ERGONOMICS OF THE OPERATIVE FIELD IN PAEDIATRIC MINIMAL ACCESS SURGERY

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May 2008

A thesis submitted

for the degree of Doctor of Philosophy

at the University of London

To

Angela and my parents

Declaration

I declare that the experiments described in this thesis were carried out by myself in the Department of Biosurgery and Surgical Technology, St Mary's Hospital, Imperial College London under the supervision of Mr George Hanna. The clinical data were collected under the supervision of Mr Munther Haddad. This thesis has been composed by myself and is a record of work which has not been submitted previously for a higher degree.

Alex Chi-Hang LEE

May 2008

Acknowledgements

I am greatly indebted to Mr George Hanna, my supervisor, for his continual guidance, encouragement and support during my research, preparation of the thesis and writing the manuscripts originated from the project.

I wish to express my gratitude to Mr Munther Haddad for his paediatric surgical advice and input during my research.

I would like to thank Dr Dan Elson for his assistance in the LED and laser illumination experiments, Dr Mark Neil and Dr Fernando Bello for their efforts and contributions to the development of the LED endo-illuminator and Dr Bingo Ling for sharing his expertise in digital signal processing.

I am privileged for having Dr Sopark Manasnayakorn and Dr Morkos Fakhry as my colleagues in the Ergonomics Laboratory.

I would like to convey my thanks to Professor Lord Ara Darzi, head of the Department of Biosurgery and Surgical Technology, for his guidance and support.

I am grateful to all volunteer participants who took part in the project.

I would also like to thank Mrs Storz of Karl Storz, the Central Research Fund and the Sir Richard Stapley Educational Trust for their financial support.

Last but not least, I would like to express my heartfelt thanks to my fiancée, Angela, for her time and efforts in helping me with proof reading the manuscripts and for her patience and understanding in the last few years.

Publications originated from the thesis

Lee ACH, Haddad MJ, Hanna GB. Influence of instrument size on endoscopic performance in paediatric intracorporeal knot tying. *Surgical Endoscopy* 2007; 21: 2086-2090

Lee ACH, Elson DS, Neil MAA, Kumar S, Ling BWK, Bello F, Hanna GB. Solid-state semiconductors are better alternatives to provide efficient and uniform endoscopic illumination in minimal access surgery. *Surgical Endoscopy* 2009; 23:518-26

Lee ACH, Hanna GB. Perception of moving shadows in endoscopic surgery. (Submitted)

Presentations to learned societies

Lee ACH, Haddad MJ, Hanna GB. Human Reliability Analysis: A Human factors approach to analyse technical errors and complications. British Association of Paediatric Endoscopic Surgeons Annual Meeting, Southampton, Sep 2005 [Winner of the Tyco Travelling Scholarship 2005]

Lee ACH, Haddad MJ, Hanna GB. Surgical Ergonomics and Paediatric Minimal Access Surgery. British Association of Paediatric Endoscopic Surgeons Annual Meeting, Southampton, Sep 2005

Lee ACH, Haddad MJ, Hanna GB. The influence of instrument size in paediatric endoscopic intra-corporeal knot tying. British Association of Paediatric Surgeons Annual Congress, Stockholm, Jul 2006 [Runner-up of the Peter Paul Rickham Prize]

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Lee ACH, Hanna GB. Visual ergonomics in endoscopic surgery: The perception of moving shadows. [Accepted for oral-poster presentation] Pacific Association of Pediatric Surgeons Annual Meeting, Hong Kong, May 2009

Abstract

Minimal access surgery (MAS) in children, particularly in infants, has additional ergonomic constraints compared to adult practice due to the small size of the operating field. This thesis studies the physical and sensorial aspects of surgical ergonomics in relation to paediatric MAS. The aims of the project are to optimise the choice of instrument size, to evaluate alternative illumination sources in paediatric MAS, and to investigate the role of shadows in potentially assisting visual perception in MAS.

Chapter one describes the background to the project which led to the author's choice of investigating certain aspects of the physical and sensorial visual ergonomics in paediatric MAS.

In chapter two, a literature review is presented on the development, clinical practice and ergonomic constraints in paediatric MAS, and the imaging of the paediatric endoscopic field.

In chapter three, the ergonomic limitation of the small size of the endoscopic operative field is evaluated and a paediatric simulator is developed using anthropometric data from healthy infants to provide the experimental workspace for ergonomic studies. A study on the effect of the size of instruments on paediatric endoscopic intra-corporeal knot tying shows that using smaller instruments results in faster performance and less discomfort for the surgeon without compromising knot quality, suggesting that smaller instruments should therefore be used when operating on infants.

In chapter four, the development of solid-state semiconductor lighting technology as an alternative to the conventional arc-lamp light source is discussed. A light-emitting diode (LED) based endoscopic illumination system, the LED endo-illuminator, is developed with favourable characteristics and fine details recognition is shown to be better compared to the conventional illumination methods. A study on distance estimation in static images does not show that the presence of endoscopic shadows improves depth perception. A further experiment shows that when the light source moves, the resultant shadow movements can give conflicting information to the viewer in the interpretation of the endoscopic scene. Therefore the light source should be stationary if endoscopic shadow is produced in the MAS illumination system. A laser-based illumination system is also developed and proof-of-concept tests show promising characteristics. Its low intensity precludes its use in large cavities but would suit the small endoscopic field in paediatric MAS.

This thesis suggests that better awareness and application of ergonomic principles would improve the practice and safety of paediatric MAS, which would benefit both the surgeon and the patient.

Contents

List of figures

List of tables

List of abbreviations

AC	Alternating current
ANOVA	Analysis of variance
BNC	Bayonette Neil-Concelman
CCD	Charge-coupled device
CRT	Cathode ray tube
DC	Direct current
DOF	Degrees of freedom
DVD	Digital versatile disc
EMG	Electromyography
HD	High definition
Hz	Hertz
InGaN	Indium gallium nitride
IQR	Inter-quartile range
JPEG	Joint photographic experts group
K	Kelvin
KQS	Knot quality score
LED	Light emitting diode
lm/W	Lumen per watt
mA	Milliampere
MAS	Minimal access surgery/surgical
min	Minute
MPEG	Moving picture experts group
mm	Millimeter
mW	Milliwatt
nm	Nanometre
nW	Nanowatt
N	Newton
NOTES	Natural orifice trans-luminal endoscopic surgery
OATV	Optical axis to target view
PQS	Performance quality score
RMS	Root mean square
s	Second
SD	Standard deviation
SEM	Standard error of mean
SSL	Solid-state lighting
VAS	Visual analogue scale
V	Volt
W	Watt

1 INTRODUCTION

1.1 Background of the project

Minimal access surgery (MAS) has been widely adopted in adult general surgical practice over the past two decades. The minimally invasive approach is also increasingly popular in paediatric surgery amongst surgeons and parents of the younger patients. From his first-hand experience in paediatric MAS as a trainee surgeon, the author of this thesis recognised that the psychomotor skills required in MAS are very different from those in open surgery and even for relatively 'simple tasks' in open surgery such as knot tying, they can become more challenging in MAS. The differences in visual perception of the endoscopic operative field is also evident, in particular difficulties in depth perception, which can result in extra compensatory movements by the surgeon.

The author also observed others, including senior surgeons, having similar difficulties, but at the same time, some surgeons seem to be able to perform MAS with relative ease. Why was it difficult to suture or move inside the cavity especially under dim lighting conditions? Is that due to the inadequacy of equipment and instruments, especially when operating on small infants? Clearly some surgeons are innately better at the technique than others, but that does not provide the answer to all these problems. There are also some surgeons who believe that they can compensate for and adapt to the equipment available and do not feel the need to use alternative equipment depending on the size of the patient being operated upon.

In the search for solutions to some of these problems, the author came across the scientific discipline of ergonomics which has been used in various industries for a long time to improve safety and efficiency. Ergonomics has also been increasingly recognised in medical practice to improve patient safety. The high incidence of

medical errors, which unfortunately led to a high number of mortality and morbidity, has been acknowledged in the literature and in publicity. Many errors are preventable, including those which are secondary to inadequate system or equipment design. With the advent in MAS, the importance of ergonomics in surgery has become more evident.

There are broadly three areas in surgical ergonomics, which will be discussed in more detail in Chapter 2, namely physical ergonomics, sensorial ergonomics and cognitive ergonomics. All these aspects have important impact in the practice of paediatric MAS. In the initial planning stage of the project, the author sought to concentrate on the physical aspects of ergonomics in paediatric MAS. However, the difficulty in depth perception in the small endoscopic operative field encountered by the subjects was evident during the research. This led to further investigation in the sensorial ergonomic aspects of MAS.

1.2 Overall aim of the project

The overall aim of the project is to improve the physical and sensorial ergonomics of the small operative field in paediatric MAS. This project will be divided into two major parts and the following aspects will be studied:

a. Physical ergonomics – the size of the operative field in paediatric MAS and the effect of instrument size on the performance of a paediatric MAS task;

b. Sensorial ergonomics – the effect of a novel alternative endoscopic illumination system on the operative field; and the effect of static and moving shadows on visual perception in MAS.

The aims of the first part are to quantify the physical environment of the paediatric MAS operative field in neonates and infants anthropometrically, and to investigate the influence of instrument size on task performance and its impact on surgeons when operating within a small endoscopic field in paediatric MAS. As for the second part which deals with the sensorial aspects of ergonomics, the aims are to develop an alternative illumination system in MAS using the LED technology and to investigate its characteristics and feasibility for future use in MAS. The role of shadows in potentially assisting the visual perception in MAS will also be investigated. The operative field of paediatric MAS in neonates and infants is an ideal platform to test this new illumination technology due to the smaller operative space. However the results may also be applicable to MAS in older children and adults. Ultimately the project aims to help surgeons of all abilities in different specialties to perform MAS more efficiently and safely which should benefit patients under their care.

2 LITERATURE REVIEW

2.1 Paediatric minimal access surgery

2.1.1 Introduction

Traditional open surgery involves making an incision of sufficient size to allow direct vision and access to the operative field. The notions that "large problems require large incisions" and "large incision big surgeon, small incision little surgeon" have dominated traditional surgical thinking as adequate exposure was the key to a safe and successful operation (Bax, 2008, Tantoco et al., 2005). Paediatric surgeons have always sought for less invasive surgical approaches, e.g. supraumbilical incision for pyloromyotomy (Tan and Bianchi, 1986) and muscle sparing thoracotomy (Soucy et al., 1991). Adequate exposure can now be achieved with minimal skin incisions and the use of minimal access techniques which minimises morbidity in stress and pain as well as unsightly scars caused by larger wounds.

In minimal access surgery (MAS), the operative field is visualised using a thin endoscope inserted through a small incision of 2-12mm in size. Illumination is provided from an external arc-lamp source via the fibreoptics of the endoscope. A charge coupled device (CCD) camera is attached to the proximal end of the endoscope which transmits images of the operative field onto a television monitor. Separate incisions are made for the insertion of instruments used for the procedure. Surgical manoeuvres such as tissue dissection, suturing and knot tying are carried out under indirect visualisation via the video-endoscopic system. The main obstacles for the progress of endoscopy in general, especially in paediatric endoscopic surgery, are due to technical difficulties with lighting, image transmission and limitations of the operative space.

2.1.2 Historical background

Physicians have attempted to examine the human body cavity and its contents with less invasive techniques for many centuries. The earliest description dated back to the Hippocrates era when a rectal speculum, with ambient light as the illumination source, was used. The modern era of endoscopy started about 200 years ago. Bozzini in 1805 developed the candle-powered Lichleiter scope in an attempt to view the bladder of a woman. He was criticised for using this method by the contemporary medical community (Tantoco et al., 2005). The first effective open-tube endoscope was developed by Desormeaux in 1853 using a kerosene lamp as the light source, by igniting a mixture of alcohol and turpentine to produce light for viewing the urinary bladder, cervix and uterus. It reached the stomach but light was insufficient (Lau et al., 1997). In 1868, Bruck introduced electrical illumination and used a platinum loop heated by electric current. The incandescent bulb produced by Edison in 1880 improved visibility tremendously. In 1883, Newman used a miniature version of the bulb mounted at the end of the cystoscope. The major problem with this device was that too much heat was produced and therefore it was dangerous to use (Tantoco et al., 2005). Laparoscopy examination of the peritoneal cavity was reported in 1901 by Kelling using a Nitze cystoscope, firstly in a live dog and subsequently in humans. However, advances were hampered by poor exposure and inadequate visualisation.

In the 1950s, there were two milestone inventions in the evolution of endoscopy: the rod lens system by Hopkins and the fibre-optic light transmitting system (Hopkins and Berci, 1976, Hopkins and Kapany, 1954). The optics for visualisation was much improved. However, it was still necessary for the surgeon to hold the scope up to his eye with one hand and operate with the other hand. The first laparoscopic

appendicectomy was performed in conjunction with a gynaecological procedure using this technique (Semm, 1983). The development of the video computer chip in the 1980's allowed magnification and projection of images onto television (Berci et al., 1986). Bimanual tasks via multiple ports to gain access to internal organs became possible. Since then, there has been an explosion in MAS both as a diagnostic tool and an interventional technique in all surgical specialties (Lau et al., 1997). The illumination source and the structure of rigid endoscopes have remained unchanged.

In this thesis, the main consideration will be on MAS or endoscopic surgery as applied to the body cavities (e.g. laparoscopy/thoracoscopy) rather than its use in hollow organs (e.g. gastroscopy).

2.1.3 Advantages and disadvantages

MAS provides an alternative means of carrying out the same procedure as in open surgery. Benefits are mainly seen in terms of quality of life after the procedure (Tam, 2000). The main advantages are less post-operative discomfort, reduced wound complications, smaller scars, less adhesions, blunting of metabolic responses, shorter hospital stays and earlier return to full activities. The latter will allow minimal disruption to the child's education and activities, and also the ability for the carers to return to work earlier. For the surgeon, the enhanced visualisation in deep cavities in MAS compared to that in an open procedure, such as the hiatus in patients with narrow subcostal angle, and the narrow pelvis in some patients, improves performance due to better illumination and magnification (Tam, 2000). The real time operative images are available for all the staff to watch, which would facilitate communication and training (Berci et al., 1986).

MAS requires large capital costs and uses expensive consumables. A long learning curve further increases the cost. It poses a greater challenge for paediatric surgeons compared to adult surgeons because adult surgeons have a regular index procedure, laparoscopic cholecystectomy, to refine their skills. There are few, if any, accepted gold standard cases for MAS in paediatric surgery. Series published on laparoscopic cholecystectomy suggested that the learning curve for this procedure ranged from 10-75 (Firilas et al., 1998). Meehan reported that proficiency in Nissen fundoplication in children can be achieved in 25 cases (Meehan and Georgeson, 1997). The need to re-learn a new technique has prevented some surgeons from adopting this new approach as they are more comfortable using existing open procedures which give known results, especially when suitable paediatric MAS instruments are not readily available.

Training using inanimate bench models have been shown to improve performance in the operating theatre (Coleman and Muller, 2002, Korndorffer et al., 2005). Standard adult-size mechanical and virtual reality simulators were usually used. Simple simulator boxes are readily available to enable surgeons to practice eye-hand coordination skills and also simple tasks such as suturing using different MAS instruments (Lee, 2003, Najmaldin, 2007). A structured training programme has been shown to be effective for non-MAS paediatric surgeons to become familiar with basic MAS skills (Nakajima et al., 2003). Despite increasing interests in paediatric MAS, training models with a small operative space similar to that in reality are not commercially available. Generally speaking, experience in infant MAS can only be acquired from patients in the operating room. Live New Zealand rabbits have been used as an in vivo model for training as their dimensions compared closely with that of neonates (Kirlum et al., 2005a, Kirlum et al., 2005b, Luks et al.,

1995). An inanimate model using the dimensions of the peritoneal cavity of a rabbit was compared with rabbits in vivo (Heinrich et al., 2006). Similar learning effects on isolated mechanical tasks were seen in both models, but in vivo performance of the same task was better with live training. However, the use of live animals for training is not allowed in the United Kingdom. In some paediatric MAS courses, sacrificed animals, usually porcine, are used. However, no animal model or standard training simulator box represents the size of human neonates or infants.

2.1.4 Use of MAS in paediatric surgery

Paediatric surgeons were among the pioneers of MAS in the early 1970's (Bax, 2004, Gans and Berci, 1971, Lobe, 1997), but for the following two decades its use was strictly confined to diagnostic purposes (Tam, 2000). MAS development in paediatric surgery lagged behind that in adult surgery, except for a few ethusiasts in the early 1990's who paved the way despite resistance from others (Bax, 2004, Tam, 2000). The great resistance to apply MAS in children and infants was due to a number of reasons. There was a traditional belief that infants do not experience pain. Some people felt that MAS was too difficult to do or to learn and it took too long to set-up and perform the cases. Many also believed and boasted that the incisions they used were already very small and that the efficacy of the MAS technique has not been proven. In addition, the costs of laparoscopy or thoracoscopy with disposable instruments were very high. The equipment developed for adults were also not small enough for infants and children. Earlier attempts to make the telescope smaller resulted in unacceptable optics and poor vision. However with the advances in fibre-optic light sources, lens systems and video cameras, it became possible to develop a small telescope with superior optics and adequate light.

