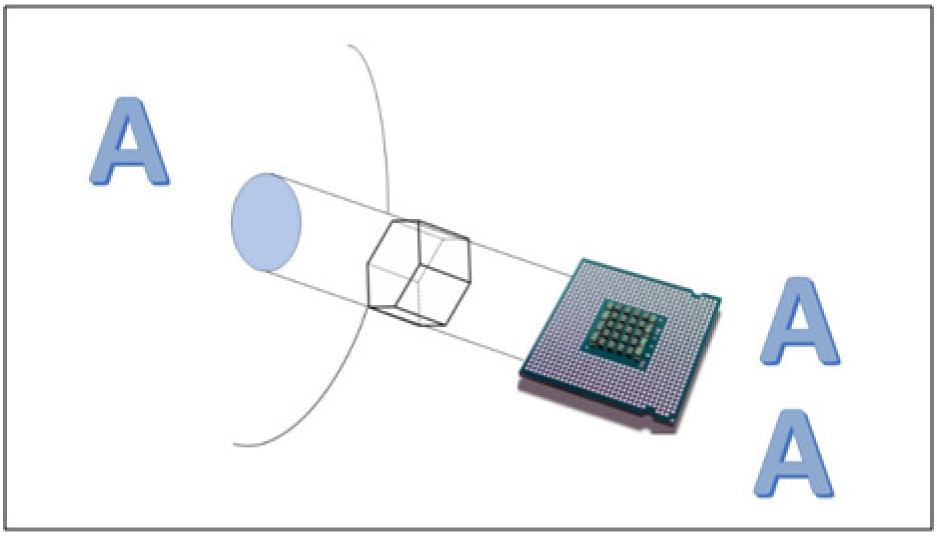


Figure 2: single channel system with a filter extracting two perspectives from a single point of view

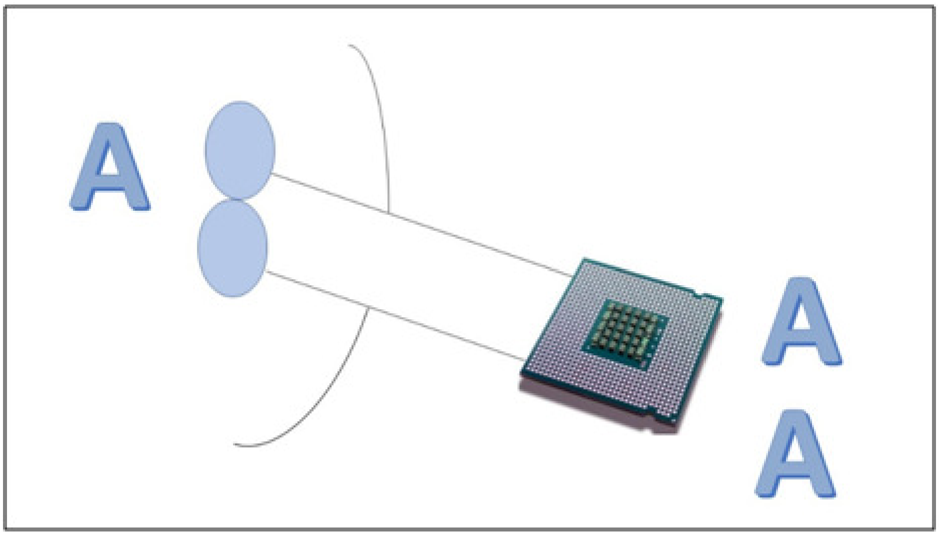


Figure 3: dual channel system with two camera on the tip extracting two real perspectives of the same image

Single channel system has the positive aspects to have a greater optic channel able to produce images with greater clarity and resolution than dual channel camera. On the other hand, it can produce a 3D vision only in close distances, whereas dual channel camera provides good stereoptic vision with greater distance from the end of the laparoscope to the surgical field (1, 2).

The perception of the surgical field in 3D mode is finally obtained thanks to the reworking made by the human neurological vision system. This happens because the brain receives two different images. The active systems project the right and the left image alternately on the screen. Thanks to the active shutter glasses (called in this way because they need battery and an infrared sensor to synchronized with the screen), each eye captures the corresponding right or left image (Figure 4) showed on the screen. The opening and the closing of the shutter is so fast that our eyes see the images as a continuous (3). These active systems cause visual sickness due to the conflict of accommodation and discomfort for the heavy glasses. The newer passive systems use passive polarizing glasses, which allow to project on the screen 2 different images simultaneously with different wavelenght (Figure 5). Each eye sees only one image because the different polarization for each lens. Schwab et al published a very significant review in 2017 in which the author concludes that dual channel system provides a greater and more accurate stereopsis (4). Recently a "glass free" 3D-dysplay has been proposed, but this project is in an embryonic phase and it needs to be developed more.

Figure 4: active 3D glasses

Figure 5: passive polarizing glasses

Based on these data, all the companies developed new 3D-laparoscopic technology with dual-channel camera, passive projection video with HD resolution and with 0 or 30 fixed degree laparoscope. Table 1 reports the current situation of the systems available in Europe.

Table 1: companies and type of 3D technology

	Camera Configuration	Video 26 or 32 inches	Glasses	Prize	Notes
Olympus	dual channel	3D HD	passive	120 K	0° or 30° switch 2d/3d
Storz	dual channel	3D HD	passive	60-150 K	0° or 30° switch 2d/3d
Conmed	dual channel	3D HD	passive	80 K	-
Viking	dual/single	3D HD	passive	100 K	0° or 30°
Wolf	dual channel	3D HD	passive	-	25°; big camera head
Aesculap	dual channel	3D HD	passive	-	0° or 30°

1.2.2 Validation in-vitro

The introduction of 3D perception in the laparoscopic systems had the target to empower the two-dimensional laparoscopic surgery, allowing a faster learning curve with shorter operative time and less postoperative serious complications. The results of the studies published at the end of 90's that have examined the potential advantages and disadvantages of the first generation 3-D systems are contradictory. The exercises performed in all the studies were executed in laparoscopic trainer (Fig 6) and consisted in: grasp and move an object, perform a running suture, stitch and tie, tie and remove the needle from the box, etc. Some authors have concluded that three-dimensional imaging significantly improves performance (5, 6, 7), while others claimed that there is no significant difference in task performance between 2-D and 3-D (8, 9). The same differences emerged analyzing surgeons with different grades of experience (novices versus consultants). These results forced all the companies to improve the 3D systems (10).

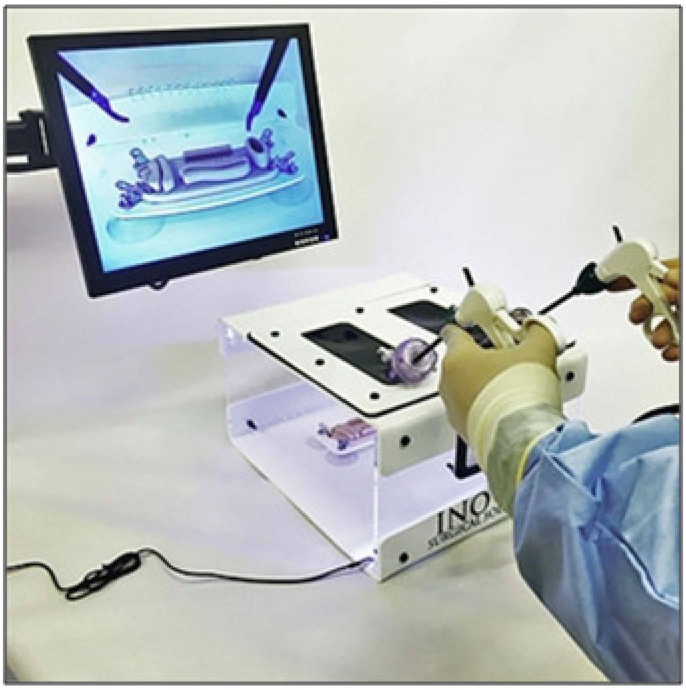


Figure 6: Laparoscopic trainer

In the beginning of 2000', thanks to the development of the 3D vision in the Da Vinci robotic system (11) that showed the superiority of the 3D stereoscopic vision (12, 13) a revival of 3D systems begun. The validation of the second generation 3D technology showed better results. This time the conclusions were different: better results, better vision, shorter exercises, no difference of visual sickness (15, 16, 17).