With more experience in paediatric MAS and the development of better instruments in recent years, the trend is moving towards the application of MAS in different conditions. It is now known that neonates, including premature infants, can mount a considerable endocrine and metabolic response to surgery and that neonates experience pain (Anand et al., 1985). Many have found that shorter hospital stays, decreased post-operative pain, quicker return to normal activities, and parents' earlier return to work counterbalanced the higher cost of MAS (Tam, 2000). The use of reusable instruments further lowered the cost of MAS. In addition, paediatric instruments are now available in the market (Harmon, 2008). As the benefits of the MAS approach became more evident, even senior paediatric surgeons are adopting this surgical approach (Chang et al., 2001). More recently, randomised trials and meta-analyses in paediatric MAS (Aziz et al., 2006, Hall et al., 2004), though with small numbers, are starting to emerge in the literature.

The initial novelty of MAS in paediatric surgery has become standard practice and is now used in most areas in paediatric surgery in many centres around the world. Advances in instrumentation and equipment have expanded the application of MAS to patients ranging in age from premature neonates to teenagers. However, small infants present significant technical challenges related in part to the small working area. The performance of suturing and intracorporeal knot tying is difficult and presents possibility for injury to surrounding organs. Procedures such as fundoplication, pyloromyotomy, nephrectomy and pull-through for Hirschsprung's disease are commonly approached by MAS. Neonatal procedures, including those under 1.5kg, e.g. repair of the oesophageal atresia, have been achieved by MAS (Holcomb et al., 2005, Rothenberg et al., 1998). Though enthusiasts claim that almost all open surgery can be performed by MAS (Bax, 2005), some remained

cautious, especially in neonatal surgery, as the current systems used are mainly adopted from the experience from adult practice.

2.2 Ergonomics

2.2.1 Ergonomics in general

2.2.1.1 Definition

The word 'ergonomics' comes from the Greek words 'ergos' (work/labour) and 'nomos' (natural law). Ergonomics is the scientific study of the interaction between humans and their working environment. It is synonymous to a large extent with the terms "Human Factors", with emphasis in the capabilities and limitations of humans, and "Inclusive Design", with emphasis on broad-spectrum solutions with universal applicability to a wide range of users. Ergonomics is closely associated with several disciplines (including anatomy, physiology, biomechanics, psychology and engineering) which can be combined in a systems approach (Hanna and Cuschieri, 2008). Ergonomic studies include the analysis of tasks, equipment design, workplace layout, work environment, safety, productivity, skill acquisition and training (Patkin and Isabel, 1995). It aims to achieve optimum task performance with a low risk of error and injury by fitting the job to the worker and the product to the user. Hence the working principle is to adapt the environment to the workers, instead of adapting the workers to their environment.

2.2.1.2 Ergonomics in industry

The importance of ergonomics depends on the context of its use. In safety-critical industries such as the aerospace, aviation, transport, nuclear energy and the military, ergonomic considerations can be of critical importance for safe and efficient deployment. For some product development and design, good ergonomics will make a product more pleasurable to use and therefore more marketable. Not surprisingly,

there are large amount of investments in ergonomics in the safety-critical industries, design and manufacturing industries and related commercial sectors.

Substandard ergonomic designs can lead to an increased economic burden due to additional training and maintenance costs needed for the inadequate systems. The well-being of the staff involved may be affected. In the healthcare sector, patient safety may also be jeopardised. Findings from the UK, US, Australia, New Zealand and Denmark all suggest that about 10% of patients admitted to hospital may suffer some kind of adverse outcome. It is estimated that at least 44,000 and perhaps up to 98,000 people die in US hospitals each year as a result of medical errors (Kohn et al., 2000). Although not all of these fatalities can be attributed directly to human errors involving equipment or technology, many of them might have been avoided if ergonomic considerations were adopted in the design of the systems. The Harvard Medical Practice Study reported that 3.7% patients were identified with disabling injuries from medical treatment and nearly half of the adverse events were related to an operation (Leape et al., 1991).

The International Ergonomics Association broadly divides the discipline of ergonomics into 3 domains of specialisation (International Ergonomics Association, 2000):

(1) Physical ergonomics is concerned with the human anatomical, anthropometric, physiological and biomechanical characteristics as they relate to physical activity. The relevant topics include work postures, workplace layout, equipment handling and work related musculoskeletal disorders such as repetitive strain injury.

(2) Cognitive ergonomics is concerned with the mental processes, such as perception, memory, reasoning, and motor response, as they affect interactions among humans and other elements of a system. The relevant topics include decision-making, mental workload, skill performance, human-computer interaction, human reliability, and training as these may relate to human-system design.

(3) Organisational ergonomics is concerned with the optimisation of socio-technical systems, including their organisational structures, policies, and processes. The relevant topics include communication, teamwork, crew resource management, design of roster and working patterns.

2.2.2 Ergonomics in surgery

There are many mental and physical similarities between surgery and skilled industrial/military jobs. Surgery requires a high level of intellectual preparation, an efficient and controlled workspace, fine motor skills for instrument handling and physical endurance at various work postures. In addition, a surgeon must be competent in decision-making and emergency response with good communication and team working skills, often in the context of a target-driven clinical environment with limited resources. However, compared to other industries, there are relatively few studies on ergonomics in surgery. Surgeons are traditionally trained in an environment which discourages complaints about stress and fatigue (Berguer, 1999). They have learnt to adapt to unsuitable conditions and such adaptation often lead to inefficiency, errors and physical or mental stress. Conventional open surgery has relatively low technological demands. However, with advances in surgical

technology especially in MAS, the ergonomic challenges to the surgeon and the operating room environment have become more evident.

The three domains of ergonomics specialisation can be appropriately applied in the surgical practice. Surgical ergonomics can also be divided along the human functions into physical ergonomics, sensorial ergonomics and cognitive ergonomics (Goossens and Van Veelen, 2001), but they are not exclusive to each other.

2.2.2.1 **Physical ergonomics**

This area of ergonomics studies the functions of the human musculoskeletal system which is used to adopt postures, to move limbs and to conduct external forces through the body. It is primarily concerned with the surgeons' posture and how instruments may affect the surgeons during the operation.

Endoscopic surgery has changed the way surgeons interact with the surgical field and therefore also changed the surgeons' posture. Performing endoscopic surgical procedures requires the surgeon to assume awkward body positions for a significant period of time. The often uncomfortable and potentially harmful postures adopted can cause static muscle loading and fatigue as well as impaired psychomotor task performance. Berguer and Cuschieri reported that endoscopic surgeons experience extreme muscle fatigue and chronic injury as a result of their position (Berguer, 1998, Berguer et al., 1997, Cuschieri, 1995).

Ergonomic assessment of surgeons' postures during endoscopic surgery can be carried out using either direct observation (Berguer et al., 1997, Berguer et al., 2001b) or equipment such as motion analysis systems (Emam et al., 2001, Person et al., 2001). A video technique was used to compare the head and back posture of the

surgeon during laparoscopic and open operations and found surgeons exhibit decreased mobility of the head and back and less anteroposterior weight shifting during laparoscopic manipulation despite a more upright posture. Such restricted posture may induce fatigue by limiting the natural changes in body posture that occur during open surgery (Berguer et al., 1997). In another ergonomic analysis of neck, trunk, shoulder, elbow, and wrist movements during laparoscopic surgery, it was also observed that the surgeons adopted a more static posture compared to open surgery (Nguyen et al., 2001). An infra-red motion analysis system was used to show lower angular velocity at the shoulder and elbow joints, less supination and more pronation of the forearm during simulated endoscopic suturing with the ergonomic rocker and ball needle drivers when compared to the conventional finger loop instruments (Emam et al., 2001). An optoelectronic motion analysis system was developed to track and record surgeon's posture and showed that the ergonomic stress scores, particularly in the wrist, were comparatively high during endoscopic tissue manipulation tasks (Person et al., 2001).

Instrument handles form an important physical interface for the laparoscopic surgeon. Ergonomics should therefore play an important role during the instruments design process. However, most of the currently available laparoscopic instruments are developed by a technology-driven (and not clinically-driven) approach and only ergonomically evaluated after the product is on the market (Breedveld et al., 1999, Goossens and Van Veelen, 2001).

Recently, more attention has been paid to the ergonomics of endoscopic surgery instruments. Laparoscopic instruments are subjectively and objectively evaluated using different techniques such as questionnaires (Berguer, 1998, Van Veelen and

Meijer, 1999), EMG parameters, performance parameters and motion analysis (Berguer et al., 1999b, Emam et al., 2001, Van Veelen and Meijer, 1999). Most laparoscopic instruments have ergonomically inadequate handle designs and inefficient handle-to-tip force transmission, which lead to surgeon fatigue, discomfort, and hand paraesthesias (Berguer, 1998).

The use of ergonomic rocker and ball needle drivers resulted in the reduction in muscle power exertion and the absence of muscle fatigue during endoscopic suturing as compared to the conventional finger loop instruments (Emam et al., 2001). Some authors recommended that physical, cognitive and emotional comfort of the surgeons should be considered in laparoscopic instruments design in order to optimise human-products interaction (Goossens and Van Veelen, 2001). A list of 14 criteria for more ergonomically adequate laparoscopic instruments handles design was proposed (Matern et al., 1999). Such criteria should be considered by surgeons when evaluating handles for endoscopic surgery.

2.2.2.2 **Sensorial ergonomics**

Sensorial ergonomics studies the factors that influence the senses input which in turn affect the perception of visual, auditory and haptic information. Visual perception is almost the only sensorial impression from the operating field in endoscopic surgery (Schurr et al., 1999). Warning alarms such as insufflation pressure of the pneumoperitonum provide auditory information. Useful tactile feedback from the instruments in MAS is also limited compared to open surgery. Such loss of sensorial haptics input increases the difficulty in tissue manipulation as the hand-to-tip force transmission is reduced (Berguer, 1998).

Endoscopic surgery alters the surgeon's natural view of the operating field. In contrast to open surgery, visual feedback is achieved through an image display system which becomes the visual interface between the surgeon and the operative field. The position of the visual image display and the quality of the information are both important. It has been shown that there is an improvement in task performance when the image display is placed in front of the surgeon, at the level of the hands and close to the operative field (Erfanian et al., 2003, Hanna et al., 1998b). This optimum ergonomic position would also improve the surgeon's posture (which is mainly within the domain of physical ergonomics). The inversion of the normal laparoscopic image around the Y-axis has been shown to facilitate the rate of learning of a laparoscopic task in novice subjects but has a detrimental effect on the performance of experienced laparoscopic surgeons (Crothers et al., 1999).

There are three main aspects of image representation – acquisition, processing, and display. Accordingly, the quality of the image presented by the video-endoscopic system is dependent on the optical characteristics of the endoscope lens system, the camera and the display system.

2.2.2.3 **Cognitive ergonomics**

This domain of ergonomics is concerned with mental processes such as memory and reasoning, which includes understanding the function of the instruments, decision making and training (Goossens and Van Veelen, 2001). Different methods have been used to study the best training and assessment methodologies for laparoscopic surgical skills. Micro-processor controlled psychomotor testers have been developed to evaluate psychomotor skills related to endoscopic surgery. They provide real-time objective scoring systems that have several aspects of face validity to the real

endoscopic environment (Hanna et al., 1997a). A laparoscopic hernia simulator was used to evaluate the impact of a laparoscopic hernia curriculum on resident surgeons' operative performance (Hamilton et al., 2002). Time-action analysis enabled the objective measurement of correctness in task performance as well as time and action efficiency in learning laparoscopic skills (den Boer et al., 2001). A survey was used as an evaluation of laparoscopic training practices in surgical residency programmes (Marks et al., 2001). A virtual reality simulator was used to assess the laparoscopic skills of a group of trainees (Torkington et al., 2001) and there may be benefits in incorporating the use of virtual reality simulation into established surgical training programmes (Aggarwal et al., 2006). The development of a simulated operating theatre also facilitate technical and non-technical skills training in a realistic environment (Aggarwal et al., 2004).

2.2.3 Evaluation methods in surgical ergonomics

The aim of ergonomic evaluation is to identify ergonomic risk factors and determine the most effective strategy for controlling them. The methods used in surgery can be broadly divided into 3 aspects - impact to surgeon, process of activity and task outcome.

2.2.3.1 Impact to surgeon

Objective measurements can be made to determine the physical and mental workload experienced by the surgeon.

Electromyography (EMG) is commonly used for physical workload evaluation by measuring the summation of action potentials generated by the contracting muscle cells (De Luca, 2002, Kamen and Caldwell, 1996) and have been used in surgical

research (Berguer et al., 1999a, Berguer et al., 2003, Berguer et al., 1999b, Berguer et al., 2001a, Berguer et al., 1998, Berguer et al., 1999c, Emam et al., 2002a, Emam et al., 2002b, Matern et al., 2002, Smith et al., 1998, Van Veelen et al., 2002). The signal is acquired via electrodes placed on the skin surface over the muscle of interest. It has a voltage range of 0-10mV and frequency range of 10-500Hz which is similar to electrical noise (De Luca, 2002). The sampling rate should be at least twice of the highest frequency (Kamen and Caldwell, 1996), the Nyguist frequency, as data sampled by a lower frequency may not be able to fully reconstruct the signal. A sampling rate of 1000Hz is generally used.

EMG obtained can be subjected to amplitude or frequency analysis. The amplitude of the EMG represents the underlying muscular recruitment and activity. Raw EMG signals require processing for meaningful interpretation. This is first performed at the pre-amplification/amplification stage. Further signal processing is performed by using software dedicated for EMG analysis. The direct current offset of the EMG signal from the electronics and instrumentation is removed. Conversion to monopolar data is necessary for quantification and root mean square (RMS) is a commonly used method, where S denotes window length (points) and f(s) denotes data within the window:

$$RMS = \sqrt{\frac{1}{S}\sum_{1}^{s} f^2(s)}$$

Calculations are performed within a moving window of data (Figure 1).

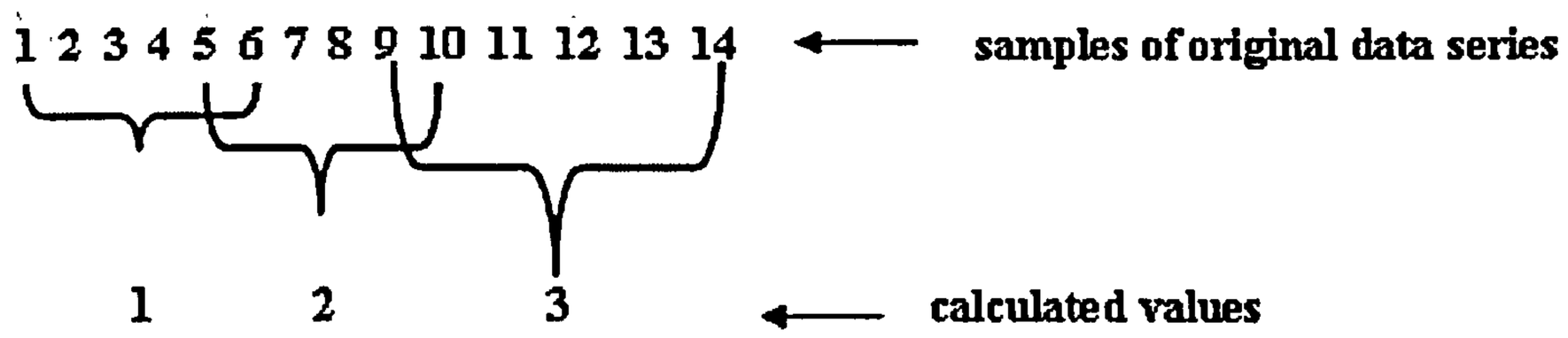

Figure 1 Moving window of data for calculation.

The signal amplitude can be affected by muscle fibre diameter/size, length (which changes during dynamic movements), skin surface to muscle fibre distance, skin condition, electrode position, cross-talk between muscle groups, motion artefacts and other noise signals (e.g. from nearby electrical motor) (Kamen and Caldwell, 1996).

In order to use the EMG signal for comparisons between subjects, sessions, muscles and studies, a normalisation method comparing the data with a reference EMG is used (Kamen and Caldwell, 1996). Non-normalised EMG provides information for intra-subject comparison if the electrodes are not moved. Isometric normalisation is a common normalisation method. This uses the EMG signal during a controlled isometric contraction of the muscle as the reference. The maximal voluntary isometric contraction or a submaximal (or relative) voluntary contraction against a fixed load can be used as the reference contraction (Kumar and Kumar, 1996). This method is not ideal for physical workload evaluation during surgical tasks as the muscles are not isometric (Mirka, 1991). Motivation and familarisation are also known to affect the normalisation reference (De Luca, 1997). The non-linear correlation (De Luca, 1997, Kamen and Caldwell, 1996) of the force-EMG relationship especially at high force levels also makes the use of maximal voluntary isometric contraction unreliable as surgical tasks utilise much lower forces.

An alternative method, using EMG during a dynamic task, has been used in gait analysis studies (Yang and Winter, 1984). The peak or mean RMS of the amplitude of the EMG during a dynamic task is used as the reference point, known as peak dynamic or mean dynamic normalisation respectively (Burden and Bartlett, 1999, Soderberg and Knutson, 2000, Yang and Winter, 1984). The subsequent measurements will then be calculated relative to the maximum or mean activity during the dynamic task. This method, however, does not provide information on how much activation is required to do a task using a fixed reference point but allows comparisons between different dynamic tasks.

Fatigue can be measured from the median or mean frequency of the EMG signal (De Luca, 1997, Kumar and Kumar, 1996). The frequency decreases as the muscle becomes more fatigued. It is also essential that the muscle is in isometric and isotonic contraction during testing, which is not the case during manipulation in surgical tasks as previously explained. If the limitations of EMG are not recognised, large amount of data may be collected which cannot be interpreted meaningfully (De Luca, 1997).

Mental workload can be measured physiologically by eye blinking rate, heart rate variability and skin conductance. The impact to the surgeon can also be assessed by self-reporting questionnaires and observational methods.

2.2.3.2 Process

Ergonomic evaluation of the surgeon's movements or posture can be performed by direct observation using video-recordings or motion analysis systems using electromagnetic or infra-red tracking as discussed in Section 2.2.2.1. Task analysis

methods including human reliability analysis (HRA) are also used to assess the process of tasks executed (Tang et al., 2004a, Tang et al., 2004b).

2.2.3.3 **Outcome**

Execution time is a useful and convenient measure for task outcome but it does not reflect the quality of the task, for example, in a knot tying task (Ritter et al., 2005). Knot quality score takes into consideration the slippage of the knot as well as the break force and is a useful task outcome measurement in knot tying tasks (Hanna et al., 1997b). Error analysis and global scoring systems can be used for outcome analysis (Mackay et al., 2003, Martin et al., 1997, Tang et al., 2004a, Tang et al., 2004b).

2.3 Constraints in paediatric minimal access surgery

MAS carries a set of mechanical and visual constraints in the execution of surgical tasks (Hanna and Cuschieri, 2008, Reyes et al., 2006). Compared to conventional open surgery, MAS require the surgeon to operate remotely using instruments inserted into the body cavity with the operative field provided via a two-dimensional video-endoscopic system. Such arrangements cause degraded task performance and surgeon discomfort.

2.3.1 Mechanical constraints

Each degree of freedom (DOF) of movement allows the instrument to move in an independent direction. The movements of MAS instruments are restricted by the entry point in the body wall, and the resulting fulcrum effect leads to poor mechanical advantage. There are 4 DOF of movement, namely across in the X axis, up and down in the Y axis, in and out in the Z axis and rotational movements. This compares unfavourably to the 36 DOF of movement in open surgery where all joints of the upper limbs from shoulder to finger tips provide movements (Patkin and Isabel, 1995).

Direct tactile feedback is lost in MAS and indirect tactile feedback from the instruments tip to the handles is reduced due to the dampening frictional effect of the length of the endoscopic instruments and friction between the instrument and the port. Proprioceptive feedback regarding position and the ability to identify the nature of tissue components and planes are therefore diminished (Hanna and Cuschieri, 2008).

The designs of MAS instruments were adapted from equivalent instruments used in open surgery with modifications to enable them to be inserted into the body cavity. The diameter of the endoscopic instruments is therefore limited by the size of the access port, the latter of which ranges from 2mm to 12mm in diameter. Long thin instruments have poor mechanical advantage and the narrow sharp distal end may cause damage to tissues during gripping of tissues with the small jaws or if the instrument moved outside the endoscopic view. Surgeons have limited freedom of movement to adjust their body posture and arm positions due to the fixed point of insertion through the body wall. In addition, prolonged shoulder abduction is necessary especially when the table height is not suitably lowered (Berquer et al., 2002, Van Veelen et al., 2002). The presence of the assistant (e.g. holding the camera in front of the surgeon) may further prevent the surgeon as well as the assistant from adopting a comfortable posture.

Because of the extra-corporeal shaft length, the use of a long instrument will result in a large external arc of arm movement if the corresponding intra-corporeal shaft length is short. Experimental study has shown that intracorporeal to extra-corporeal ratio between 1:1 to 2:1 is associated with improved task performance (Emam et al., 2000).

Locations of the ports are determined by the surgeon according to the available space in the surface of the body cavity. These are known to have crucial effects on task performance (Hanna et al., 1997d). The manipulation angle is defined as the angle between the 2 instruments (active and assisting). The elevation angle is the angle of the instrument against the horizontal plane. The best endoscopic manipulations and task performance are obtained when manipulation angle is between 45° and 75°, the

ideal being 60°. Wide manipulation angles necessitate wide elevation angles for optimal performance and task efficiency. Generally elevation angle of 45°-60° are most suitable (Hanna et al., 1997d).

Most MAS instruments require flexion and ulnar deviation at the wrist which decrease maximum grip force. Also, the handle configuration often requires the surgeon to use opposing thenar and hypothenar muscles for gripping, rather than the more powerful deep flexor muscles of the forearm. The muscle contraction force for MAS grasping is 3-5 times higher than that for open instruments. In addition, the inefficient transfer of the mechanical force from handles to tip of the instrument causes further discomfort and fatigue (Berguer, 1998, Berguer et al., 2003, Berguer et al., 1999c).

Many laparoscopic instruments have a narrow surface for contact and are not designed to accommodate the fingers comfortably. Several reports have documented nerve compression and neuropraxia from the handles affecting the digits or the palm (Majeed et al., 1993, van der Zee and Bax, 1995).

2.3.2 Visual constraints

Instead of having a direct vision of the operative field, the use of an image display system as the visual interface between the surgeon and the operative field results in several visual limitations in MAS. Such limitations account for the degraded task performance in endoscopic surgery compared to direct normal vision in open surgery (Crosthwaite et al., 1995).

The endoscopic field of vision is determined by the direction of the endoscope with its peripheral field limited by the optical component of the endoscope. The viewing

angle refers to the angle formed by the outer limits of the endoscopic field. The field of view is the area as seen by the objective of the endoscope, the full extent of which may not be completely picked up by the camera head, most evidently when zoomed in with further loss of the peripheral vision. The restricted field of endoscopic vision contributes to incidental tissue injury when instruments move outside the view (Hanna and Cuschieri, 2008, Majeed et al., 1993, van der Zee and Bax, 1995).

Linear magnification is inversely proportional to the object distance. Therefore, more detail can be obtained when the object is placed close to the distal endoscopic end. However as magnification increases, the apparent speed of movement, including tremor, also increases. Therefore the operator has to mentally adjust the speed and magnitude of movement accordingly.

The use of standard 2-D video-endoscopic systems in MAS means there is a loss of the important binocular cue for steropsis because both retinas are receiving the same information from the screen. Other physiological cues from accommodation and vergence are also lost as the image is in a fixed position, as opposed to the real objects and background which are at variable distances. Therefore, surgeons need to rely on other indirect visual cues to reconstruct a 3-D anatomy from the 2-D image on the screen. This requires intense perceptual processing which has to be sustained for the duration of the operation. The lack of depth perception accounts for the overshooting, undershooting and imprecise staggered deliberate reach employed by surgeons to determine the location of anatomical structures during MAS (Hanna and Cuschieri, 2008).

A number of 3-D systems are available but the advantages over the standard 2-D systems are not as expected as shown by a number of studies (Hanna and Cuschieri,

2000, Hanna et al., 1998a). The stereoscopic system captures two slightly different views of the operative field to produce left and right images. These are displayed to the surgeon wearing an active eyeware made of liquid crystal glasses containing a shutter technology. Alternatively a monitor which contains a special shutter that changes polarisation and synchronises with the right and left image signals is viewed by the surgeon wearing a passive eyeware with polarized lenses. The surgeon's brain fuses these images into a 3D image. However, these systems do not provide real stereopsis and the depth enhancement they generate is artificial. It has been reported that these 3D systems can cause visual strain and headache and do not necessarily result in better performance (Chan et al., 1997, Hanna and Cuschieri, 2000).

Shadows are important pictorial cues which are not available with the current rigid endoscope due to its co-axial arrangement for the optics and illumination. Generally, the illumination is provided by means of fibre-optics arranged in a circular or semi-circular fashion around the central optical element. As a result, the target object in view is directly illuminated with its associated cast shadow behind the object. Experimental studies have shown that illumination systems with cast shadows improve task performance (Hanna et al., 2002, Mishra et al., 2004).

The location of the optical port, the viewing angle of the endoscope and its angular position determine the optical axis of the endoscopic viewing. For intra-corporeal knot tying task in the adult operative space, a distance of 75-150mm between the endoscope and target is optimal for task performance (Hanna et al., 1997c). At this distance, instrument clashing is minimised. However, this is not applicable in infants as such space is not available.

Optimum task performance is obtained when the optical axis of the endoscope is perpendicular to the target plane, i.e. optical axis to target view angle (OATV) equals 90° (Hanna and Cuschieri, 1999). The direction of view of the endoscope (0°, 30°, 45°) has no significant effect on task performance when the optical axis subtends the same angle with the target surface (Hanna et al., 1997c). It is therefore preferable to use an oblique-viewing endoscope or a chip-on-tip endoscope with flexible tip, because a 0° forward-viewing endoscope will only provide a perpendicular view at one axial position only. The oblique viewing endoscopes also provide more visual information to allow viewing from different angles by rotating the endoscope, and consequently may enhance both the correct interpretation of the anatomy and the execution of advanced laparoscopic procedures.

Azimuth angle is the angle between the instrument and the optical axis. Improved task efficiency is achieved with an equal azimuth angles on either side of the optical axis (Hanna et al., 1997d). If this is not possible, off axis endoscopic viewing from the non-dominant side gives better performance (Emam et al., 2002a). When the optical axis is above the instrumental plane, the instruments appear to enter the operative field from the sides (real side). Conversely, when the optical axis is below the instrumental plane, the instruments appear to enter the operative field from the opposite side which is unintuitive (Patil et al., 2004). The ports for the endoscope and instruments should be aligned in the same direction to avoid manipulation against the camera from the opposite direction. Such mirror image makes manipulation extremely difficult (Cresswell et al., 1999). Although some individuals can adapt to reverse alignment, this adaptation requires increased mental processing thereby accelerating mental fatigue (Corballis and McMaster, 1996).

The best task performance is obtained when the monitor is placed in front of the surgeon at the level of the surgeon's hands and to allow a gaze-down viewing of the operative field (Hanna et al., 1998b). Conventional cathode ray tube (CRT) monitors are heavy and are usually placed on top of the MAS equipment trolley. The presence of other free-standing equipment may prevent optimal position of the stack which may also be limited by the length of the wires and cables, in particular the relatively short light cable. Therefore, surgeons who usually operate from the side may not have the monitor in front of them. As a result, the visual axis between the surgeon's forward gaze is no longer aligned with the hands and the instruments. If the monitor is placed too far from the surgeon, it creates additional visio-spatial discordance which further degrades task performance. Ideally a large 19-inch high-resolution monitor should be placed 1000mm in front of the operator. The path of vision may also be obstructed especially if the surgeon is seated during the operation. Changing the position of the monitor in-line with the surgeon has been shown to improve operating time in laparoscopic appendicectomy in children by over 10% (Erfanian et al., 2003).

2.3.3 Surgeon fatigue and discomfort

Cuschieri described a "surgical fatigue syndrome" which occurs after operating MAS for more than four hours due to the intense physical, visual and cognitive demands of endoscopic manipulations (Cuschieri, 1995). This is manifested by mental exhaustion, increased irritability, impaired surgical judgment and reduced level of psychomotor performance. Surgeons often adopt static postures for prolonged periods during MAS, in particular, there is reduced mobility of the head and neck region and anteroposterior weight shifting. The restricted posture limits the natural posture changes that occur in open surgery (Berguer et al., 1997). This is worsened

when MAS is performed from the side of the patient requiring rotation of the surgeon along the head-neck spine axis.

2.3.4 Specific considerations in paediatric minimal access surgery

Paediatric surgeons deal with patients of varying age, size and physiology, ranging from premature neonates to adolescents. The operative field is significantly reduced in infants due to the small operative workspace and minimal distension created by the low pressure pneumoperitoneum. Availability of specific instruments may be limited, especially small ones which are only used in small children, and spare sets may not be available in the operating theatre. Very small instruments of < 3mm are fragile and bend easily. Inadvertent injuries may also occur due to their sharper ends. In addition, excessively firm grasping may cause tissue injuries by the working distal end on small surface area (Bax, 2003).

In neonates, the liver, and urinary bladder are intra-abdominal organs and the abdomen is greater transversely than lengthwise. This further limits available areas for port insertion and optimal port positions may not be achieved.

The use of unilateral lung ventilation is difficult to achieve and poorly tolerated in small children. It is therefore seldom used in paediatric thoracic MAS and the lung needs to be collapsed to create space for the operative procedure. Movements of the incompletely collapsed lung may obscure the operative field causing problems in visualisation.

In addition to the small internal space, the external space is also limited over an infant. Excessive cluttering of instruments can cause inefficiency and potential dangers, particularly with cables and electrical wires (Alarcon and Berguer, 1996).

The limited space for the assistant can be problematic especially when the assistant has a large body habitus. The anaesthetist may also be in close proximity and care must be taken not to dislodge the ventilatory tubings.

The thin body wall in infants provides less grip for anchoring the cannula. As the internal space is limited, the length inserted should be kept to a minimum. This predisposes to dislodgement (Bax and van der Zee, 1998) and the port should be suitably secured. Some paediatric patients have a deformed body torso, e.g. kyphoscoliosis in cerebral palsy patients, and the positioning of the patient and surgical crew will need to be modified accordingly.

On the other hand, the small operative space could be an advantage. Shorter distance between the illumination and the target requires a less powerful light source. Illumination other than conventional arc-lamp may be used, as in wireless intra-luminal capsule endoscopy (Iddan et al., 2000) where four white light emitting diodes (LEDs) are used for close mucosal inspection with a range up to 30mm.

2.4 Equipment and the operative field in paediatric minimal access surgery

2.4.1 Equipment

The equipment and instruments used in paediatric MAS are mostly the same as those used in adult MAS. There are some specific instruments used in paediatric MAS which also have originated from adult MAS and/or open surgery. The quality of the endoscopic image is dependent on the illumination condition as well as the characteristics of the video-endoscopic equipment such as the endoscopic optical lens system, the camera and the display monitor.

2.4.1.1 Creation of the operative workspace

Creation of pneumoperitoneum by insufflation is necessary to create the operative space and to support the anterior abdominal wall. Abdominal wall lifters have been used in adult MAS and also experimentally in rabbits (Luks et al., 1999), but these are not widely used in paediatric MAS as they do not provide the optimal amount of space (Bax, 2003, Luks et al., 1999). Although the thoracic cage provides support to the thoracic wall, the lung needs to be collapsed sufficiently to allow operative manoeuvres. Artificial tension pneumothorax using CO2 with an insufflation pressure of 5-8mmHg is usually used (Bax, 2003, Luks et al., 1995).

2.4.1.2 Operating instruments

MAS instruments are usually inserted into the body via ports (also known as trocars or cannulae). The size of the port used depends on the instrument to be used, with some ports allowing small instruments to be used without the need for adaptors. The length of the port is important. Long ones are heavy and if they are inserted too deep

into the body cavity, intra-corporeal movements are severely limited. On the other hand, short ports increase the risk of dislodging due to the thin body wall of infants (Lobe, 2003). There are various ways to fix a port after insertion into the body (Bax and van der Zee, 1998) and some ports have been designed to prevent slippage with a screwing-in shaft or radially dilatation sheath (Bax, 2003).

Working instruments used in MAS include graspers/dissectors, scissors, retractors, clippers/staplers, ligature placing devices, energy supplying devices, and tissue retrieving bags. Some of these instruments can be disposable. Most instruments have the following parts – handle, shaft and working end. They have pistol grip or in-line handle which may or may not have a ratchet-locking mechanism. Most needle-holders have an in-line handle design. The size of the shaft is usually 3mm or 5mm in diameter, with the latter being more readily available in the operating theatre, especially in general hospitals. More recently, there has been heightened interest in the use of a master-slave tele-manipulator, such as the da Vinci surgical robot, due to the increased degree of freedom of movements of instruments and the true stereoscopic vision it provides. However, its large physical size and costs are prohibitive in neonatal surgery because of the relatively low caseloads. More experience is being accrued as robotic surgery is becoming more acceptable, but so far its practice has been confined to a few paediatric MAS centres only.