Analyzing deeply the development of 3D technology, data available in literature are very heterogeneous and hardly comparable mostly because different technology are studied. Comparing the 2D with 3D vision, it has to be consider the technology used, i.e. the camera system and the projection technology. Single and dual channel camera works completely different, as well as active or passive glasses (4). Studies comparing single channel 3D-camera and active glasses 2D laparoscopy reported poor outcomes, visual strain, headaches and nausea with the 3D systems (Table 2). In the 3D robotic vision with fixed-head mounted projection, the stereoptic vision seemed to obtain better performance in the Da Vinci over the 2D mode (Table 3). Finally considering the 3D technology with dual-channel camera and passive polarized glasses, there was a general improvement of 3D over 2D, independently of surgeon's experience (Table 4).

The 3D dual channel with passive projecting vision system and passive polarized glasses seems to allow the best vision with the least visual sickness.

Table 2: Single channel scope versus 2D scope, Schwab et al, Evolution of stereoscopic imaging in surgery and recent advances, World J Gastrointestinal 2017 August16;9(8): 368-377

Reference	3D projection system	Who and what assessed	Objective outcomes	Subjective outcomes
McDougall 1996	Active shuttering screen and glasses	22 urological and gynaecological surgeon, non novice Pig-lab, laparoscopic vessel dissection and securing, suturing and knot tying	Time for completion No significant difference found	3D not felt to enhance image quality or enhance performance, blurred vision and eye fatigue 3D
Dion 1997	Active shuttering screen and glasses	Surgeons and non-surgeons. Lab visual (n 8) and motor skills (n 9)	Time and errors, improvement in both with 3D	Glasses bothersome and dizziness reported
Chan 1997	Active shuttering screen and glasses	32 surgeons, 11 with and 21 without lps experience, 1 lab based skills task	Time for completion in 2D and 3D, no significant difference	50% felt no improved performance although 66% felt depth perception improved, 40% felt reduced image quality and dimmer, 10% reported dizziness and eyestrain
Hanna 1998	Active shuttering screen and glasses	4 surgical SpRs performing 60 lps chole	Time for completion and errors No significant differences	Visual strain, headache and facial discomfort with 3D system
Mueller 1999	Active shuttering screen and glasses	30 subjects (10 with and 20 without lps	Time for attempts, and success/failure of	Reported loss of concentration,

		experience), 4 x lab based skills tasks for all, then experienced did suturing tasks	attempt, no significant difference	headaches and distraction with 3D system
Herron1999	Active shuttering screen and glasses, 3D HMD	50 lps novices, 3 x lab based skills tasks	Time to completion of 3 skills tasks in each visual system (2x repitions), no significant difference	Although 48% preferred 3D A/S screen over all, 7% and 25% respectively reported headaches with 3D screen and 3D HMD, 82% found HMD uncomfortable
Mueller-Richter 2003	Active shuttering screen and polarizing glasses	59 lpsnovices, 3lab based skills tasks	Number of completions in time limit and subjective difficulty, No significant difference	Flickering reported with both 3D systems
Bhayani 2005	HMD	24 surgical residents, minimal lps experience, 1 x lab based skills task	Time for completion in 2D and 3D, significant reduction in time	>50% preferred the 3D system and found task easier in 3D, no subjective assessment on physical symptoms
Patel 2007	HMD	15 novices and 2 experts, 5 x lab based skills tasks	Time and accuracy in 2D and 3D of the novices compared to the experts, significant difference in both for novices only in 3D	NA
Bittner 2008	HMD	2 novices, 2 intermediate and 2 experts, 2x lab based suturing tasks	Time and accuracy in 2D and 3D, no significant difference	83% felt improved depth perception. No reported physical symptoms
Votanopoulos 2008	HMD	36 surgical residents and medical students (11 with and 25 without lps experience), 6x lab based skills tasks	Time and errors in 2D and 3D, significant improvement in time and errors in novice group only	NA
Kong 2009	HMD	21 novices and 6 experienced surgeons, 2x lab based skills tasks	Time and errors in 2D and 3D, significant reduction in errors in 3D novices, no other significant difference noted	Dizziness and eye fatigue in novice with 3D system which improved with time
Mistry 2013	Passive polarising screen and glasses	31 medical students, 4x lab based skills tasks (MISTELS)	Task performance in 2D and 3D as per MISTELS scoring system, no significant difference	No detrimental symptoms with 3D

Table 3: Dual Channel laparoscopes – Robotic fixed screen versus 2D scope, Schwab et al, Evolution of stereoscopic imaging in surgery and recent advances, World J Gastrointestinal 2017 August16;9(8): 368-377

Reference	3D projection system	Who and what assessed	Objective outcomes	Subjective outcomes
Falk 2001	Da Vinci	15 experienced laparoscopic surgeons, 6 lab based skills tasks	Time and errors in 2D and 3D and 2DHD, significant differences in time and errors in 3D	Only 33% felt 3D better view, no detrimental symptoms reported
Munz 2004	Da Vinci	11 experienced laparoscopic surgeons, 4 lab based skills tasks	Errors and performance	NA
Moorthy 2004	Da Vinci	10 surgeons of varying experience, lab based suturing task	Significant difference in both 3D, time and distance travelled of instruments in 2D and 3D	NA
Badani 2005	Da Vinci	7 surgeons, 2 lab based suturing tasks	Significant difference in both 3D	NA
Blavier 2007	Da Vinci	40 medical students, lab based skills task	Errors, performance and learning, significant	No detrimental symptoms reported

			difference in 3D	
Bym 2007	Da Vinci	12 surgeons of varying experience, 4 lab based skills tasks	Time and errors in 2D and 3D, significant difference in 3D	No detrimental symptoms reported
Blavier 2007	Da Vinci	60 medical students, a lab based skills task	Specific performance metric score, significant difference in 3D in all tasks	No detrimental symptoms reported
Fishman 2008	Da Vinci and prototype Ames stereoscopic camera	12 subjects of varying exposure to stereoptic systems	Time for completion while altering binocular disparity of stereoptic camera until 0% (matching 2D vision)	NA
Blavier 2009	Da Vinci	Lab based skills tasks using Da Vinci manipulator, 80 novices and 20 expert lps surgeons, lab based task	Significant difference with 3D from binocular disparity, time for task completion and estimation of time in 2D or 3D not both significant difference in 3D for novices, similar results for experts	NA

Table 4: Dual Channel laparoscopes versus 2D scope, Schwab et al, Evolution of stereoscopic imaging in surgery and recent advances, World J Gastrointestinal 2017 August16;9(8): 368-377

Reference	3D projection system	Who and what assessed	Objective outcomes	Subjective outcomes
Birkett 1994	Active shuttering screen and glasses then polarized glasses vs 2D	10 experienced subjects 2 x lab based skills tasks	Time take for repetitive cycles, no difference in simple task, reduced time in complex task	NA
Peitgen 1996	Active shuttering screen and glasses	60 subjects (20 novices, 20 beginners, 20 advanced surgeons) 2 x lab based skills tasks	Time and accuracy of tasks, both significantly improved in 3D, independent of experience	NA
Wentink 2002	Active shuttering screen and polarized glasses vs TFT display vs projection vs standard (2d)	8 surgeons with lps experience lab based skills task	Time for task completion, 10 repetitions but only 2 surgeons per visual system, no improvement with 3D	Felt image quality poorer with 3D
Jourdan 2004	Active shuttering screen and glasses	8 experienced lps surgeons, 5 x lab based skills tasks	Time and errors, 10 repetitions each, in each visual system, significant improvement in both in 3D	NA
Feng 2004	Active shuttering screen and glasses then polarized glasses (SD vs 2D vs 2D HD)	27 subjects (16 novices, 11 with different lps experience) lab based skills task	Time and economy of movement, time significantly improved over both 2D systems in 3D, economy of movement improved in 3D vs HD, not SD 2D	Felt improved depth perception in 3D
Hubber 2003	Prototype passive polarising screen and glasses	16 medical students, lab based skills tasks	Time and performance (ICSAD), improvements in 3D significant over 2D	NA
Honeck 2012	Passive polarizing screen and glasses	10 novices and 10 experienced lps surgeons, 5x lab based skills tasks	Time and errors (1 repetition, in only 1 of the visual systems) no significant improvement in time, reduction in errors significant in both groups in 3D	No impairment felt in subjective feedback when using the 3D system
Smith 2012	Passive polarizing screen and glasses	20 novices, 4 x lab based skills tasks	Time and errors (10 repetitions of each task in each visual condition) significant improvement in time and errors in 3D	NA

1.2.3 Validation in vivo

The analysis of the "3D-system validation" in the clinical setting is difficult because the lack of experience reported in literature.

Few surveys have compared 2D versus 3D laparoscopic cholecystectomy (lap-chole) showing shorter execution time using the 3D mode mostly in novices surgeons (18, 19). A Cochrane review published in 2011 concluded that there is no evidence of the 3D lap-chole superiority over the standard 2D. It has to underline that this Cochrane analyzed only 60 patients with high risk of bias without reporting type of camera system used by the investigators (20). A more recent review published in August 2017 (21) analyzed five randomized controlled studies concluding that 3D lap-chole is shorter with better vision than the 2D. Few are also the experiences in laparoscopic surgery for gastro-intestinal disease. These experiences reported shorter operative time and a good depth perception performing right hemicolectomy, gastrectomy and esophagectomy (22, 23). Poor results are available in gynecology and bariatric surgery as well (24).

In conclusions the stereoptic vision offered by the new generation 3D-camera systems offer a good vision with poor visual sickness in case of dual-channel HD camera, passive projecting video and passive polarized glasses. The clinical validation of this innovation is based on still poor clinical experiences.

Chapter 2

Visual Load

2.1 Objective Tests

The interest over the brain modifications during the use of 3D screen started since the introduction of the first 3D movie (Avatar 2009).

Exist many reports (25) of visual discomfort watching 3D videos feeling headaches, nausea, dizziness and some viewers reported also the incapacity to view in 3D continuously. It is not clear if the use of the virtual stereoscopic vision causes temporary or persistent modification in the eyes or in the central neurological vision system. The uncomfortable vision of the single-channel camera felt by surgeons performing the first laparoscopic skills, added to the visual sickness felt by people wearing the 3D active shuttering glasses in the cinemas, suggested that some modifications could occur during the 3D vision.

The causes of the visual discomfort are to be find in technological and neurophysiological field. One of the main theory, proposed to explain the discomfort in the 3D viewing, lies in the principles of 3D technology.

Considering how the images are projecting on the screen there are two categories of 3D screen: video projecting simultaneously two images and video projecting the two images alternatively. The first group needs passive polarized glasses, the second group needs active shuttering glasses. Considering that the time to transfer the image from the retina to the visual cortex through the visual nerve is around 100 msec (t_0) (26) and the active shuttering glasses open and close shutter every 240 times per second, exists a slight deviation of the decoding mechanism in the occipital cortex (t_0+t_1) for the 3D vision. At this process, it has to be added the physiological presence of eye blinks. We usually blink eyes around 10 times per minute (27). If the eye blink corresponds with the viewing of the second image there is a break in the 3D viewing and users may see in 3D for a while and then in 2D (Figure 7). This continuous breaking mechanism can be at the base of the visual sickness felt by people watching in 3D.

Image 1	Image 2	Image 2	Image 2	Image 1 …	Image 2	Image 1	Image 2
Left eye	Right eye	Eye blink			Left eye	Right eye	Left eye
4 ms	4 ms	100 ms			4 ms	4 ms	4 ms
Normal 3D viewing		Eyes Closed			View in 2D	View in 2D	View in 3D

Figure 7: possible scenario how 3D visualization is influenced by using active shuttering glasses (Malik et al, BioMedical Engineering Online 2015: 14-21)

Different methods have been used to evaluate the modifications happening during the 3D vision: heart rate (HR), electromyography (EMG) and electroencephalogram (EEG) are the most used objective methods, while skin temperature and galvanic skin response are less investigated.

The HR is a very simple, direct and cheap data available during the 3D vision. It reflect the autonomic neurological system work (28) As happened before, results are unfortunately contradictory. Few studies show a significant increase HR and an increase Very Low Frequency/High Frequency ratio (VLF/HF) in 3D vision (a measure of autonomic balance), compared to those in the 2D-group, indicating that autonomic balance is not stable in the 3D-group (29). Others surveys on the contrary report a lower HR and VLF watching 3D movies (25). Regardless the different results, these experiments show how the 3D vision determines alteration in human para-sympapehetic neurological system.

Using the EEG waves to study the 3D vision is more complex. Neurologist report how the frontal and the central motor regions are related to motor planning, parietal lobe is related to calculations, reasoning and execution, finally the parietal lobe is involved in hearing and emotional process (30, 31).

Comparing the EEG waves during 2D and 3D (active and passive glasses) vision, the following are the results:

- 2 mode versus 3 mode with active shuttering glasses: all EEG bands appear higher in the 2D vision in all lobes;
- 2 mode versus 3 mode with passive polarized glasses: higher activation in 2D mode for delta, beta and gamma waves, higher activation for theta and alpha in 3 mode
- 3 mode with active glasses versus 3 mode with passive glasses: greater power of all waves in all lobes for 3D with passive polarized glasses.

Considering these results, the brain seems to be more involved with global processing during the 3D vision with passive polarized glasses as compared with active shuttering glasses. It is more difficult to find differences between 2D mode and 3D passive mode, even if in the former seems to be present a more global brain data processing. Working memory and attention is increased in 3D viewing probably because the processing of more data.

In laparoscopic surgery the absence of stereoscopic vision and ergonomic instruments cause muscular fatigue, mostly in long operations where the surgeons experience and ability are necessary to solve these aspects (32, 33, 34). The introduction of the three-dimensional view has been proposed as the possible solution of the muscular stress. In this light, few surveys have investigated the EMG of muscles of the upper right and left arm involved in the surgical movements (35). These preliminary studies, performed on expert and young surgeons during short exercises in laparoscopic trainer, show a tendency to have lower muscle contraction in the right arm and higher muscle contraction in left arm. Probably the stereopsis leads to reach a more ergonomic position and lower the muscular fatigue (Figure 8).

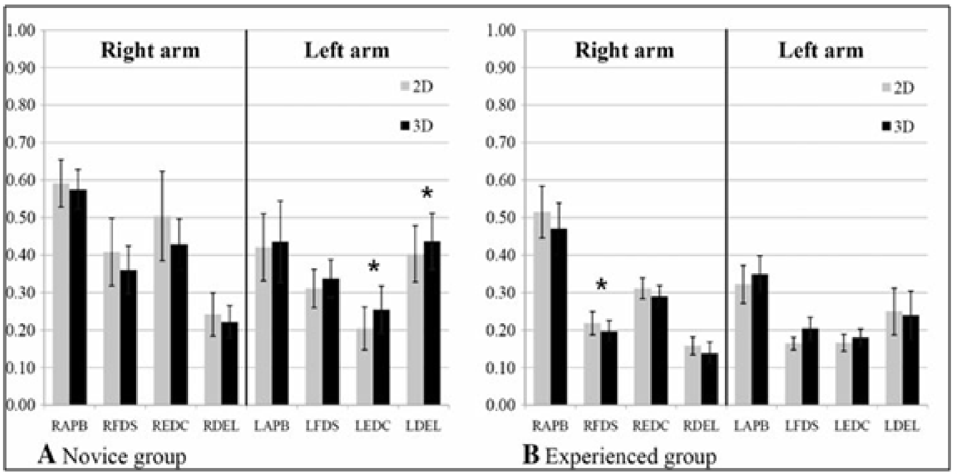


Figure 8: EMG muscles activity in upper arms during surgical movements

2.2 Subjective Tests

The 3D-minimally invasive surgery has to demonstrate to improve the normal clinical work-flow. Fatigue, mental and visual work load are associated with long and complex tasks. If these values determine higher rate of errors, the 3D technology has no validation. The presence and type of subjective mental and visual work load using 3D vision has not been studied deeply. In chapter 2.1 it has been reported the objective tests used to show the alteration in human muscles and neurological system. The National Aeronautics and Space Administration-Task Load Index (NASA-TLX) and the Simulator Sickness Questionnaire (SSQ) are two tests able to investigate the subjective mental and visual effort felt by people during the tasks performance.