2.4.1.3 Endoscope

The Hopkins rod lens endoscope contains optical lenses in the centre and illumination fibre-optics in the periphery. Various sizes and lengths are available, and the viewing angle or optical axis varies from 0° to 70° from the physical axis of the endoscope. Endoscopes of 3-5mm in diameter are usually used in infants.

Generally, smaller endoscopes have lower optical resolution and greater distortion compared to the larger ones. The amount of light transmitted by smaller endoscopes would also be less (Bax, 2003).

2.4.1.4 **Video camera**

Single chip cameras are increasingly being replaced by 3-chip cameras which have one channel for each of the three primary colours. Some cameras are also equipped with a parfocal zoom which allows enlargement of the image without moving the endoscope. However, zooming results in less resolution, illumination and perception of depth (Bax, 2003).

2.4.1.5 **Monitor**

The three major components that determine the image quality of the display are resolution, luminance and chroma. Resolution determines the clarity of the image; luminance is associated with the brightness of the signal; and chroma represents the intensity/hue and saturation of colour (Hanna and Cuschieri, 2001). Large CRT monitors are usually placed on top of other equipment in the MAS tower. Modern lightweight thin film transistor (TFT) monitors are usually adjustable to allow changes in position. Systems with projected images on a white screen have also been explored, but the resolution is found to be inferior compared to existing monitors (Brown et al., 2003). More recently, high definition (HD) camera system and monitor display are increasingly used in the operating theatre, in parallel with the rapid growth in the consumer HD television market. HD endoscopic systems have been shown to be superior to standard definition systems, in subjective comparison, in actual adult surgical operations and also in objective laboratory experiments involving suturing and knot tying tasks (Hagiike et al., 2007).

2.4.1.6 **Illumination**

Illumination is the act of placing light on an object. This allows stimulation of the human visual system and hence the sense of sight is allowed to function. Light is a part of the electromagnetic spectrum, lying between wavelength limits of 380nm to 760nm. In this wavelength region, radiation is absorbed by the photoreceptors of the human visual system, which initiates the process of seeing (Boyce, 1997).

The measurement of electromagnetic radiation emitted by a source is known as the radiant flux. It measures the rate of flow of energy emitted and the unit is watt (W).

Luminous flux is used to quantify the total light output of a light source in all directions and the unit is lumen. Luminous flux is the radiant flux multiplied by the relative spectral sensitivity of the human visual system over the wavelength range of 380nm to 760nm. The relative spectral sensitivity is based on the perception of relative brightness for each wavelength in the visual region. A monochromatic light source emitting an optical power of 1/683 W at 555nm has a luminous flux of 1 lumen.

Luminous intensity quantifies the luminous flux in a given direction and the unit of measurement is candela. One candela is equivalent to one lumen per steradian. Hence a monochromatic light source emitting an optical power of 1/683 W at 555nm into a solid angle of 1 steradian has a luminous intensity of 1 candela.

The luminous flux falling on a unit area of a surface is called the illuminance. and the unit of measurement is lumen per metre square or lux (Boyce, 1997). This is used to characterise the illumination in certain environments.

2.4.1.6.1 *Illumination in minimal access surgery*

The current arc-lamp light sources use halogen or xenon lamps in an external light fountain box with electrical power around 150 - 300W. Light is transmitted via a fibre-optic light cable which is connected to the light post of the endoscope in a non-coherent manner, i.e. the fibres are not in the exact position in the coupling. A suitable light cable in good working order is very important to transmit light from the light source to the endoscope with minimise light loss. Size mismatch between the light cable and endoscope, loose connections and/or broken fibres within the light cable will result in light loss and heat production. From the light post, light is then transmitted along the optical fibres within the endoscope which provides illumination from its tip.

2.4.1.6.2 *Limitations of current endoscopic illumination*

Current endoscopic illumination systems have several limitations in terms of their physical characteristics, the illumination field they provide and their costs for practical use.

The electrical to light power conversion of an arc-lamp is very inefficient with around one hundredfold reduction of final light output at the distal end compared to the input power (Hensman et al., 1998). The arc-lamp is not really a "cold" light source as the lost energy is converted into heat which can allow temperatures to reach over 1000°C. The resultant excess heat needs to be dissipated remotely, usually as an external light box in the MAS equipment trolley. This means that the light must be coupled from the external source to the operative field by means of fibre-optic light guides, commonly known as light cables. The coupling mismatches at the fibre-optic interfaces resulting in light loss and heat production. Even with

heat filtering, the temperature at the distal end of the fibre-optic cable can reach 239°C and the tip of an illuminated endoscope can reach up to 95°C (Hensman et al., 1998), which creates a potential hazard for thermal injuries or damage. Also, the thick and short fibre-optic cable which often crosses the operative field adds complexity to the ergonomic layout. In addition to this, arc-lamps are bulky and fragile. They also require a starter or ballast circuit as well as a fan for cooling, and therefore need to be placed remotely in an external box. Furthermore, arc-lamps are inherently unstable and an extremely well regulated direct current (DC) power source is required to minimise wandering or fluttering of the ionised arc within the gas filled discharge tube.

The illuminated field from an arc-lamp endoscope is not uniform, as the intensity of the directed light beam decreases radially. This results in darker peripheries with a bright or over-exposed centre, commonly known as white-out if significant. Also, when the scope is directed to a surface from an angle, the distant view will be significantly darkened. The illumination intensity is adjusted by the automatic shutter in most current video-endoscopic imaging systems in order to reduce central glare, or whiteout, which is common when the endoscope is placed close to the tissue surface. As the transmitted light is focused over a smaller area through a small paediatric endoscope compared to a larger endoscope, as the smaller endoscope approaches the tissue central glare is common (Harmon, 2008). An alternative illumination technology with a uniform distribution may be more suitable for use in paediatric MAS than those used in conventional adult MAS. Such illumination alternatives, however, can be less powerful due to the shorter distance between the light source and target tissue in the paediatric MAS operative field.

Current rigid endoscopes have a co-axial alignment for the viewing optics and illumination fibres. Generally, illumination is provided by means of fibre-optics arranged in a circular or semi-circular fashion around the central image optics. As a result, the target object in view is directly illuminated with its associated shadow casted behind it. This produces a shadowless operative field and important pictorial cues are thus lacking (Hanna et al., 2002).

Lastly, the running costs of arc-lamps are very high and the lamps themselves need to be replaced approximately every 500 hours to maintain adequate light output. In 2005, an endoscope costs about £4000, and together with an extra xenon arc-lamp light source and light cable, the cost will be almost £7000. Commercially available dual output light cable, e.g. Storz 495UD, allows simultaneous light transmission for 2 endoscopes from a single light source. However, this arrangement would still require an additional endoscope for the secondary illumination.

2.4.2 Perception

The study of sensation or sensory processes is concerned with the initial interaction between the subject and the environment. On the other hand, the study of perception relates to our conscious experience of objects and object relationships and how we form a conscious representation of the outside environment (Coren et al., 2004a).

During MAS, the viewing monitor provides visual information of the operative field to the surgeon. This image is sensed by the rods and cones in the retina and the information is then processed. The final interpretation of the target depends on the surgeon's perception of the target's brightness, colour and position in space. The lack of depth perception in particular causes difficulties in visualisation in MAS.

Misinterpretation of the perceived anatomy, or misperception, can have very serious consequences in clinical practice. For example, in a study of 252 bile duct injuries which occurred during laparoscopic cholecystectomy, it was found that misperception accounted for 97% of the injuries (Way et al., 2003).

2.4.2.1 Depth perception

Depth or space perception consists of the judgment of absolute distance of the object from the observer (egocentric localisation) and relative distances (object relative localisation) (Coren et al., 2004b). Information for depth perception is provided by several cues.

2.4.2.1.1 *Pictorial cues*

These cues require only one eye to register and appear in 2-D pictures (Coren et al., 2004b):

(1) Occlusion/overlapping/interposition - nearer objects tend to obscure the view of a more distant one.

(2) Shadows – attached and cast shadows of illuminated objects offer clues about the 3-D nature of the object and its relationship to other objects and the observer.

(3) Aerial perspective - more distant objects tend to be hazier and less clearly defined.

(4) Familiar size – for common objects not at extreme distances, familiar size can give absolute depth information and not merely relative depth cue.

(5) Relative size - for objects of similar sizes, those projecting a smaller visual image on the retina are assumed to be further away.

(6) Linear perspective - when two converging lines are seen, the observer assumes that they are two parallel lines receding in depth.

(7) Texture gradient - the more distant parts of the texture have smaller elements that are more densely packed together.

(8) Height in plane - the proximity of the object to the horizon line signals a greater distance.

(9) Proximity-luminance covariance - continuous reduction in illumination and intensity is assumed to signal receding distance (Dosher et al., 1986).

2.4.2.1.2 *Kinetic cues*

Objects that are closer to the moving observer show greater relative motion than those at more distance. The differential velocities of points on the retina produce motion parallax during head movements. Kinetic depth effect is a special form of motion parallax where motion cues can give us information about the relative depth of parts of an object (Coren et al., 2004b).

2.4.2.1.3 *Physiological cues*

The human eyes are separated horizontally. Therefore, the retinal images are slightly different giving rise to binocular vision which confers a great advantage to the estimation of relative depth (Coren et al., 2004b).

Accommodation and convergence are physiological depth cues which are somewhat weaker cues as other depth cues are preferentially used (Coren et al., 2004b). The default distances for human resting point of accommodation and resting point of vergence are 75-85cm and 80-100cm respectively. Beyond these distances, accommodation and vergence are not necessary (Reyes et al., 2006).

2.4.3 Shadows

Shadow is a useful pictorial cue in depth perception to provide three-dimensional information in two-dimensional images (Mamassian et al., 1998, Ramachandran, 1988). Standard endoscopes do not cast shadows behind an object, such as the instrument, due to the co-axial arrangement between the illumination and imaging optics. The use of separate ports for imaging and illumination to provide shadow in the standard 2-dimensional endoscopic image has been shown to improve task performance, especially with overhead illumination and a balanced shadow contrast (Hanna et al., 2002, Mishra et al., 2004).

There are different methods of casting shadow in endoscopic surgery. Illumination can be introduced in the same imaging port by employing additional illumination fibres at a distance behind the front lens, thereby resulting in an angle between the illumination and the viewing direction (Lapalux shadow telescope II, MGB, Berlin, Germany) (Kunert et al., 1997, Schurr et al., 1996). Alternatively, illumination can be provided by mounting the optical fibres on the instrument port as a light trocar (Park et al., 2007), thus separating it from the imaging optics. In both methods as the illumination source is not stationary, the effects are counter-intuitive as we assume in daily life that it is the object, rather than the light source, that moves (Mamassian et al., 1998). This may account for the lack of interest in those techniques in spite of shadow being a strong depth cue with current 2-dimensional imaging systems (Hanna et al., 2002, Mishra et al., 2004).

Nevertheless, the new generation of minimal access surgical equipment which employs different channels for the instrument, illumination and imaging will inevitably create shadow. There have been changes in the ergonomics of the

endoscopic field, such as the introduction of intracorporeal mobile cameras (Rentschler and Oleynikov, 2007) and recent advances in endoscopic instrumentation including the increasing interest in natural orifice trans-luminal endoscopic surgery (NOTES) and combined endoscopic and laparoscopic procedures (Park et al., 2007, Rentschler et al., 2007). It is important to study the perception of the endoscopic field based on the appearance of cast shadows in the endoscopic images, as this is crucial for instrument design and the handling of instruments during surgical procedures.

2.5 Conclusions from the literature review

The ergonomic constraints in MAS in adult surgical practice are also applicable in paediatric surgery. However, there are additional ergonomic constraints in the paediatric endoscopic operative field which is made more pronounced by the use of equipment that are originally designed for adult MAS. Most of the reported research in paediatric MAS relate to the clinical feasibility of various open procedures performed with MAS. However, very little work is available on the impact of the ergonomic constraints (for example, from the use of existing MAS instruments) to the surgeon performing paediatric MAS.

There are several limitations with the current MAS illumination systems, the general design of which has not changed significantly in the past few decades. Alternative illumination sources using solid state lighting (SSL) have not been explored despite the crucial importance of light provision to allow visual perception of the operative field. The small paediatric endoscopic operative field would be an ideal platform to investigate new lighting technologies even though the current SSL devices have not yet achieved high enough luminous output for illumination in the larger adult endoscopic operative field (Kumar, 2004).

In addition, the visual perception of the operative field under different lighting conditions, including depth perception with the aid of static and moving shadows, have not been extensively evaluated. A deeper understanding of the visual perception in an endoscopic environment would allow improved instrument design and better handling of instruments during MAS.

2.6 Objectives of the project

The overall aim of the project is to improve the physical and sensorial ergonomics of the small operative field in paediatric MAS.

The specific objectives are:

(1) To investigate the physical limitations of the small endoscopic operative space in paediatric MAS:

a. To obtain abdominal anthropometric measurements from neonates and infants and to use the data for the construction of paediatric simulator boxes – one of them representing an average neonate and another one representing an average infant, which are suitable for use in laboratory ergonomic studies.

b. To study the influence of instrument size on paediatric intracorporeal knot tying within a small operative field similar to that encountered in neonatal MAS. The study was designed to test the hypothesis that the performance of intracorporeal knot tying, in terms of the impact on the surgeon and the quality of the task, improves when the smaller paediatric needle-holders are used.

(2) To investigate an alternative illumination technology for use in MAS by:

a. The development of a working prototype, the LED endo-illuminator, for MAS illumination using SSL technology.

b. User testing of the LED endo-illuminator, and to test the hypothesis that the LED is a better additional light for shadow producing illumination.

c. Quantification of the illumination characteristics of the LED endo-illuminator, in terms of illumination intensity, stability, uniformity and shadow sharpness.

(3) To evaluate the visual perception in MAS under different illumination conditions.

a. To test the hypothesis that fine details discrimination in the peripheral endoscopic operative field is better under the LED illumination.

b. To investigate the role of static and moving shadows in the endoscopic operative field by testing the hypotheses that:

i. Shadow enhances depth perception for distance estimation in static images

ii. Moving shadows are assumed to be due to object movements,

iii. It is more difficult to determine the source of shadow movement when the light is moving.

3 PHYSICAL ERGONOMIC FACTORS

3.1 Introduction

Ergonomic constraints have been recognised to affect the surgeons' well-being and surgical task performance (Berguer et al., 1999b, Cuschieri, 1995). Surgeons often have to work in sub-optimal conditions, adopt awkward postures and endure extra cognitive workload when using inappropriate equipment under poor operative set-up. These situations are commonplace during MAS (Berguer et al., 1999b, Berguer et al., 1997)

There are increasing numbers of complex MAS procedures in infants, including thoracoscopic oesophageal atresia repair (Holcomb et al., 2005), laparoscopic duodenoduodenostomy (Rothenberg, 2002) and laparoscopic porto-enterostomy for biliary atresia (Martinez-Ferro et al., 2005), some of which require anastomosis in small neonates weighing less than 1.5kg (Rothenberg et al., 1998). The use of various tissue-approximating devices is often not possible because of the restricted operative workspace and comparatively fragile tissues. Appropriate choice of instruments to allow secure knot tying is important for safe and effective performance of MAS in these small patients. Nevertheless, the use of equipment is generally guided by financial constraints, instrument availability and the personal perception of the need for specific paediatric equipment, rather than through objective ergonomic evaluations to determine suitability (Vereczkel et al., 2003). The commercial surgical healthcare market and current hospital theatre inventory are geared towards adult MAS because of its higher workload. For instance, adult needle holders are commonly used in paediatric MAS in spite of the availability of smaller instruments that have been specifically designed for use in infants.

MAS simulator box trainers of the size of adult torso are widely available commercially and have been used in MAS training as well as in laboratory based studies. A simulator box of the size comparable to infants, especially neonates, is not available and is required to provide a simulated operative field for the investigation of the ergonomic set-up in paediatric MAS.

The aims of this part of the study are two-fold:

(1) To quantify the physical environment of the paediatric MAS operative field in neonates and infants anthropometrically in order to construct two paediatric simulator boxes with the sizes equivalent to that of an average neonate and that of an average infant.

(2) To investigate the influence of instrument size on task performance and its impact on surgeons when operating within a small endoscopic field, using the neonatal simulator box constructed in the first study.

3.2 Size of the paediatric operative field

3.2.1 Aim

The aim of this part of the study was to obtain abdominal anthropometric measurements for the construction of paediatric simulator boxes suitable for laboratory experiments for the evaluation of ergonomics in paediatric MAS. In particular, data that are representative of 6-8 month old infants and term neonates were examined in order to have the data to construct the mechanical simulators for the ergonomic experiments pertained to infants in this research project.