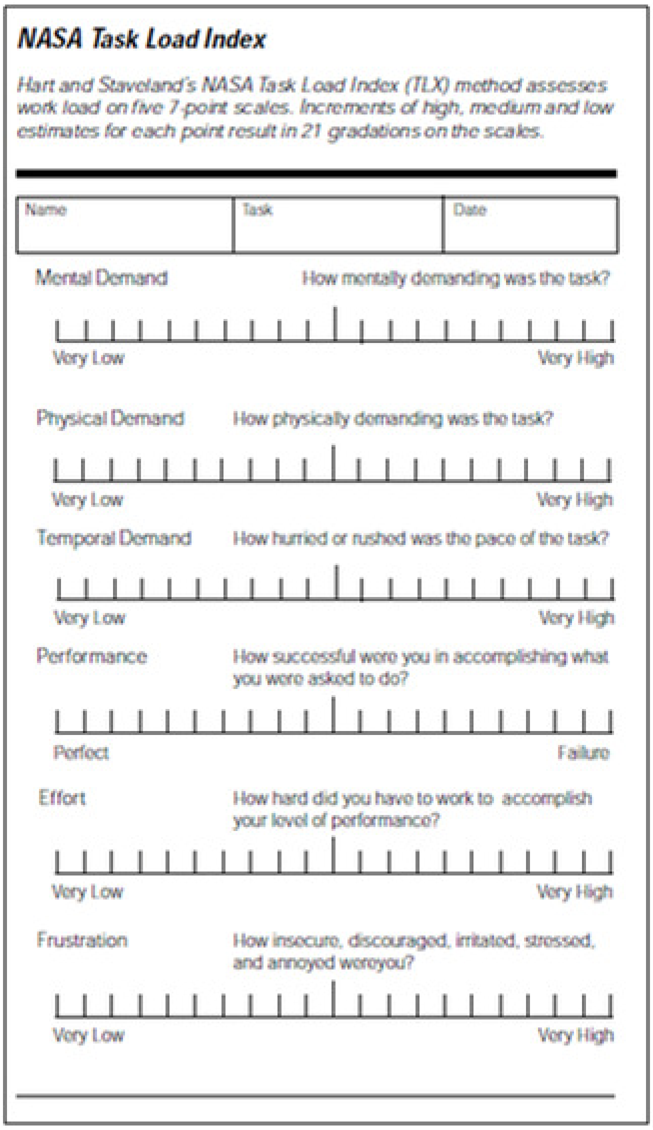
2.2.1 The National Aeronautics and Space Administration task load index test

The NASA-TLX is a subjective and multidimensional tool used to measure the perceived workload during a task or an exercise in order to estimate various aspects of the performance. It was developed in 1980 at the NASA Ames Research Center's Sandra Hart, with the aim to create a subjective tool able to measure subjective workload in different fields (36). Originally present as a paper form, today is available on line through an app (https://humansystems.arc.nasa.gov/groups/TLX/). It has cited and used in hundreds of surveys and in different domains like aviation, social domain and healthcare systems (37).

The NASA TLX divides the total workload into six subscales:

- Mental Demand
- Physical Demand
- Temporal Demand
- Performance
- Effort
- Frustration

The form offers for each subscale a description that the subject should read before filling in the scale (Fig 9). The second part of the form requires that the subject chooses which subscale is more important for him/her to determine the workload. Many researchers have not used this second part, not reducing the test validity (Raw NASA TLX) (36).


NASA Task Load Index

Hart and Staveland's NASA Task Load Index (TLX) method assesses work load on five 7-point scales. Increments of high, medium and low estimates for each point result in 21 gradations on the scales.

Name	Task	Date

Mental Demand — How mentally demanding was the task?

Very Low — Very High

Physical Demand — How physically demanding was the task?

Very Low — Very High

Temporal Demand — How hurried or rushed was the pace of the task?

Very Low — Very High

Performance — How successful were you in accomplishing what you were asked to do?

Perfect — Failure

Effort — How hard did you have to work to accomplish your level of performance?

Very Low — Very High

Frustration — How insecure, discouraged, irritated, stressed, and annoyed wereyou?

Very Low — Very High

Figure 9: the NASA TLX rating scale

The NASA TLX has been used in few clinical setting comparing 3D and 2D laparoscopic operations like appendectomy or cholecystectomy. These preliminary results show increased personal felt of safety and efficiency using 3D imaging, not correlating the NASA score with clinical outcomes (38, 39). Other experiences rate the visual work load with the NASA TLX in preclinical settings (laparoscopic trainer) reporting that 3D laparoscopy can facilitate the learning curve for young surgeons (40).

2.2.2 The Simulator Sickness Questionnaire test

The SSQ is a questionnaire born to score the sickness felt by aviators during long time exercises in flight simulator. During the simulations, the aviators perceive discrepancies between the movements of the simulator and that experienced on the screen. These result in nausea, headache, fatigue and many more symptoms. Interestingly in 1989 the United States Army Aeromedical Research Laboratory reported that the greater is the experience of the pilot and the longer are the interval between the simulations, the greater is the sickness felt (41).

The SSQ is a well known and standardized tool able to rate the simulator sickness (42, 43). The SSQ is a self-report symptom checklist. It includes sixteen symptoms that are associated with simulator sickness. Participants indicate the level of severity of the sixteen symptoms (Fig 10) that they have experienced. For each symptom there are four levels of severity (none, slight, moderate, severe).

The SSQ can be divided in three subscales:

- Nausea: salivation, sweating, nausea, stomach awareness, burping
- Oculomotor subscale: fatigue, headache, eyestrain, difficulty focusing
- Disorientation subscale: vertigo, dizzy (eyes open), dizzy (eyes closed), and blurred vision

The SSQ has been largely used in military aeronautics researches (43), but only few are the experiences that assess the validity of the SSQ test grading the sickness in 3D vision compared with the 2D (44, 45). These preliminary studies conclude that seeing 3D screen or operating in wrong position (not perpendicular) induce visual discomfort.

No______________ Date____________________

SIMULATOR SICKNESS QUESTIONNAIRE

Kennedy, Lane, Berbaum, & Lilienthal (1993)***

Instructions : Circle how much each symptom below is affecting you right now.

1. General discomfort	None	Slight	Moderate	Severe
2. Fatigue	None	Slight	Moderate	Severe
3. Headache	None	Slight	Moderate	Severe
4. Eye strain	None	Slight	Moderate	Severe
5. Difficulty focusing	None	Slight	Moderate	Severe
6. Salivation increasing	None	Slight	Moderate	Severe
7. Sweating	None	Slight	Moderate	Severe
8. Nausea	None	Slight	Moderate	Severe
9. Difficulty concentrating	None	Slight	Moderate	Severe
10. « Fullness of the Head »	None	Slight	Moderate	Severe
11. Blurred vision	None	Slight	Moderate	Severe
12. Dizziness with eyes open	None	Slight	Moderate	Severe
13. Dizziness with eyes closed	None	Slight	Moderate	Severe
14. *Vertigo	None	Slight	Moderate	Severe
15. **Stomach awareness	None	Slight	Moderate	Severe
16. Burping	None	Slight	Moderate	Severe

* Vertigo is experienced as loss of orientation with respect to vertical upright.

** Stomach awareness is usually used to indicate a feeling of discomfort which is just short of nausea.

Last version : March 2013

***Original version : Kennedy, R.S., Lane, N.E., Berbaum, K.S., & Lilienthal, M.G. (1993). Simulator Sickness Questionnaire: An enhanced method for quantifying simulator sickness. *International Journal of Aviation Psychology*, 3(3), 203-220.

Figure 10: the SSQ and the 16 symptoms

Chapter 3

Aims of the Study

3.1 Endpoints: study 1 and study 2

The aim of this Ph D research is to evaluate the application of the three dimensional technology in minimally-invasive surgery through a in-vivo prospective observational clinical trial, in order to validate this new methodic as a safe and feasible technique (study 1) and to study the visual work-load of surgeons operating with 3D screens and glasses in comparison with standard 2D-full HD screens (study 2).

The main endpoints were:

1. Study 1: to compare the surgical outcomes of patients underwent colorectal resection with 3D versus 2D laparoscopy;
2. Study 2: to measure and compare the visual work load during 3D versus 2D operations, scoring these data with the NASA task load index and the Simulator Sickness Questionnaire.

Chapter 4

Patients, Materials and Methods

4.1 Study overview

All procedures and data collections took place between January 2015 to September 2017 at the General and Mininvasive Surgery Department, Pederzoli Hospital, Peschiera del Garda, Italy. The study was designed to compare the effectiveness of 3D-MS performing long time operations compared to standard 2D-HD laparoscopic procedures.

It was a single-center prospective observational clinical trial, divided in two sub-study with a single patients-population.

For each study, there was a primary endpoint:

- Primary endpoint for Study 1: incidence of Clavien grade 3, 4 and 5 post-surgical complications in patients undergone 3D colorectal resection
- Primary endpoint for Study 2: to grade the visual work load of surgeons operating with 3D screens and glasses.

Secondary endpoints:

- Surgical times
- Incidence of significant (> 250 ml) intra-operative blood loss
- Incidence rate of conversion laparoscopy-laparotomy
- Postoperative length of stay
- Visual sickness causing conversion 3D-2D: NASA TLX and SSQ

Data have been collected before, during and at the end of surgery; and 30 days after surgery.

Surgical equipment

Video system

The Karl-Storz TIPCAM 1 SPIES 3D (CE approved) system has been used for the entire research.