3.2.2 Methods

3.2.2.1 Existing anthropometric data

A search for existing abdominal anthropometric data for infants was performed and the Anthrokids database, was the only one found. This was based on a study of normal children and infants performed in 1977 in the United States and is currently available from the United States National Institute of Standards and Technology website (Ressler, 1977). The abdominal measurements taken from the infants were waist circumference and waist breadth at the level of the umbilicus. The data was categorised according to age in months: 0-2 months, 3-5 months, 6-8 months, 9-11 months, 12-15 months, 16-19 and 20-23 months. There were 28 to 45 infants in each age category. The mean value, SD and range were available in the database. There were no abdominal anthropometric data specifically on newborn babies available. Therefore, the information from the Anthrokids database alone was inadequate to meet our needs for the construction of the paediatric simulator boxes. In order to fulfil our purpose, we collected our own abdominal anthropometric data.

3.2.2.2 Ethical approval

Research ethics approval for anthropometric data collection at the outpatients department was granted by the St Mary's Hospital Local Research Ethics Committee (reference no. 05/Q0403/32). Further amendments were approved to allow data collection from neonatal patients in the postnatal ward (reference no. 05/Q0403/32).

3.2.2.3 Subjects

Infants and neonates were considered as two separate groups.

3.2.2.3.1 *Infants*

The subjects were recruited in the paediatric out-patients department at St. Mary's Hospital. Infants less than 10 months old according to the clinic booking list were considered. Babies born very prematurely, those with known deformities of the body torso and those with medical conditions affecting development were excluded.

3.2.2.3.2 *Neonates*

The subjects were recruited in the postnatal ward at St. Mary's Hospital. Parents in the postnatal ward who have had a baby born within 3 days were approached. Neonates needing high dependency or intensive care treatment, those born before 35 weeks of gestation, and those with known deformities of the body torso or medical condition affecting development were excluded.

Permission from the consultants in charge of the clinics and the neonatology department were obtained. Informed consent was obtained from all parents.

3.2.2.4 **Anthropometric measurements**

For each of the following landmarks in the subjects, three measurements were taken and the mean was calculated:

(i) Xiphoid-umbilicus distance (xiphoid to upper edge of umbilicus);

(ii) Umbilicus vertical diameter (between upper and lower edges of umbilicus);

(iii) Umbilicus-pubic symphysis distance (between lower edge of umbilicus and pubic symphysis);

(iv) Bi-iliac distance (between the anterior superior iliac spine on both sides);

(v) Abdominal width (the maximum width of the abdomen);

(vi) Abdominal girth (the maximum girth of the abdomen);

(vii) Iliac depth (the vertical height from the anterior superior iliac spine to bed surface);

(viii) Abdominal depth (the vertical height from the most anterior point of the anterior abdominal wall to bed surface);

(ix) Subcostal angle (between the subcostal margins);

(x) Supra-pubic angle (between anterior superior iliac spine pubic symphysis and anterior superior iliac spine on the other side).

In the out-patients department, measurements were taken in the weighing room using a tape measure for length and goniometer for angles. Measurements were taken immediately after the babies' routine neonatal check in order to minimise disturbances to the baby. Care was taken to avoid unnecessary exposure of the infant. A clinical research fellow with experience in paediatric surgery and medical neonatology took all the measurements.

3.2.2.5 **Analysis**

The age, gestation at birth, weight and other demographic details were recorded. The weight centile was determined by plotting the weight on the UK90 growth

reference chart (Freeman et al., 1995). The mean and standard deviation of the abdominal measurements were determined. Infants with age limited to 6-8 months and neonates born with gestational age limited to 39-41 weeks were selected for subgroup analysis. Subjects within these age ranges and whose weight was between 25^{th} to 75^{th} centile were further analysed. The anthropometric data within the age and weight limits in the subgroup analyses would represent the average sizes of an infant and a term neonate respectively.

3.2.3 **Results**

The first column in Table 1 shows the mean values and standard deviation of anthropometric measurements obtained from 22 infants (17 male and 5 female) at the out-patients department. Their clinical problems ranged from dermatological to urological conditions but none have had abdominal surgery or deformities in the torso. The first column in Table 2 shows the mean values and standard deviation of measurements from the neonates recruited in the postnatal ward. One parent declined recruitment as she was very tired after a caesarean section. Data was obtained from 37 neonates (19 male and 18 female). No abnormalities were noted in any of the neonates.

Inclusion subgroups	**All infants**	**Age specific**	**Age and weight centile specific**
Age limited to	2-10months	**6-8 months**	**6-8 months**
Weight centile limited to	$0.2^{th} - 98^{th}$	$0.2^{th} - 98^{th}$	**$25^{th} - 75^{th}$**
Number of infants	22	13	2
Gestation at birth	39weeks (2)	39weeks (9)	40weeks (0)
Age with gestational age corrected	26weeks(9)	31weeks(4)	30weeks(5)
Birth weight	3.0kg(0.9)	3.2kg(0.7)	4.2kg(0)
Current weight	7.3kg(1.4)	7.9kg(1.2)	8.3kg(0.3)
Abdominal measurements			
(i) Xiphoid-umbilicus	76mm(14)	81mm(13)	89mm(10)
(ii) Umbilicus vertical diameter	9mm(3)	10mm(3)	11mm(3)
(iii) Umbilicus-pubic symphsis	56mm(10)	60mm(7)	60mm(9)
(iv) Bi-iliac distance	128mm(15)	132mm(12)	131mm(32)
(v) Abdominal width	145mm(22)	154mm(20)	179mm(13)
(vi) Abdominal girth	405mm(54)	420mm(36)	407mm(59)
(vii) Iliac depth	58mm(11)	65mm(8)	64mm(11)
(viii) Abdominal depth	101mm(14)	124mm(17)	103mm(17)
(ix) Subcostal angle	122° (17)	124° (17)	151° (4)
(x) Supra-pubic angle	131° (12)	134° (7)	132° (12)

Table 1 Abdominal anthropometric data of infants recruited in the out-patients department. First column - 2-10 months infants, second column – limited to 6-8 month old only; third column – limited to 6-8 month old with weight within 25^{th} and 75^{th} centile only. Values shown as mean (SD).

Inclusion subgroups	**All neonates**	**Age specific**	**Age and weight centile specific**
Gestation at birth limited to	>35weeks	**39-41weeks**	**39-41weeks**
Weight centile limited to	$0.2^{th} - 98^{th}$	$0.2^{th} - 98^{th}$	**$25^{th} - 75^{th}$**
Number of neonates	37	31	17
Gestation at birth	40weeks(1)	40weeks(1)	40weeks(1)
Age with gestational age corrected	2.9days(7.8)	1.7days(5.7)	1.2days(6.3)
Birth weight	3.3kg(0.5)	3.3kg(0.4)	3.4kg(0.2)
Abdominal measurements			
(i) Xiphoid-umbilicus	64 mm (6)	63 mm (5)	63mm (5)
(ii) Umbilicus vertical diameter	13 mm (2)	13 mm (2)	13 mm (2)
(iii) Umbilicus-pubic symphsis	39 mm (18)	39 mm (19)	43 mm (25)
(iv) Bi-iliac distance	95 mm (5)	96 mm (5)	97 mm (6)
(v) Abdominal width	111 mm (8)	110 mm (7)	113 mm (6)
(vi) Abdominal girth	322mm (28)	319 mm (28)	321 mm (31)
(vii) Iliac depth	42 mm (5)	42 mm (4)	43 mm (4)
(viii) Abdominal depth	87 mm (7)	87 mm (8)	88 mm (6)
(ix) Subcostal angle	109° (10)	110° (10)	109° (12)
(x) Supra-pubic angle	128° (10)	129° (10)	127° (10)

Table 2 Abdominal anthropometric data of neonates recruited in the post-natal ward. First column – neonates born after 35 weeks gestation, second column – limited to neonates born between 39 and 41 weeks of gestation; third column – limited to neonates born between 39 and 41 weeks of gestation with weight within 25^{th} and 75^{th} centile only. Values shown as mean (SD).

In order to have more specific target sizes for the purpose of constructing the paediatric simulator boxes, 13 infants of 6-8 months corrected age and 31 neonates of 39-41 corrected gestation weeks at birth were selected and the data are shown in the second columns of Table 1 and Table 2. The weight centile distribution of the infants and neonates within these age ranges are shown in Figure 2.

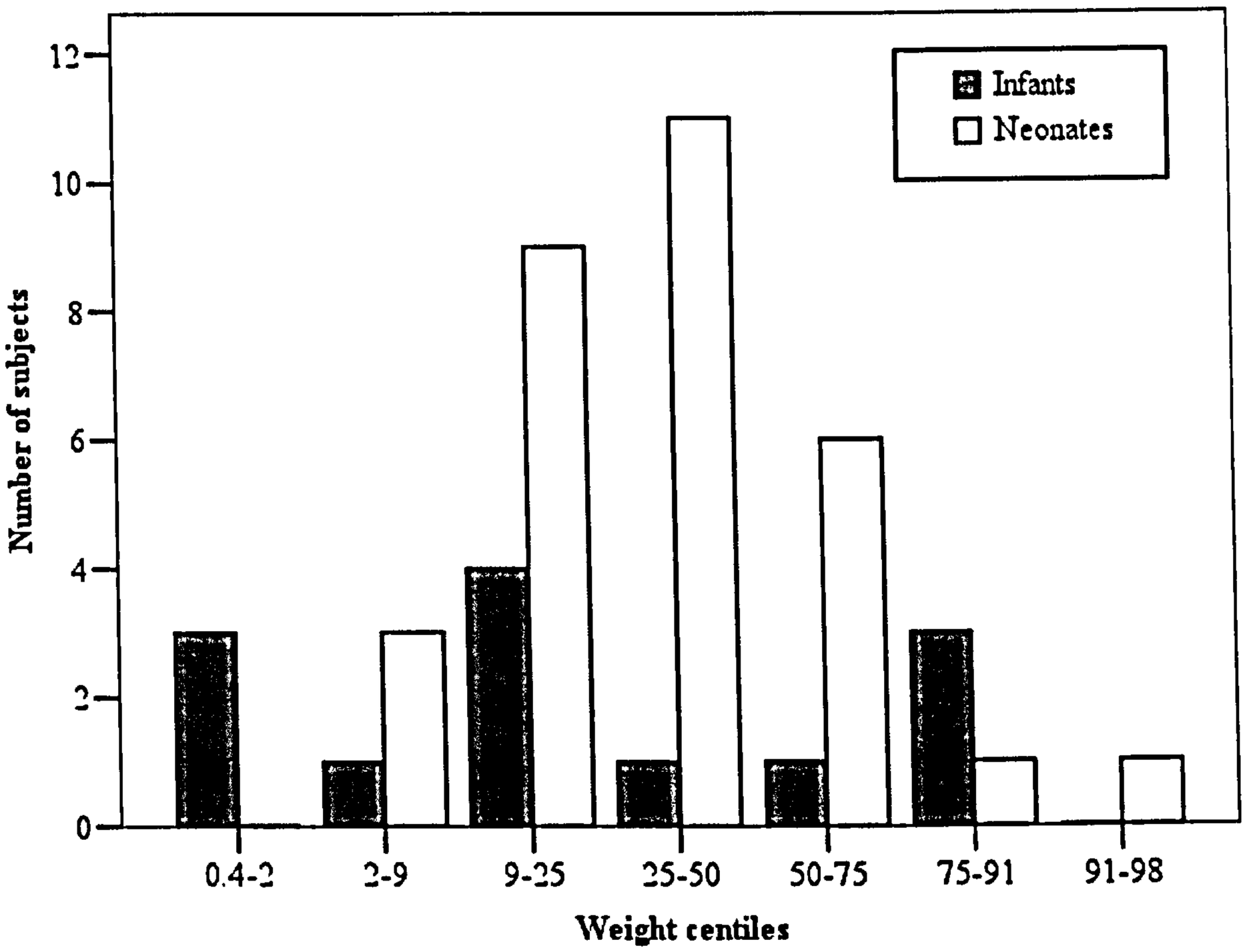

Figure 2 Weight centile distribution of 13 infants (aged 6-8month) and 31 neonates (born at 39-41 weeks of gestation). The weight centiles of the neonates (white bars) have a normal distribution whereas the infants (gray bars) represented a more heterogeneous population.

The subjects with weight within the 25th and 75th centiles were further analysed as shown in the third columns of Table 1 and Table 2. These included 2 infants and 17 neonates. The data of these subjects were representative of the size of an average 6-8 month old infant and a term neonate respectively and will be used for the construction of two paediatric simulator boxes.

3.3 Construction of the paediatric simulator boxes

3.3.1 Aim

To construct mechanical simulator boxes, one for 6 to 8 month old babies and one for neonates, for laboratory experiments for the evaluation of ergonomics in paediatric MAS.

3.3.2 Materials and methods

The main materials used for the construction of the simulator boxes were polystyrene boxes (260mmx190mmx120mm and 230mmx190mmx100mm) with a wall thickness of 40mm and a neoprene sheet (4mm thick). The neoprene sheet is of the same type as those used in standard adult-size MAS training boxes which are commercially available.

Using the data from the previous section, the measurements representative of a 6-8 month old with weight within 25th to 75th centile from 2 infants and those of a term neonate born at 39-41 weeks of gestation with weight within 25th to 75th centile from 17 neonates were used for the construction of each of the simulator box. Two simulator boxes were made according to the measurements as shown in the third columns of Table 1 and Table 2.

The height of the polystyrene box was trimmed to the iliac and abdominal depth data. Cardboard cross bars were placed across the box to provide a slightly dome-shaped surface as well as support. The top was covered with the neoprene sheet trimmed to cover the top of the box and with the abdominal surface delineated by a cut-out piece of paper. Therefore, only the exposed neoprene, in the shape of a hexagon, was available for insertion of MAS instruments (Figure 3). The neonatal

box has surface dimensions of 110mm long and 120mm wide delineated, and the infant box has surface dimensions of 160mm long and 180mm wide delineated.

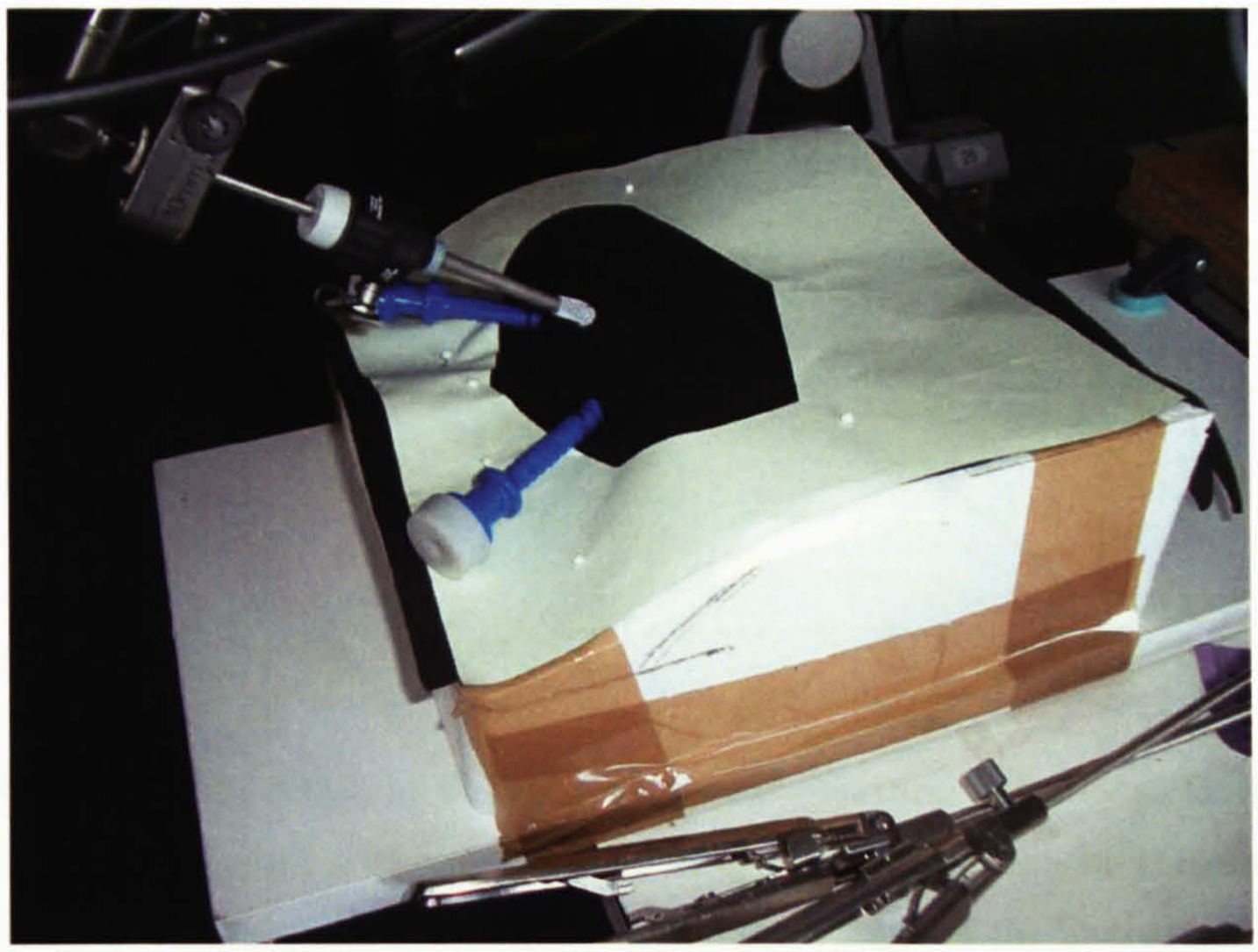

Figure 3 Neonatal simulator box. The polystyrene box was trimmed according to the abdominal anthropometric data. The surface was covered with a neoprene sheet. A piece of paper with a hexagon centre cut out in the centre simulating the abdominal surface of a term neonate.

An Excel (Microsoft, Seattle, USA) datasheet macro was written with input values for the position of the target from the surface (H), the desired manipulation (2θ) and elevation (α) angles (Hanna et al., 1997d). The macro can then be used to calculate the surface distance between the port site and the target. The ideal position of the port site can then be determined by trigonometric calculations. Only the left half of the set-up is shown in Figure 4.

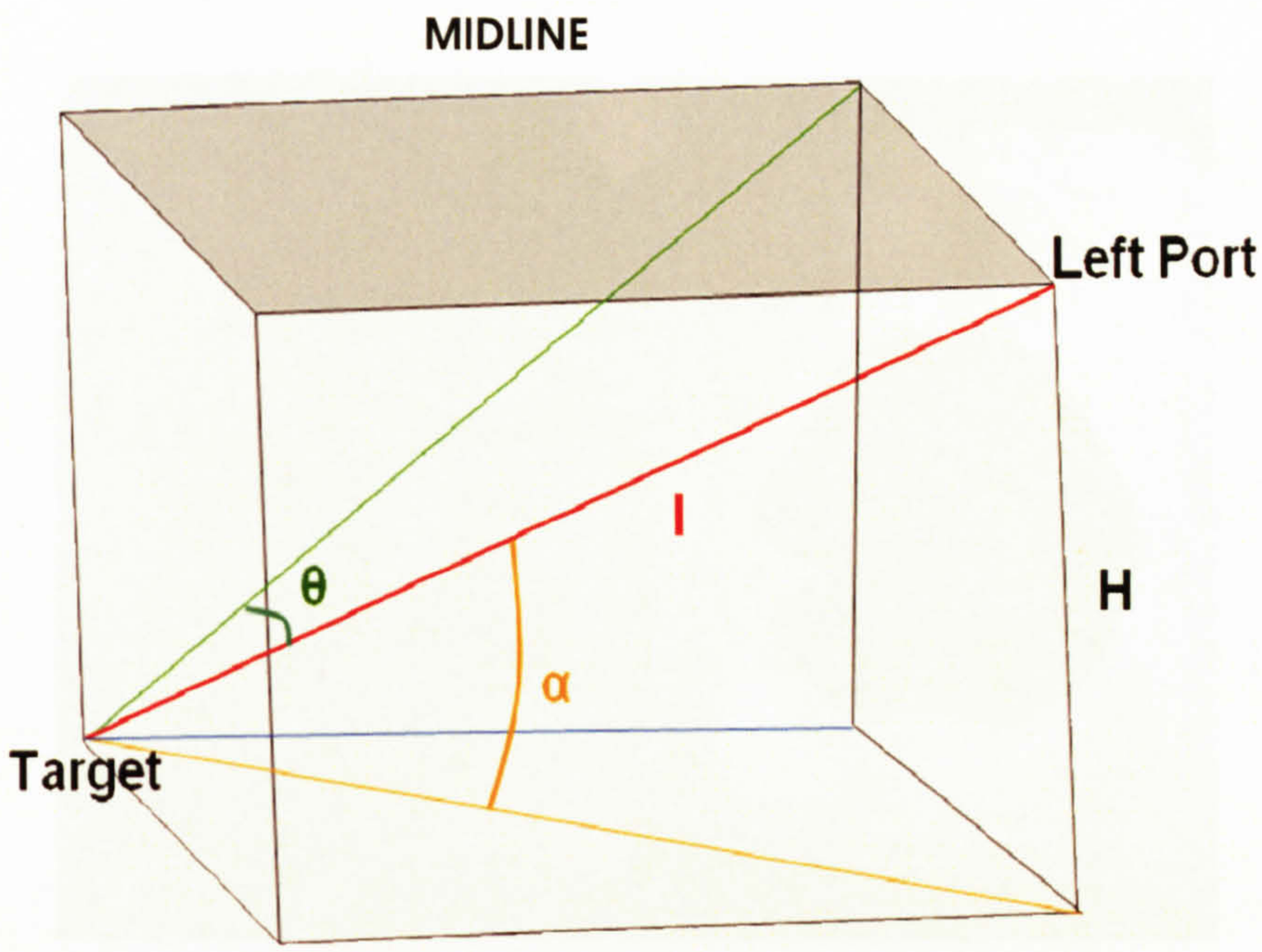

Figure 4 Trigonometric details of the instrument port and target positions. Only the left side is shown. For a given target position, the position of the left port can be calculated from the distance between the surface and the target (H), elevation angle of the instrument (α), and half of the manipulation angle (θ). The distance between the port and target (I) is the intracorporeal length of the instrument.

3.3.3 **Results**

The two boxes constructed were equivalent to the sizes of the abdomen of a 6-8 month old infant and that of a term neonate respectively. MAS ports and instruments can be inserted and small task rigs can be placed inside the boxes for MAS manoeuvres. The boxes are robust enough for repeated use.

The difference in size is more evident when the neonatal and infant simulator boxes are compared with a commercially available MAS simulator box trainer as shown in Figure 5. Preliminary end-user opinion from several surgeons, including two consultant paediatric surgeons, concluded that instrument manipulation within the boxes have similar realistic feel compared to operating within the operative space of infants (Figure 6).

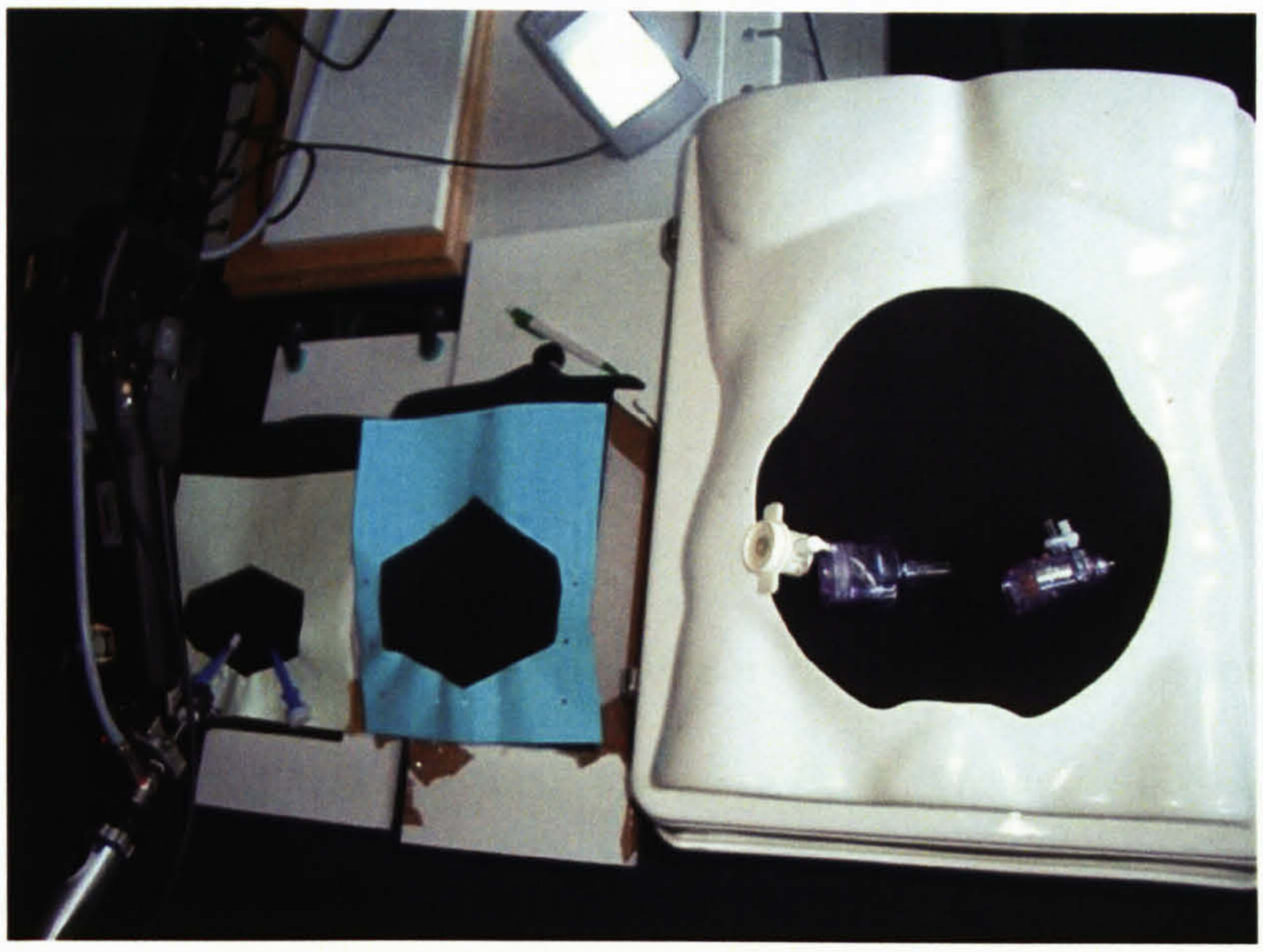

Figure 5 Side by side comparison of the neonatal simulator box (left), infant simulator box (centre) and standard MAS trainer box of the size of an adult (right).

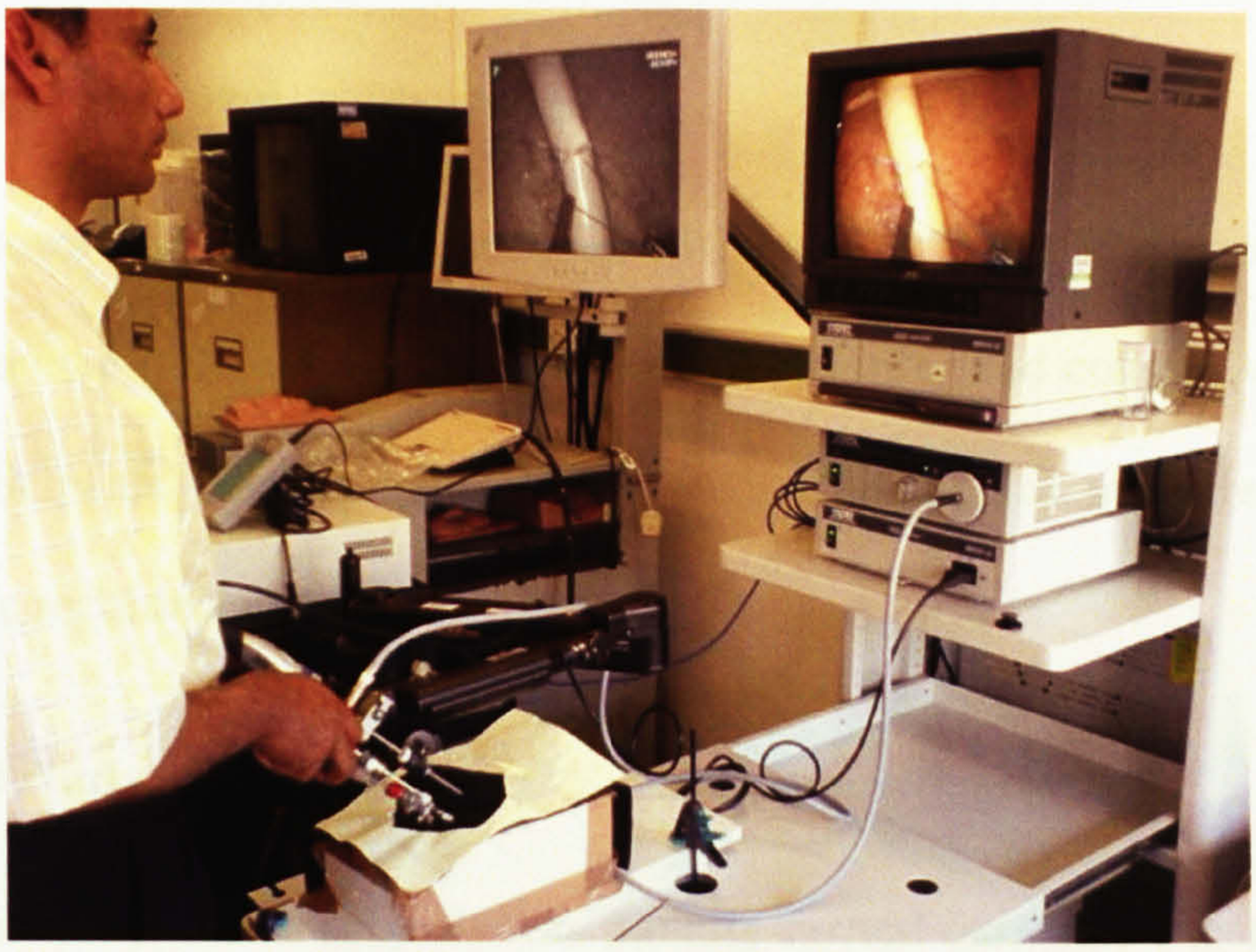

Figure 6 End user testing of the neonatal simulator box by a surgeon. Anastomosis on inanimate bowel being performed.

3.4 Influence of instrument size on task performance in paediatric intracorporeal knot tying

3.4.1 Introduction

3.4.2 Aim

This study aims to investigate the influence of instrument size on paediatric intracorporeal knot tying within a small operative field. The study is designed to test the hypothesis that the performance of intracorporeal knot tying, in terms of the impact on the surgeon and the quality of the task, improves when the smaller paediatric needle-holders are used.

3.4.3 Methods

3.4.3.1 Ethical approval

Ethical approval for the study was granted by the St Mary's Hospital Research Ethics Committee (reference no. 05/Q0403/31) and informed consent was obtained from all participants. Demographic details and anthropometric measurements of the subjects were recorded.

3.4.3.2 Pilot study

A small pilot study with 6 subjects was initially carried out. The execution time of tying intracorporeal knots using needle holders of different sizes was measured. The larger infant paediatric simulator box with surface dimensions of 160mm long and 180mm wide delineated on the neoprene surface was used. Its size was equivalent to the abdomen of a 6-8 month old infant. Preliminary results showed a shorter execution time and the participants reported more discomfort when using the larger

instruments. A newly acquired EMG system was also tested. Based on the results of the pilot study and review of the literature, the main study was designed and carried out as described below.

3.4.3.3 **Subjects**

Sixteen surgeons of various levels of experience (specialist registrar to consultant level) were invited to participate in the study. All subjects have completed their basic surgical training and obtained membership or fellowship from one of the Royal Colleges of Surgeons in the UK or equivalent. All subjects have previously had laboratory intracorporeal knot tying skills training and experience in MAS as a primary surgeon and/or as an assistant. Individual instructional coaching were given to subjects with no or minimal prior clinical experience in intracorporeal knot tying in patients.

3.4.3.4 **Task**

Endoscopic intracorporeal knot tying was selected as the standard task because it is an important advanced skill essential for tissue approximation in complex procedures where automated devices such as staplers cannot be used. All knots tied in this study were surgeon's knots with 2=1=1 configuration. The task rig consisted of a halved synthetic skin pad (model 00074; Limbs and Things, Bristol, UK) measuring 65mm wide x 145mm long x 15mm thick with a longitudinal groove of 145mm x 25mm x 12mm in the back foam where a plastic tube with a diameter of 25mm and 145mm in length was housed. The pre-inserted 3/0 silk suture (Sofsilk; USSC, Norwalk, CT, USA) through the 3mm skin was passed around the plastic tube and exited through the adjacent skin at a distance of 6mm from the entry point. Equal lengths of 40mm of the suture protruded from the skin surface at both ends for the tying task.