The camera system is based on a dual channel technology with two distal chip on the tip of the scope. The maximum resolution is 1920 x 1080 pixel. The TIPCAM is a fixed camera system disposable in 0 or 30 degrees.

The 3D video is a 32 inches monitor with 16:9 imaging and maximum resolution 1920 x 1080 pixel. Passive polarized glasses are necessary for the 3D vision.

Stapler

In all 313 laparoscopic operation, the first surgeons used the Echelon Flex Powered Endopath Stapler (http://www.ethicon.com/healthcare-professionals/products/staplers/endocutters/powered-echelon-flex) with a stapler line length of 60 or 45 mm. A blue reload was used in case of ileo-colic anastomosis. A green reload was used in case of colo-colic anastomosis or in case of left colon, sigma and the rectum resection. This type of stapler is able to articulate and to rotate its tip, reducing the tissue trauma. Each reload has 3 line of staplers at both side of the knife.

Intra-abdominal Anastomosis

In case of intra-abdominal anastomosis, the *Filblocc* (CE approved) suture was used. It is a new generation suture with a self-locking system with a final lock clip. It is a synthetic monofilament absorbable made by polydioxanone. In each case a 3-0, 15 cm length Fillblocc was used. The suture strength is 70% in 28 days, 55% in 42 days, with a complete absorption within 180-210 days.

4.2 Study population

Partecipants include patients aged eighteen years old and above, eligible for colorectal resections for neoplastic or inflammatory diseases. Patients scheduled for an elective laparoscopic colorectal resection were recruited at the outpatient clinic (n = 313 total).

- Inclusion Criteria
    1. Patients of both gender
    2. 18 years old and above
    3. Spoken and written command in italian
    4. Ability to understand and follow the study procedures and sign the informed consent
- Exclusion Criteria
    1. Patients younger than 18 years
    2. Emergency operations
    3. Pregnant women

Four experienced surgeons in colorectal and laparoscopic surgery participate in the study. Each surgeon follows the standard laparoscopic surgical rules performing the different type of colorectal resection, regardless the study subgroup.

Study 1: Eligible patient is identified and verified during the first evaluation at outpatients clinic. The surgeon determines indications and date of surgery and if the patients agrees, the surgeon introduces the study in detail. The patient signed the consent form for the operation, study enrollment and anesthesia during a preoperative establishment, that takes place one week before the surgery date. Data are collected at the preoparative clinic, during surgery, during the hospitalizations and at the short term follow-up (30^{th} days).

Two group of patients are compared:

- Group 1 - Control Group: patients undergone colorectal resections with 2D laparoscopic technique;
- Group 2 - Experimental Group: patients undergone colorectal resections with 3D laparoscopic technique.

Study 2: at the end of each procedure (2D and 3D) the first surgeon has to fill in the two different subjective questionnaire to grade the visual sickness felt during the operation (NASA TLX and SSQ). The paper and pencil form is administrated immediately at the end of the operation.

Surgical Technique

All colorectal resections are performed according the usual laparoscopic technique and protocol. Eight types of procedures are performed in the study population:

- Right hemicolectomy
- Transverse resection
- Left colic flexure
- Left hemicolectomy
- Sigmoidectomy
- Anterior low rectal resection
- Total colectomy
- Miles operation

In case of rectal, sigmoid and left colon resections, the anastomosis is performed according the Knight-Griffen technique (end to end, stapled) (Fig. 11). A defunctioning stoma is performed according to the intraoperative data (level of transaction, thickness of colonic wall). Side to side anastomosis is performed with a stapler (Fig. 12) and with a double layer autofixed enterotomy closure, in case of ileo-cecal resection, right hemicolectomy, transverse resection and left colonic flexure resection.

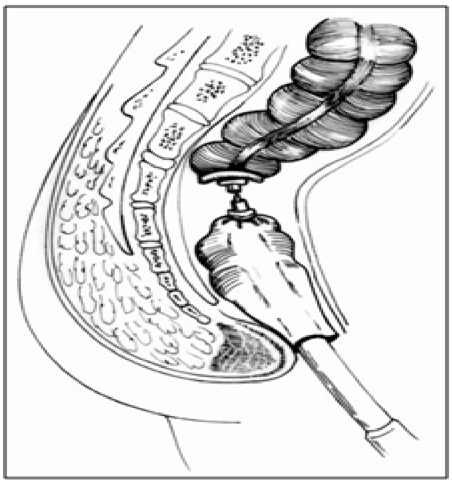


Figure 11: The Knight-Griffen end to end anastomosis

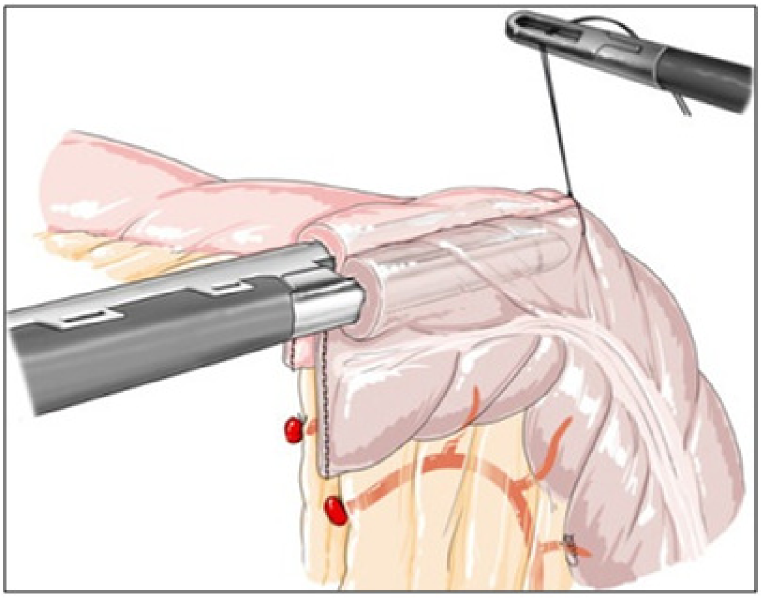


Figure 12: Laparoscopic side to side anastomosis

Post-operative Care

Postoperative care follows a institutional protocol that can include the ERAS guidelines (46, 47). There are no differences between the two study groups. All patients are review in outpatients clinic at 10th postoperative day (POD), if discharged, and at the 30th POD.

Statistical Analysis

Discrete variables were described as medians with interquartile range (IQR) and categorical variables were described as totals and frequencies. Univariable comparisons were assessed using the chi-squared test or fisher's exact test as appropriate. All analyses were carried out with STATA version 13.0 (StataCorp, College Station, TX), and a P-value of < 0.05 (two-tailed) was considered statistically significant.

Chapter 5

Results

From January 2015 to September 2017, 313 patients were enrolled in the study: 82 in the 2D group, 231 in the 3D group. Right hemicolectomy (RH) was the most frequent procedure performed (n 104, 33.23%), followed by rectal low anterior resection (LAR) (n 67, 21,4%) and sigmoidectomy (SG) (n 57, 18.21 %) (Table 5). Challenging procedures like LAR, Miles and total colectomy (TC) were more frequent in the 3D group than the 2D group.

Table 5: Type of colorectal laparoscopic resection

	Total (n=313)	**2D (n=82)**	**3D (n=231)**
Right Hemicolectomy	104 (33.23)	29 (27.88)	75 (72.12)
Left Hemicolectomy	31 (9.90)	5 (16.13)	26 (83.87)
Splenic flexure resection	7 (2.24)	3 (42.86)	4 (57.14)
Transverse colon resection	26 (8.31)	10 (38.46)	16 (61.54)
Sigmoidectomy	57 (18.21)	18 (31.58)	39 (68.42)
Total colectomy	12 (3.83)	2 (16.67)	10 (83.33)
Low Anterior Rectal resection	67 (21.41)	13 (19.40)	54 (80.60)
Miles resection	6 (1.92)	1 (16.67)	5 (83.33)
Others	3 (0.95)	1 (33.33)	2 (66.67)

5.1 Study 1: 3D versus 2D colo-rectal resections

Preoperative Data: Table 6 reports the demographics data. Age, sex, ASA score were comparable between the two groups. Colorectal cancer was the main indication for surgery (n 235, 75.1%), followed by colonic diverticulosis, benign polyposis and inflammatory bowel diseases (IBD), respectively 43 (13.8 %), 25 (7.9 %) and 10 (3.2 %).

Intraoperative Data: Over 313 laparoscopic procedures, only 1 case, belonging to the 3D group, was converted in laparotomy because of fibrosis due to neo-adjuvant radiotherapy for T4 rectal cancer. The median operative time showed no statistically significant difference between the 3D and 2D groups (p 0.611). Less drains were positioned at the end of the 3D operations comparing with 2D procedures (p 0.013). The stapled anastomosis was the most frequent performed over other techniques. The other intra-operative findings showed no significant difference between the two study groups (Table 6).

Table 6: Clinical and operative characteristics of patients undergoing colorectal resections

	Total (n=313)	**2D (n=82, 26.2%)**	**3D(n=231, 73.8%)**	**P value**
Age (IQR)	68.5 (58-82)	71 (60-79)	71 (60-79)	
Sex (%)				
M	181 M (57.83)	44 (56.66)	137 (59.31)	0.374
F	132 F (42.17)	38 (46.34)	94 (40.69)	
ASA				
1-2	230 (73.72)	64 (78.05)	166 (72.17)	0.299
3-4	82 (26.28)	18 (21.95)	64 (27.83)	
Operative time (median, IQR) min	160 (125-190)	150 (120-180)	160 (130-190)	0.611
Drain				
Y	284 (90.73)	80 (97.56)	204 (88.31)	**0.013**
N	29 (9.27)	2 (2.44)	27 (11.69)	
Blood loss >250ml				
Y	2(0.64)	1 (1.22)	1 (0.43)	0.442
N	311 (99.36)	81 (98.78)	230 (99.57)	
Anastomosis				
Stapled	299 (95.53)	73 (24.41)	226 (75.59)	**0.001**
Others	14 (4.47)	9 (64.29)	5 (35.71)	

Postoperative Data: postoperative morbidity was 23.96 % of which 8.94 % were classified as 3 – 4 – 5 Clavien grade (48). Only one case of post operative death (POM), belonging to 3D group, occurred within the first 30 postoperative days. The median hospitalization and the reoperation rate showed no difference between the two groups (Tab 7).

Table 7: Postoperative data

	Total (n=313)	**2D (n=82, 26.2%)**	**3D(n=231, 73.8%)**	**P value**
Postoperative complication				
Y	75 (23.96)	23 (28.05)	52 (22.51)	0.313
N	238 (76.04)	59 (71.95)	179 (77.49)	
Severe postoperative complication				
Clavien 1 – 2	47 (62.66)	16 (69.56)	31 (59.61)	0.271
Clavien 3 – 4 - 5	28 (37.33)	7 (30.43)	21 (40.38)	
30^ POD mortality				
Y	1(0.32)	0 (0.00)	1 (0.43)	0.551
N	312 (99.68)	82 (100.00)	230 (99.57)	
Reoperation				
Y	30 (9.58)	6 (7.32)	24 (10.39)	0.417
N	283 (90.42)	76 (92.68)	207 (89.61)	
Hospitalization (median, IQR) days	8.5 (6-9)	8.4 (6-10)	8.6 (6-9)	0.843

A second statistical analysis was performed dividing the procedures in two sub-groups according to the colonic anatomy and type of anastomosis:

- Lower group: LAR, SG, left colon resections, TC and others operations;
- Upper group: RH, transverse colon and splenic flexure procedures.

Lower Group

Table 8 reports the intra-operative and post-operative data of the Lower Group. The median operative time showed no statistically significant difference between the 3D and 2D operations. There were no differences in terms of postoperative complications, POM and hospitalization.

Tab 8: intra and post-operative data of the Lower group

	2D (n=34, 23.94%)	**3D (n=108, 76.06%)**	**P value**
Age (IQR)	70 (58-83)	68 (52.5-76)	
Sex (%)			
M	16 (47.06)	68 (62.96)	
F	18 (52.94)	40 (37.04)	
ASA			
1-2	27 (79.41)	84 (77.78)	
3-4	7 (20.59)	24 (22.22)	
Operative time (median, IQR) min	170 (120-180)	180 (140-230)	0.619
Drain			
Y	33 (97.06)	103 (95.37)	0.670
N	1 (2.94)	5 (4.63)	
Blood loss >250ml			
Y	1 (2.94)	1 (0.93)	0.384
N	33 (97.06)	107 (99.07)	
Postoperative complication			
Y	10 (29.41)	22 (20.37)	0.271
N	24 (70.59)	86 (79.63)	
Severe postoperative complication			
Clavien 1 – 2	7 (70.00)	9 (40.91)	0.150
Clavien 3 – 4	3 (30.00)	13 (59.09)	
30^ POD mortality			
Y	-	-	-
N			
Reoperation			
Y	3 (8.82)	14 (12.96)	0.517
N	31 (91.18)	94 (87.04)	
Hospitalization (median, IQR) days	7.5 (6-10)	7 (6-9)	0.583

Upper Group

Table 9 reports the intra-operative and post-operative data of the Upper Group. The intra-abdominal anastomosis was performed more frequently in the 3D group than the 2D group (p 0.001) and less drains were positioned in the 3D upper group then the 2D (0.006). This might suggest a more safeness felt by surgeons during the operations with the 3D technology. No others differences were found.

Table 9: intra and post-operative data of the Upper group

	2D (n=48, 28.07%)	3D (n=123, 71.93%)	P value
Age (IQR)	68.5 (59-81.5)	76 (66-80)	
Sex (%)			
M	28 (58.33)	69 (56.10)	
F	20 (41.67)	54 (43.90)	
ASA			
1-2	37 (77.08)	82 (66.67)	
3-4	11 (22.92)	41 (33.33)	
Operative time (median, IQR) min	150 (120-180)	150 (120-180)	0.868
Drain			
Y	47 (97.95)	101 (82.11)	**0.006**
N	1 (2.08)	22 (17.89)	
Blood loss >250ml			
Y	0	0	-
N	48 (100)	123 (100)	
Anastomosis			
Stapled	39 (81.25)	118 (95.93)	**0.002**
Others	9 (18.75)	5 (4.07)	
Postoperative complication			
Y	13 (27.08)	30 (24.39)	0.715
N	35 (72.92)	93 (75.61)	
Severe postoperative complication			
Clavien 1 – 2	9 (69.23)	22 (73.33)	0.770
Clavien 3 – 4	4 (30.77)	8 (26.66)	
30^ POD mortality			
Y	48 (100)	122 (99.19)	
N	0	1 (0.81)	
Reoperation			
Y	3 (6.25)	10 (8.13)	0.677
N	45 (93.75)	113 (91.87)	
Hospitalization (median, IQR) days	8.6 (6-10)	8.4 (6-9)	0.84

5.2 Study 2: visual work load

During the same period of study 1, the four surgeons performing the 313 operations with 3D or 2D technology, have scored the visual work load. Two different subjective questionnaire were used: the NASA TLX and the SSQ. All the form were filled in at the end of each operations.

NASA TLX results

The NASA TLX questionnaire was filled in at the end of each operations. Four experienced surgeons with equal experience in colo-rectal and laparoscopic surgery performed all the procedures. The statistical analysis done over all 313 cases divided in 2D and 3D did not reveled significant difference of the visual work scored by the NASA TLX (Tab 10).

Even when considering the 2 sub-group of Lower and Upper operations, it did not emerge a difference of the visual work load between the procedure done in 3D versus 2D (Tab 11, 12). The four surgeons did not report a significant higher visual work load operating with 3D technology.

Table 10: NASA TLX questionnaire results

	Total (n=313)	2D(n=82)	3D (n=231)	P value
Mental Demand (IQR)	8.1 (5-12)	7.6 (5-10)	8.3 (5-12)	0.520
Physical demand (IQR)	6.02 (2-8)	5.33 (3-7)	6.27 (2-10)	0.126
Temporal demand (IQR)	1.8 (0-2)	1.57 (0-2)	1.9 (0-3)	0.384
Performance (IQR)	2.19 (1-2)	2.07 (2-2)	2.24 (1-2)	0.89
Effort (IQR)	6.04 (2-8)	5.74 (2-7)	6.15 (2-9)	0.524
Frustration (IQR)	1.94 (1-2)	1.82 (1-2)	1.98 (1-2)	0.456

Table 11: NASA TLX questionnaire results, Lower group

	2D (n=34)	3D (n=108)	P value
Mental Demand (IQR)	7.8 (5-10)	8.5 (5-12)	0.409
Physical demand (IQR)	5.5 (3-7)	6.3 (2-9.5)	0.337
Temporal demand (IQR)	1.5 (0-2)	2.3 (0-4)	0.203
Performance (IQR)	2.1 (2-2)	2.3 (1-3)	0.457
Effort (IQR)	5.5 (3-7)	6.2 (3-9.5)	0.438
Frustration (IQR)	1.8 (1-2)	2.04 (1-2)	0.366

Table 12: NASA TLX questionnaire results, Upper group

	2D (n=48)	3D (n=123)	P value
Mental Demand (IQR)	7.5 (5-10)	8.07 (4-12)	0.599
Physical demand (IQR)	5.2 (2-6.5)	6.2 (2-10)	0.247
Temporal demand (IQR)	1.6 (0-1.5)	1.57 (0-2)	0.927
Performance (IQR)	2.02 (1-2)	2.01 (1-2)	0.690
Effort (IQR)	5.9 (2-7)	6.08 (2-9)	0.837
Frustration (IQR)	1.85 (1-2)	1.93 (1-2)	0.798

SSQ Questionnaire results

The SSQ is a well known and standardized tool able to rate the simulator sickness. Participants indicate the level of severity of the sixteen symptoms (Fig 10) that they have experienced. For each symptoms there are four levels of severity (none, slight, moderate, severe) divided in 3 subscales: nausea, oculomotor symptoms and disorientation.