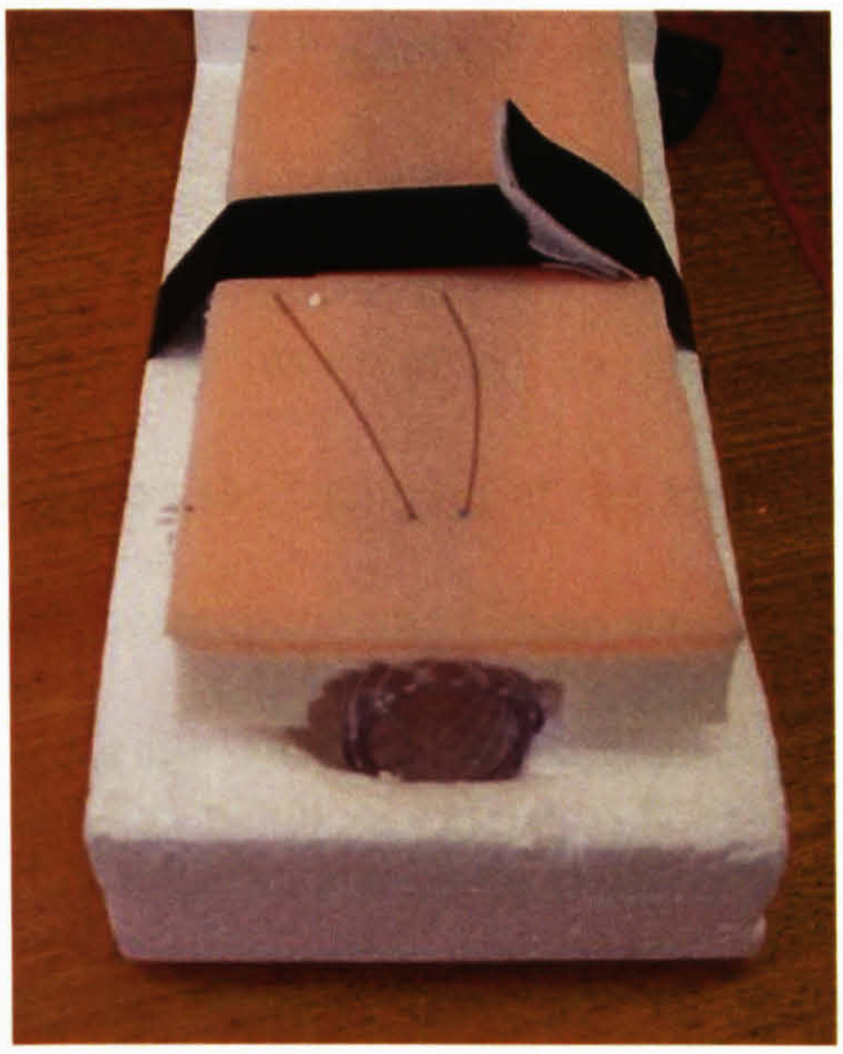

Figure 7 Task rig with a 3/0 silk suture mounted.

The assembled task rig together with a polystyrene base (Figure 7) was stablised inside the neonatal simulator box. The smaller box was used to increase the challenge of the task. This simulator box has surface dimensions of 110mm long and 120mm wide delineated on a neoprene sheet equivalent to the abdomen of a term neonate and the internal midline depth was 20-30mm. Vertical movement (<10mm) was possible as the neoprene sheet can be gently stretched.

3.4.3.5 **Procedure**

The standardised task consisted of tying intracorporeal knots using paired commercially available needle-holders (Carb-Bite 630-250 and Carb-Bite 600-200; Jarit, Tuttlingen, Germany). They have shaft diameters of 3.5mm and 5mm, lengths of 240mm and 325mm, jaw sizes of 10mm and 15mm, and weights of 82g and 106g respectively. They have very similar mechanical constructions, especially in the handle and ratchet. The smaller pair of instruments will be described as paediatric needle-holders and the larger pair of instruments as adult needle-holders. Their use

in clinical practice is obviously not necessarily limited to the described age-related population.

Verbal and written instructions were given to all participants and they were specifically asked to emphasise the tightness of the knots tied rather than the speed of performance. The tasks were performed over two days, each started with two "warm-up" knots using the adult needle-holders in an adult simulator box. On the first day, an additional 10 familarisation knots were performed in the adult box and the standardised technique was ensured. On each day, 10 experimental knots were performed in the neonatal box with one pair of needle-holders followed by another 10 knots with the other pair of needle-holders. The order of instruments to be used was randomised.

Surface electromyography (EMG) was measured on each subject using a 16-channel EMG system (Bagnoli, Delsys, Boston, MA, USA). Fourteen differential electrodes (DE- 2.1, Delsys) with parallel-bar contacts were attached in the beginning of each experimental day and remained there for the duration of the experiment. The ground electrode was placed over the bony prominence of the ulna olecranon. The muscle groups measured were trapezius, deltoid, biceps, triceps, forearm flexors, forearm extensors and first dorsal interosseous muscles on both upper limbs (Figure 8). The placement of the EMG electrodes (Zipp, 1982) were as follows:

Trapezius – half way between the spine of the 7^{th} cervical vertebra and the acromion; Deltoid – quarter way from the acromion to the lateral epicondyle of the humerus; Biceps – two-thirds way from the acromion to the tendon of the biceps muscle in the cubital fossa; Triceps – two-thirds way from the acromion to the olecranon; Forearm flexors – quarter way from the medial epicondyle of the humerus to the skin

fold at the wrist; Forearm extensors – quarter way from the lateral epicondyle of the humerus to the midpoint between the styloid processes of radius and ulna; First dorsal interosseous muscle – half way between base of the 1st metacarpal bone and the base of the proximal phalanx of the index finger.

Figure 8 External view of the experimental set-up. The arrows indicate the EMG electrodes placed over the first dorsal interosseous muscles on both sides.

3.4.3.6 Video-endoscopic equipment and control measures

A video-endoscopic training stack was used which consisted of an 18-inch flat surgical display (National display systems, CA, USA) on an adjustable arm, an arc-lamp source (Xenon nova model 20131520, Karl Storz, Germany) and a digital camera system (Image 1 model 22200020, Karl Storz). Optimum ergonomic set-up (Hanna et al., 1997c, Hanna et al., 1997d, Hanna et al., 1998b) was ensured by

placing the flat screen one metre in front of the subject or just below the eye level and adjusting the table height such that the handles were at 100-150mm below elbow height from the floor (Berquer et al., 2002). In the experimental sessions, a paediatric 4mm forward-oblique 30° endoscope (model 26009BA, Karl Storz) held by an endoscope clamp holder was placed at a distance of 20mm from the target and the optical axis to target view angle was 90°. The manipulation angle between the instruments was set at 60° and an elevation angle of 45°. The azimuth angles between the endoscope and instruments on either side were equal. The endoscopic set-up provided a 40mm field of view (Figure 9). The positions were checked before each session using a calibration grid.

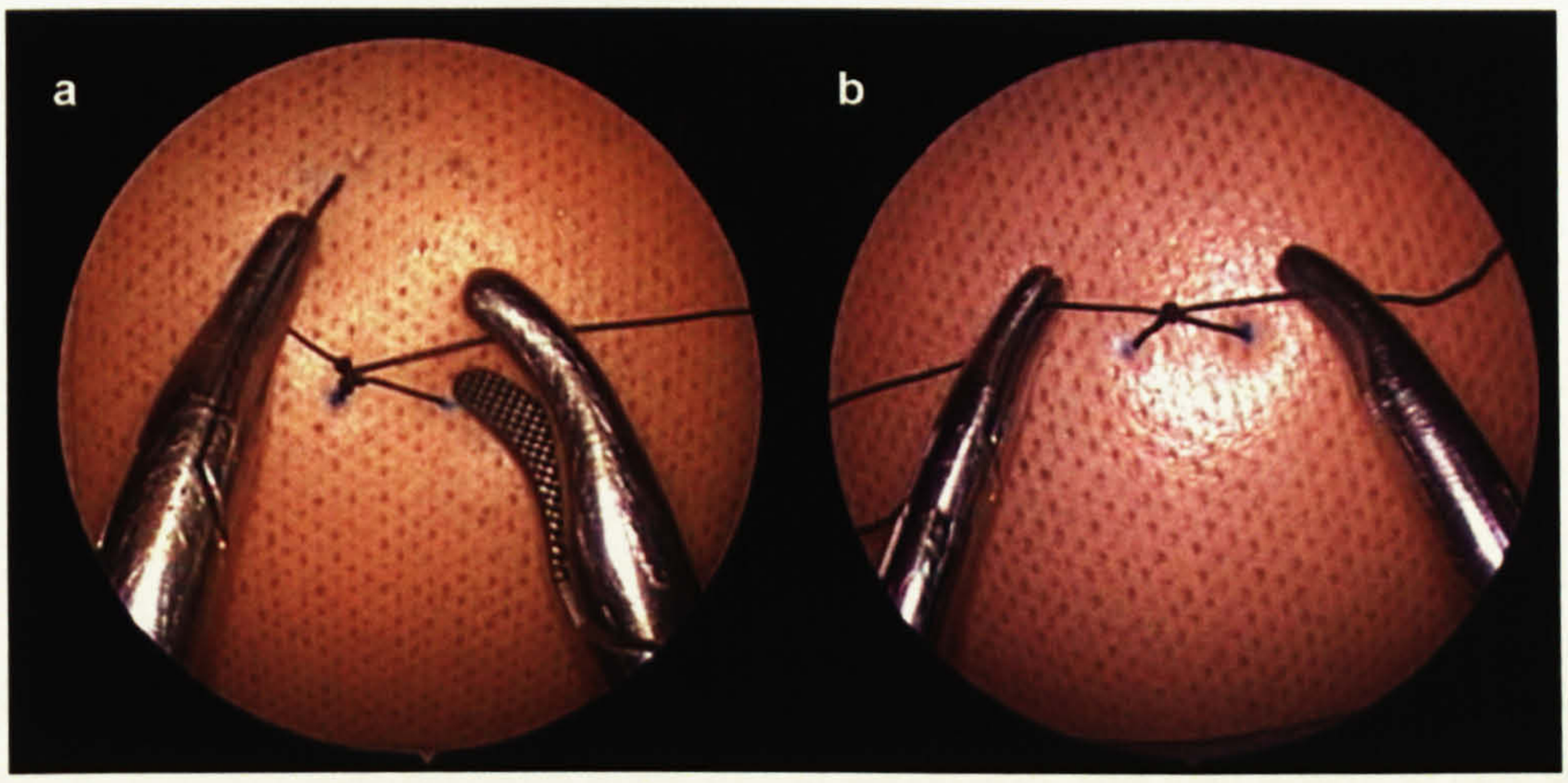

Figure 9 Endoscopic view of the experimental task in intracorporeal knot tying, a) using the adult needle-holders and b) using the paediatric needle-holders.

3.4.3.7 **Measurements**

3.4.3.7.1 *Knot Quality*

The knotted suture was removed from the task rig by dividing the suture over the plastic tube opposite the tied knot. The ends at the tied ends were trimmed to 10mm

before the knots were tested by a tensiometer (Inspec 2200, Instron, Canton, MA, USA) using specifically designed grips (Mini capstan cord and yarn grips, model 2200-302, Instron). The long ends were distracted at a distraction speed of 50mm/min. The raw data were analysed using the Instron Series IX software (version 8.34, Instron) (Figure 10).

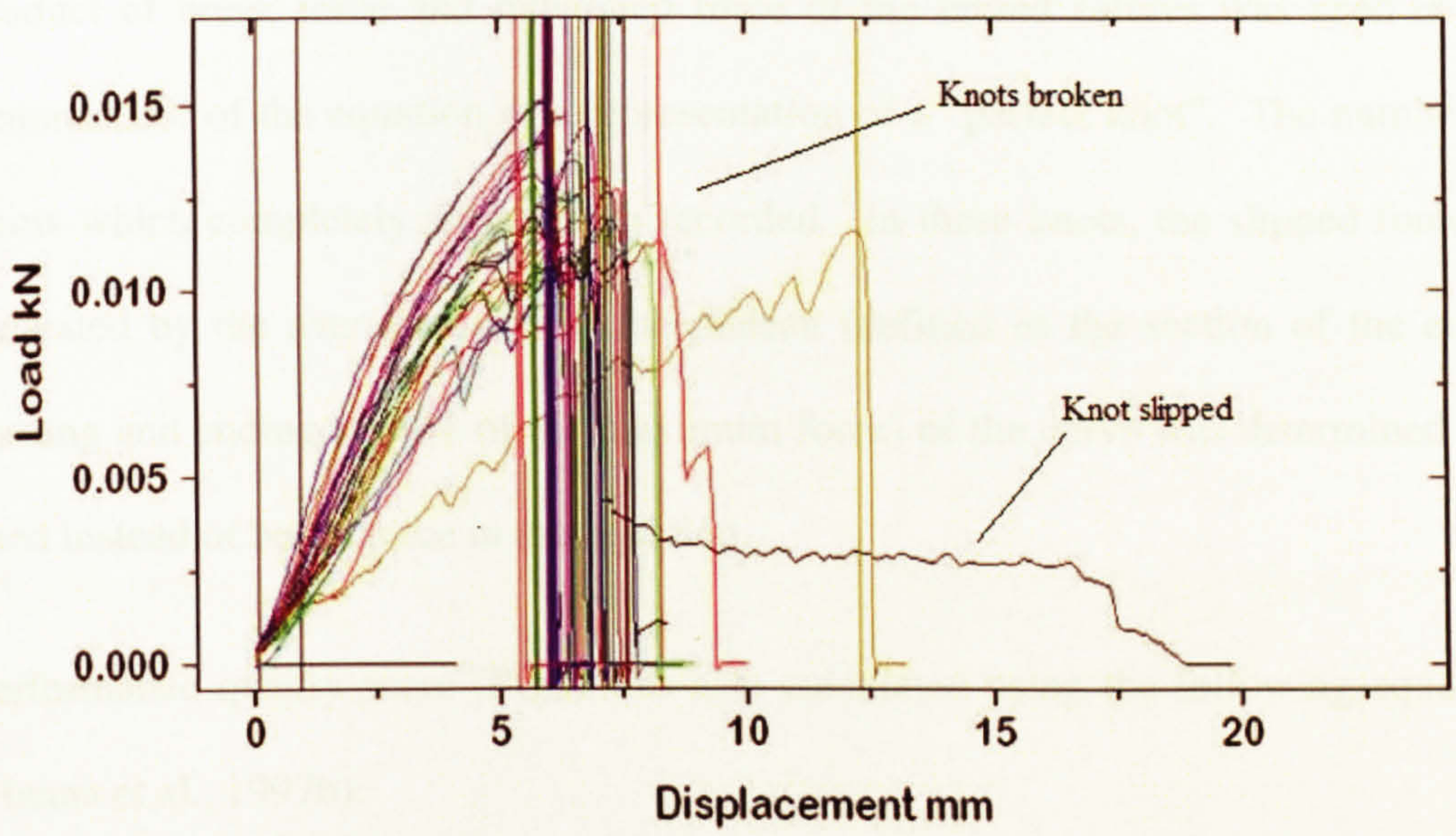

Figure 10 Load-displacement curves from the tensiometry software during knot testing. Nearly all of the knots in this batch broke during distraction. One knot slipped as indicated by the long flat curve.

Knot quality score (KQS) was calculated using the following equation (Hanna et al., 1997b):

$$KQS = \frac{Break\ force_{knot}\ (or\ slipped\ force_{knot}) \times Integrated\ force_{knot}}{Break\ force_{untied\ suture} \times Integrated\ force_{untied\ suture}}$$

In addition to the maximum load required to break the knot, i.e. the break force, the remodelling characteristics of the knot was also considered by calculating the integrated force. The integrated force represented the average force of the initial displacement when the tensiometer started to pull the suture apart. Untied sutures from the same silk batches were used to determine the initial displacement which was calculated as the mean displacement at break force (6.60mm) minus twice the standard deviation (1.10mm) of the untied sutures (ie 4.40mm). The mathematical product of break force and integrated force of the untied sutures was used in the denominator of the equation as a representation of a "perfect knot". The number of knots which completely slipped was recorded. In these knots, the slipped force as indicated by the average force of the plateau (defined as the section of the curve starting and ending at 50% of the maximum force) of the curve was determined and used instead of break force in the equation.

Performance quality score (PQS) was also calculated using the following equation (Hanna et al., 1997b):

$$PQS = \frac{KQS}{normalised\ \ execution\ time}$$

The normalised execution time was obtained by dividing the execution times of each subject by the mean execution time of the whole group.

3.4.3.7.2 *Analysis on muscle workload*

The EMG signals were captured with a gain of 1000 V/V into a personal computer via a 16-bit analogue to digital conversion card at a sampling rate of 1000Hz. The signal was processed using a dedicated software (EMGworks version 3.1, Delsys) and the mean of the RMS of the raw EMG data was calculated. Normalisation of the

data was necessary to allow intra- and inter- subject comparisons between sessions (Kamen and Caldwell, 1996) as discussed in section 2.2.3.1. The mean dynamic normalisation method was used where the experimental EMG recordings were calculated relative to the mean EMG during the dynamic tasks. This method does not provide information on how much activation is required to do a task using a fixed reference point but allows relative comparisons which is used as an outcome measure in this study.