Data emerging from the SSQ questionnaire reveled no case of moderate or severe symptoms in both groups. Considering the three subscales, only from the oculomotor subscale emerged numerous data useful for the statistical analysis. For these reasons, Authors decided to consider the SSQ data as dichotomic variables (yes - no).

Table 13 reports the SSQ data divided in 3D and 2D group. Fatigue, difficult focusing and difficult concentration were symptoms more present in the 3D group operations (Tab 13). The analysis regarding the lower and upper subgroups reported no difference between the 3D and 2D procedures(Tab 14, 15) except the difficult concentration, that was more present in the 3D-lower group than the 2D. In both analysis it emerged that the "general discomfort" was a symptom more present during the 2D procedures.

Table 13: SSQ questionnaire results

	Total (n=313)	2D (n=82)	3D (n=231)	P value
General Discomfort				
Y	8(2.53)	6 (7.32)	2 (0.87)	**0.001**
N	305(97.44)	76 (92.68)	229 (99.13)	
Fatigue				
Y	24 (7.67)	2 (2.44)	22 (9.52)	**0.038**
N	289 (92.33)	80 (97.56)	209 (90.48)	
Headache				
Y	12 (3.85)	1 (1.22)	11 (4.76)	0.15
N	301 (96.15)	81 (98.78)	220 (95.24)	
Eyes strain				
Y	8 (2.56)	2 (2.44)	6 (2.6)	0.993
N	305 (97.44)	80 (97.56)	225 (97.4)	
Difficulty focusing				
Y	12 (3.83)	0 (0.00)	12 (5.19)	**0.035**
N	301 (96.17)	82 (100.00)	219 (94.81)	
Salivation				
Y	0	-	-	-
N	313 (100)			
Sweating				
Y	0	-	-	-
N	313 (100)			
Nausea				
Y	0	-	-	-
N	313 (100)			
Difficulty concentration				
Y	10 (3.21)	1 (1.22)	9 (3.91)	**0.035**
N	303 (96.79)	81 (98.78)	222 (96.09)	
Fullness of Head				
Y	12 (3.85)	3 (3.66)	9 (3.91)	0.918
N	301 (96.15)	79 (96.34)	222 (96.09)	
Blurred vision				
Y	3 (0.96)	2 (2.44)	1 (0.43)	0.110
N	310 (99.04)	80 (97.56)	230 (99.57)	
Dizziness open				
Y	0	-	-	-
N	313 (100)			
Dizziness close				
Y	0	-	-	-
N	313 (100)			
Vertigo				
Y	0	-	-	-
N	313 (100)			
Stomach awareness				
Y	0	-	-	-
N	313 (100)			
Burping				
Y	0	-	-	-
N	313 (100)			

Table 14: SSQ questionnaire results, Lower group

	2D (n=34)	**3D (n=108)**	**P value**
General Discomfort			
Y	4 (11.76)	2 (1.85)	**0.012**
N	30 (88.24)	106 (98.15)	
Fatigue			
Y	1 (2.94)	13 (12.04)	0.121
N	33 (97.06)	95 (87.96)	
Headache			
Y	0 (0)	5 (4.67)	0.199
N	34 (100)	103 (95.33)	
Eyes strain			
Y	-	-	-
N			
Difficulty focusing			
Y	-	-	-
N			
Salivation			
Y	-	-	-
N			
Sweating			
Y	-	-	-
N			
Nausea			
Y	-	-	-
N			
Difficulty concentration	-		
Y	0 (0)	4 (2.80)	**0.324**
N	34 (100)	104 (97.20)	
Fullness of Head			
Y	1 (2.94)	4 (2.80)	0.966
N	33 (97.06)	104 (97.20)	
Blurred vision			
Y	-	-	-
N			
Dizziness open			
Y	-	-	-
N			
Dizziness close			
Y	-	-	-
N			
Vertigo			
Y	-	-	-
N			
Stomach awareness			
Y	-	-	-
N			
Burping			
Y	-	-	-
N			

Table 15: SSQ questionnaire results, Upper group

	2D (n=48)	3D (n=123)	P value
General Discomfort			
Y	2 (4.17)	0	**0.023**
N	46 (95.83)	123 (100)	
Fatigue			
Y	1 (2.08)	9 (7.32)	0.190
N	47 (97.92)	114 (92.68)	
Headache			
Y	1 (2.08)	6 (4.88)	0.407
N	47 (97.92)	117 (95.12)	
Eyes strain			
Y	-	-	-
N			
Difficulty focusing			
Y	-	-	-
N			
Salivation			
Y	-	-	-
N			
Sweating			
Y	-	-	-
N			
Nausea			
Y	-	-	-
N			
Difficulty concentration			
Y	1 (2.08)	6 (4.88)	0.407
N	47 (97.92)	117 (95.12)	
Fullness of Head			
Y	2 (4.17)	6 (4.88)	0.822
N	46 (95.83)	117 (95.12)	
Blurred vision			
Y	-	-	-
N			
Dizziness open			
Y	-	-	-
N			
Dizziness close			
Y	-	-	-
N			
Vertigo			
Y	-	-	-
N			
Stomach awareness			
Y	-	-	-
N			
Burping			
Y	-	-	-
N			

Chapter 6

Discussion

Three dimensional minimally-invasive surgery (3D-MS) added the depth perception at the standard laparoscopy. It has been introduced in the medical field during the 90’ with great expectations because it eliminates one of main problem of the 2D laparoscopy. The development of 3D technology was inspired on the human visual system that is able to feel the depth, thanks to the presence of specific neurons capable to build 3D perception starting from two different views of the same image coming from the eyes. The 3D technology is based on the same concept: two visions of the same image are necessary to have a stereoscopic vision.

Two steps are necessary to reach the 3D vision: image capture (IC) and image projection (IP). In the laparoscopic field, the IC system is formed by a camera installed on the tip of a laparoscope, that sends the image as an electrical data to an image processor (Fig 1). The two point of view of the same image necessary for the 3D vision can be obtained through two different technologies: single channel or dual channel system. Single channel system extracts the two perspectives by splitting one image thanks to a filter or a prism present in the scope (Fig 2) (1). Dual channel system provides two real different prospective of the same image thanks to the presence of two cameras on the tip of the scope (Fig 3). Based on these two technology, single-channel scope are able to produce images of greater clarity and resolution, due to a bigger size of the optic channel for light transfer, but it can produce a 3D vision only at close distance (4). On the other hand dual-channel systems reproduce a better 3D vision in larger field with less clarity resolution.

The IP is based on two connected devices: video and glasses, both necessary to deliver the final stereoscopic vision to the viewer. The older IP use active shuttering projection: left and right image are alternatively displayed on the screen. With this system, the observer wears active shuttering glasses to allow each eye to see only the corresponding right or left image. More modern technology have introduced the passive polarizing system: two images of the same field are projected simultaneously on the screen with different wave-length. The user wears passive polarizing glasses necessary to separate the two images to each eye (2, 3).

Many works evaluating 3D-MS compared to 2D standard laparoscopy are present in literature. To review all these data is mandatory to evaluate the different technology compared, i.e. single channel or dual-channel system and active or passive IP. The majority of the surveys published are in-vitro researches comparing 2D and 3D technologies performing short laparoscopic exercise in laparoscopic trainer (Fig 1). Only few are the clinical experiences (18-24). Considering all these aspects, three main comparison can be done (4). Table 2 reports 3D single channel laparoscope with active shuttering system compared with standard 2D laparoscopy. Table 3 reports 3D dual-channel laparoscope in robotic studies compared with 2D laparoscopy. Finally Table 4 reports comparisons between 3D dual-channel with passive polarized IP and 2D laparoscopy. It is clear from this complex analysis, that a technology compromising the capture of two real images does not give advantages using 3D over 2D and it is not surprising that single channel laparoscope did not show benefit of 3D laparoscopy. In studies using dual-channel laparoscope with passive polarizing projection, it is reported a better impression of stereopsis (1) with a "near natural" view. Based on these data, basically all the companies have developed a second generation 3D laparoscopic system based on dual-channel laparoscope with passive polarizing projection devices (Tab 1).

The in-vivo validation of this second generation 3D technology is based on few clinical experiences with poor number of patients and often with surgical operations with short operative time (18-21). In general, these studies have reported a good 3D perception with shorter operative time than 2D-MS. Recently the Italian society of Endoscopic and Mininvasive surgery (S. I. C. E.) have completed a national report that aimed to defined the health technology assessment regarding the 3D-MS. In this report, the efficacy of the 3D has been evaluated from the operative time point of view: contrasting data emerged considering different surgical sets (bariatric, laparoscopic surgery, liver resections, right hemicolectomy) with no clear conclusions. The same report suggested a potential economical benefit of around 200,000 euros per year in a Local Health Unit (ASL) performing 2500 surgical operations with 3D-MS. This evaluations has been done only considering data in literature with $p < 0.05$ in terms of shorter operative time of 3D technology than 2D.

The first part of this Ph D thesis (study 1, prospective observational clinical trial) reported results observed over 313 operations of colorectal resections (Tab 6) performed with 2D or 3D technology. Table 7 reports the outcomes of the 82 2D and the 231 3D operations. There were no differences between 3D and 2D groups in terms of median operative time, postoperative complications, rate of reoperation, mortality and length of hospitalization. A second statistical analysis has been done dividing the patients in two subgroups: lower and upper groups. The Lower group included LAR, TC, SG, left colon resections. The Upper group comprehended RH, transverse colon and splenic flexure resections. This second analysis aimed to analyzed deeply the operative time in different procedure: even in this second evaluation no difference emerged in terms of operative time in the Lower and Upper groups. Moreover considering the Upper group, it could be observed more intra-abdominal anastomosis and less drains positioned in the 3D than in 2D (p 0.001; p 0.006). This might suggest a more safeness felt by surgeons during the operations with the 3D technology performing right colonic resections. Considering the safeness and the efficacy of the 3D-MS compared with the 2D-MS, it emerged no difference between the two groups.

Another argument objective of this Ph D thesis was the visual discomfort felt by surgeons while viewing 3D videos. The visual sickness reported so far includes headaches, nausea, dizziness and sometimes inability of a continuous 3D view (25). As mentioned above, the first generation 3D system allowed an uncomfortable vision mostly because the use of single-channel scope and active shuttering projection system. Similar sickness was also reported by many people watching 3d movies (44). These data have proposed some concerns over the possible alterations occurred in the visual neurological system during the 3D view. A very interesting explanation is proposed by Malik et al (25), who sustain that the possible explanation rises from the contrast between the neurological human vision system and the 3D technologies. Considering that the time necessary to transfer an image from the retina to the visual cortex is 100 msec and active glasses open and close every 240 msec, it exists a slight deviation of decoding the 2 images. This delay decoding is worsen by the presence of the eye blinks, usually ten times per minute (27). All these aspects cause a breaking 3D view and the visual sickness (Fig 7). Many authors have proposed different objective methods to score the visual sickness: HR, EMG and EEG are the main. Regarding the EEG alterations, it emerges that during the 3D mode with passive polarizing projection, the brain seems to be more involved in global processing, with working memory and attention increased compared to 2D mode. Moreover the EMG studies performed on the upper arms report a lower muscle contraction in the right arm and a higher contraction in the left arm, suggesting that the 3D-MS allow a more ergonomic position during the operations (Fig 8).

The second part of this PhD research aimed to demonstrate and to score the possible presence of subjective visual sickness during long-time 3D procedures. Two type of subjective visual sickness questionnaire has been used: NASA TLX and SSQ. Both questionnaire are multidimensional tool used to score the perceived workload or visual sickness during a task performance. Both have demonstrated their validity in different context like aviation, social domain and health system (36-45). The NASA TLX has been used in few clinical setting to score the 3D view over the 2D, reporting better results in term of safety and efficacy felt during the 3D surgical operations (38, 39), while the SSQ questionnaire has demonstrated how the wrong position in front of the screen causes visual sickness (45). This field has also been investigated in the S. I. C. E. 2016 report and the visual sickness was considered as a health problem parameter. Again data available were contrasting and it did not emerged clear conclusions over the possible connection between higher visual stress and 3D-MS (http://siceitalia.com/report-health-technology-assessment-della-laparoscopia-3d-versus-2d/).

The Study 2 (3D visual sickness versus 2D) took place during the same period of study 1. It included data from the same 313 colo-rectal resections of study 1. Four experienced surgeons have filled in the NASA TLX and SSQ questionnaire at the end of each operations. The NASA TLX results did not reveal a significant major visual stress in the 3D group than the 2D and the same results rose considering the Lower and Upper groups (Tab 10-12). In the SSQ questionnaire fatigue, difficult focusing and concentrations were symptoms more present in 3D group (Tab 13). The analysis regarding the lower and upper subgroups reported no difference between the two group (Tab 14, 15) except the difficult concentration, that was more present in the 3D-lower. Interestingly it emerged that the “general discomfort” was a symptom more present during the 2D procedures.

This study attempted to answer two questions: Is the 3D-MS as safe and effectiveness as the 2D-MS? and 2. does the 3D view cause more visual work load than the 2D vision?

The Study 1 reported no differences in terms of postoperative complications, reoperation rate, postoperative mortality and length of hospitalization, suggesting that the 3D-MS is as safe as the 2D. No significant difference emerged in terms of operative time, suggesting that the 3D-MS is as effective as the standard 2D laparoscopy.

The Study 2 aimed to verify if the 3D vision causes more visual sickness than the 2D. The NASA TLX questionnaire reported no differences between the two vision systems, while the SSQ data revealed higher difficult concentration and focusing working with the 3D-MS. This last result might be due to the possible learning curve and the necessary habit to work in 3D mode and consequently the Author has evaluated the symptom “general discomfort” higher in the 2D-MS as a consequence of the adaptation of the surgeon to the 3D vision.

Chapter 7

Conclusions

The three dimensional laparoscopy is an emerging technology which has added numerous improvements to the minimally invasive surgery.

Despite many technical problems since its introduction, in less than fifteen years the 3D-MS has greatly improved and many are the systems commercially available. Dual-channel laparoscope associated with passive polarized glasses and screens have demonstrated the best results.

The validation in-vitro of this technology have reported good results in terms of safety and efficacy compared with the 2D laparoscopy. From the clinical experiences using the 3D laparoscopy, it emerged shorter operative time and same postoperative outcomes than 2D. Moreover it has been reported a potential economical saving in using the 3D technology over the standard 2D laparoscopy.

Besides the technical validation of the 3D-MS, another point deeply analyzed is the interaction between the 3D technology and the human neurological vision system. This field of interest started since the introduction of the 3D movies and the headache and visual sickness reported by many people. Different methods have been used to evaluate the modifications happening during the 3D vision. Objective methods includes EEG, EMG and HR. Subjective methods comprehend different types of subjective questionnaire (NASA TLX, SSQ). Each test concluded that 3D technology causes alteration in human neurological vision system, but how long these alterations last is still unknown.

The present Ph D dissertation aimed to answer to two main questions: Is the 3D-MS as safe and effectiveness as the 2D-MS? and 2. does the 3D view cause more visual work load than the 2D vision?

During the study period 313 patients were enrolled in the surveys and 626 questionnaire have filled in. Regarding the Study 1, the postoperative outcomes, the length of hospitalizations, the post-operative mortality and the mean operative time showed no significant difference between the 2D (control group) and the 3D laparoscopy (experimental group). Data emerging from the visual work load study (Study 2) reported no difference in the perceived workload (NASA TLX questionnaire), while the SSQ questionnaire (study 2), even if not severe symptoms emerged, reported higher rate of difficult in concentration and focusing in the 3D group.

In conclusion it has been demonstrated that 3D-MS is as safe and effective as the standard 2D laparoscopy, while the evidence of the temporary or persistent modification in the eyes or in the central neurological vision system has not been clearly demonstrated. Prospective comparative studies are warranted to better elucidate the mild risk of visual sickness emerged from the present study.

Chapter 8

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