3.4.3.7.3 *Self-reporting discomfort questionnaire*

After every 10 experimental knots, the subject filled in a questionnaire to indicate the amount of discomfort experienced in the upper limbs (above or below the elbow joint) on a visual analogue scale (VAS) using a 100mm line where zero represents no discomfort whereas 100mm represents maximal discomfort. At the end of each experimental day, the subject indicated his/her overall instrument preference for the task done in the neonatal box.

3.4.3.8 **Outcome measures**

Execution time in seconds - as the interval between grasping the suture to the completion of the knot.

Wrap length in mm - as an indication of wrap tightness around the plastic tube.

Knot quality score (KQS) - as an index of task quality.

Performance quality score (PQS) - as a measure of proficiency, taking into consideration the KQS and the execution time.

Normalised EMG – as a measure of upper limb muscular recruitment.

Subjective scoring – as an indication of discomfort whilst using the instruments and individual instrument preference.

3.4.3.9 **Statistical analysis**

Statistical analysis was performed using SPSS software (version 14.0, Chicago, IL, USA). Wilcoxon signed rank test and Fisher's exact test were used as appropriate. Significance level was set at 5% level.

3.4.4 **Results**

3.4.4.1 **Surgeons' characteristics**

The subjects represented a wide range of middle-grade surgeons - from year 1 specialist registrar to consultant (age range 29-40 years) in general surgery and paediatric surgery. There were two females and two left-handed surgeons respectively in the group. The self-reported experience as primary surgeon in MAS were <10 cases in five surgeons, 10-100 cases in seven surgeons and >100 cases in four surgeons.

3.4.4.2 **Task performance**

Six hundred and thirty eight experimental knots were completed in the neonatal box. KQS were determined in 627 knots and in 11 knots, KQS could not be calculated due to technical problems. During testing by the tensiometer, the proportion of knots slipped completely were 18.7% when using paediatric needle-holders and 21.8% when using adult needle-holders (p=0.322). Table 3 shows the task outcomes. The execution time was significantly shorter when paediatric needle-holders were used. The wrap tightness and KQS were not statistically different between the two groups.

PQS, which was dependent on execution time, was higher with the smaller instruments.

	Paediatric needle-holders	Adult needle-holders	p value
Execution time	94s (49)	103s (54)	0.014
Wrap tightness	86mm (2)	86mm (3)	0.297
KQS	0.271 (0.184)	0.260 (0.225)	0.444
PQS	0.301 (0.244)	0.242 (0.276)	0.031

Table 3 Median (interquartile range) of outcome measures in paediatric intracorporeal knot tying. Wilcoxon signed rank test (2-tailed).

3.4.4.3 Impact to surgeons

The normalised EMG values were higher in all upper limb muscle groups when the adult needle-holders were used. All except left forearm extensors showed statistical differences as shown in Table 4 and Table 5. Thirteen surgeons preferred using the paediatric needle-holders and two surgeons preferred using the adult needle-holders. One surgeon preferred the smaller instrument on day one but the adult instrument on day two. The discomfort VAS score was lower in the right forearm and hand when the paediatric instruments were used which indicated less discomfort (p=0.011). Statistically significant difference in VAS was not seen in other areas of the upper limbs as shown in Table 6.

	Paediatric needle-holders	Adult needle-holders	P value
Trapezius	0.932 (0.213)	1.128 (0.258)	<0.001
Deltoid	0.810 (0.208)	1.079 (0.277)	<0.001
Biceps	0.948 (0.214)	1.061 (0.219)	<0.001
Triceps	0.902 (0.163)	0.988 (0.173)	<0.001
Forearm flexor	0.945 (0.134)	1.001 (0.156)	<0.001
Forearm extensor	0.973 (0.181)	0.982 (0.178)	0.460
1st dorsal interosseous	0.901 (0.227)	1.004 (0.266)	<0.001

Table 4 Median (interquartile range) of normalised EMG left upper limb muscles in paediatric intracorporeal knot tying. Wilcoxon signed rank test (2-tailed).

	Paediatric needle-holders	Adult needle-holders	P value
Trapezius	0.937 (0.199)	1.114 (0.188)	<0.001
Deltoid	0.859 (0.187)	1.077 (0.202)	<0.001
Biceps	0.900 (0.219)	1.034 (0.257)	<0.001
Triceps	0.918 (0.121)	1.000 (0.135)	<0.001
Forearm flexor	0.931 (0.156)	1.006 (0.147)	<0.001
Forearm extensor	0.985 (0.138)	0.996 (0.152)	0.032
1st dorsal interosseous	0.899 (0.232)	0.983 (0.251)	<0.001

Table 5 Median (interquartile range) of normalised EMG of right upper limb muscles in paediatric intracorporeal knot tying. Wilcoxon signed rank test (2-tailed).

	Paediatric needle-holders	Adult needle-holders	P value
Right arm (above elbow)	9mm (45)	15mm (35)	0.244
Right (below elbow)	12mm (32)	29mm (47)	0.011
Left (above elbow)	10mm (37)	9mm (46)	0.194
Left (below elbow)	22mm (37)	24mm (46)	0.150

Table 6 Visual analogue scale score for discomfort in upper limbs in paediatric intracorporeal knot tying where zero represents no discomfort whereas 100mm represents maximal discomfort. Wilcoxon signed rank test (2-tailed).

3.5 Discussion

3.5.1 Measurements and construction of the boxes

The objective of constructing simulator boxes of the size of a 6-month old infant and that of a term neonate for ergonomic evaluations is fulfilled. The surface available for ports insertion and instrument manipulation is limited because of the lack of space as in real patients in paediatric MAS. As all commercially available MAS training boxes were designed for adult surgical practice, there were no suitable models appropriate for paediatric MAS ergonomic research. We therefore set out to construct suitable simulator boxes relevant to paediatric MAS using appropriate anthropometric data. Our boxes were relatively easy and cheap to construct fulfilling the financial and time constraints of the project. However, there are some limitations with this design.

The two boxes only represented the respective average size of the two age groups as it was impractical to have boxes for all sizes of infants and children which paediatric surgeons encounter, which could be from less than 1kg to more than 70 kg.

The variation in the size of patients in paediatric surgery is much greater than in adult surgery due to the rapid growth in infancy and childhood. The difference is particularly marked during the neonatal period, especially in premature babies. The challenge of performing paediatric MAS in these patients is higher because of the limited space.

Reference growth charts are widely used in paediatric practice but references are usually limited to weight, height and head circumference. Existing abdominal anthropometric databases on children, especially on infants are limited. These

databases were mostly used in the automobile industry for car safety design such as car seats. Limited data are also available in the textile industries for clothing design. In the measurements we obtained, the weight centile of the neonates has a normal distribution as they were from a homogenous population. In contrast, the out-patients infants were more heterogeneous which in part was related to an existing past medical history, which led to the attendance at the out-patients department. Although the infants who were known to have torso abnormalities were excluded at the outset, the subjects recruited in the out-patients department nevertheless still have a medical condition which were often associated with poor weight gain. Therefore, most of them were excluded in subsequent subgroup analysis and even for those recruited were mostly below 25^{th} centile in weight. Data from 2 infants aged 6-8 months and have weight between 25^{th} and 75^{th} centile were used.

The measurements of the 17 neonates would represent an average term neonate. As precise measurements were not necessary for the construction of the simulator boxes, these data were sufficient for the purposes of our experiments in this thesis. The neonatal box which represented an average term neonate would be valid for ergonomic experiments related to paediatric MAS.

Only the external abdominal anthropometric measurements are considered and the internal dimensions can only be estimated. In MAS, pneumoperitoneum provides the effective operative workspace. In an infant, this is usually in a dome-shape rather than the relatively flat surface as in the boxes constructed. Furthermore, the presence of intra-abdominal organs in the abdomen or moving lung in the thorax in a live patient would give a very different operative field compared to having materials placed within an essentially empty space for task performance evaluations. For

sophisticated evaluation of complex tasks, our boxes are too simplistic and inadequate though are still more comparable than using a standard adult size MAS trainer box (Figure 5). For the purpose of the ergonomic experiments in this thesis which primarily involve tasks such as simple transfer and knot tying, the present construction was sufficient to highlight the limited operative space available for endoscopic manoeuvres. More sophisticated models such as that reconstructed from sacrificed rabbits have been reported (Kirlum et al., 2005a, Kirlum et al., 2005b). The same group also used live animals for training purposes which of course would incur a much higher cost (Heinrich et al., 2006). A comparative anthropometric study between human and animal would be necessary to ensure validity of these models.

We have initially planned to obtain measurements from live MAS operations. However, the caseload for small infants was much less than initially predicted by the consultant paediatric surgeon who has a special interest in MAS. This also reflects the fact that MAS is still not widely used in small infants due to the perceived difficulties in these small patients and the limited availability of equipment.

3.5.2 **Influence of instrument size**

The current study has shown that intra-corporeal knot tying within a limited space using adult needle-holders was slower to perform and required more muscular recruitment than using paediatric needle-holders. The knot quality, however, was not compromised, which indicates the ability of surgeons to maintain task quality under unfavourable conditions but at the expense of execution time and muscular recruitment. However, during the performance of longer and more complex procedures, task quality may be affected when fatigue sets in (Cuschieri, 1995).

Optimising the choice of instruments is an essential step towards improved theatre ergonomics to enhance overall safety as well as the comfort of the surgeon. As paediatric surgeons become more experienced in MAS, procedures for complicated congenital anomalies are now being done even in the smallest patients (Holcomb et al., 2005, Martinez-Ferro et al., 2005, Rothenberg, 2002, Rothenberg et al., 1998). Although some instrument companies have responded to the need for an improved range of paediatric instruments, the commercial market still favours the adult range of instruments. MAS in infants poses additional ergonomic problems compared to that of adult patients. The surface available for insertion of instruments and the internal operative workspace for instrument manoeuvre are limited. The viewing endoscope needs to be placed at a short distance to the target thereby limiting the field of view. As a result, the tips of the operating instruments can move out of sight easily and can potentially cause inadvertent injuries.

The repeated measures design used in this study has allowed for the individual differences between the subjects (e.g. operative experience, gender and handedness) as they all performed the same tasks using the 2 sets of needle-holders to compare. The order effect was minimised by randomisation of the sequence of the needle-holders used. The needle-holders used in this study have identical handle mechanisms for comparisons. The main differences between the instruments are in weight, jaw size, shaft diameter and length. The weight difference of 20g is negligible when supported at the fulcrum. The small tips of paediatric instruments occupy less space and would allow better viewing and more freedom in movements within the limited operative field. The paediatric needle-holders are not only smaller in diameter but also shorter in length. Although it is possible to make alternations to the instruments (e.g. shorten the adult needle-holders), we decided to use "off-the-

shelf" instruments so that the results can be directly applied in clinical practice. The increased intra-corporeal to extra-corporeal shaft ratio (i.e. more shaft inside) has been shown to improve task performance, especially when the ratio was 1:1 to 2:1 (Emam et al., 2000). In the neonatal box, the ratio is still unfavourable even when paediatric instruments are used as there is still more shaft outside and the situation is worse with the longer adult instruments. The longer external shaft length requires the surgeon to "row" more to achieve the same internal movement compared to that obtained with a shorter instrument. We believe this was the reason for the longer execution time and higher normalised EMG values indicating more muscular recruitment in the subjects when the adult instruments were used.

However, using smaller size instruments needs special care in performing surgical tasks. Tremors and imprecise movements will be exaggerated as the small extracorporeal hand movements will be translated into relatively larger movements because of the increased intra-corporeal to extra-corporeal shaft ratio and the magnification of the operative field. In addition, the risk of puncture by inadvertent movements or damage by excessive grabbing forces is higher due to the small surface area at the tip of fine instruments. Nevertheless, when operating in infants and other small cavities (e.g. arthroscopy), we would recommend the use of smaller instruments.

4 VISUAL ERGONOMIC FACTORS

4.1 Introduction

As discussed in the previous section, the visual ergonomic constraints of the endoscopic operative field, in particular the lack of depth cues, is a major hindrance for many surgeons performing MAS. A simple method to produce additional depth cues is to introduce an illumination source at an angle to the axis of the imaging optics (Hanna et al., 2002). However, the small size of the paediatric operative field in neonates and infants precludes the use of another standard endoscope as the bulky light and camera cables would clutter the limited external operative space. Recent advances in illumination technologies using solid state light (SSL) such as light emitting diodes (LED) have attracted novel applications. Collaborating with other research groups in Imperial College London, the author sought to use the LED as a shadow producing illumination source to produce depth cues in MAS. Paediatric MAS is an ideal platform on which to test these new illumination technologies, which are still relatively not yet powerful but would sufficient for the smaller size of the paediatric operative field.

Adequate illumination of the operative field is essential for the safe and efficient performance of MAS. Historically, the development of MAS was initially hindered by insufficient illumination (Lau et al., 1997) until the development of light transmission by fibre-optics which marked the beginning of the exponential growth of MAS. The general structure of the MAS illumination system has since remained unchanged. This consists of an external light fountain where an arc-lamp light source is housed. Light is transmitted via a light cable and coupled to the light post of the viewing endoscope where the light emits from the distal end onto the operative field. As discussed in section 2.4.1.6.2, current illumination systems have several

limitations including low energy efficiency, high replacement costs, the need for it to be externally placed with the requirement for a bulky light cable for light transmission, and the absence of shadows due to the co-axial arrangement of the fibre-optics alongside with the imaging optics.

The aims of this section of the study are two-fold:

(1) to develop an alternative illumination system in MAS using the LED technology and to investigate its characteristics and feasibility for future use in MAS.

(2) To evaluate the role of static shadows in depth perception and the visual perception of moving shadows in the endoscopic operative field.

In this chapter, the development of a novel illumination system for MAS using a solid-state semiconductor lighting device, the LED endo-illuminator, is described. User testing of the LED endo-illuminator as an additional light source for shadow producing illumination is explained. Its characteristics including illumination intensity, stability, uniformity and shadow sharpness are further examined. The visual perception under illumination from the endo-illuminator and standard arc-lamp endoscopic conditions, including an investigation into the role of static and moving shadows in the endoscopic operative field, are examined.

4.2 Solid-state semiconductors

Semiconductors are solid state materials that can conduct an electrical current better than insulators but not as good as conductors. They are made up of elemental materials (e.g. silicon), compound materials (e.g. gallium arsenide), or alloys (e.g. aluminium gallium arsenide). These materials are classified according to the periodic table groups of their constituent atoms. Doping refers to the process of intentionally impregnating impurities into an extremely pure semiconductor in order to change its electrical properties. Semiconductors doped with dopant that gives out electrons are n-type semiconductors, whereas those doped with dopant that accepts electrons are p-type semiconductors. A diode consists of a piece of n-type and a piece of p-type semiconductor joined together to form a junction. It requires a minimum voltage for a current to pass through in one direction only.

4.2.1 Light emitting diodes

Light emitting diodes (LEDs) are special diodes that give out electromagnetic radiation when an electrical current passes through them.

Incandescence or heat glow is the visible electromagnetic radiation emitted by a material heated to temperatures above 750°C. By contrast, electroluminescence is the conversion from electrical potential energy to electromagnetic energy when light is emitted from a solid state material (Schubert, 2006). This phenomenon was first described in 1907 when light was observed to be emitting from a silicon carbide crystallite when it was in contact with metal electrodes (Round, 1907). At that time, the material properties were poorly controlled and the emission process was not well understood.

It was not until the development of novel III-V semiconductors which became instrumental in the development of modern LED technology. These included gallium arsenide (GaAs) and aluminium gallium arsenide (AlGaAs) which were components of the infrared and red LEDs (Schubert, 2006). In the 1960s further development was achieved with gallium phosphide (GaP) and gallium arsenide phosphide (GaAsP) LEDs doped with optically active impurities such as nitrogen. By the 1970's, LEDs producing red and green light have been used in various displays such as wrist watches and pocket calculators. However, their use was limited by two factors: firstly, the displays could not be read under bright light as the LEDs were too dim; and secondly, the power consumption was too high (Schubert, 2006).

Significant developments in LED technology occurred in the 1990s when Shuji Nakamura, who was working in the Nichia Chemical Industries Corporation in Japan, developed high quality gallium nitride (GaN) and indium gallium nitride (InGaN) semiconductors leading to the production of blue LED and blue laser (Nakamura et al., 1996). By combining blue LEDs with existing red and green LEDs, white light can be produced which is useful for common illumination purposes. Alternatively, a blue LED can be covered by a yellowish phosphor coating consisting of cerium doped yttrium aluminium oxide (Ce^{3+}:$Y_3Al_5O_{12}$), also known as cerium-doped yttrium aluminium garnet (Ce^{3+}:YAG), which converts a portion of the emitted blue light to red and green light, resulting in a broad spectrum white light. Nichia has also produced an InGaN laser diode which lases in the blue-violet region of the spectrum.

4.2.2 General use

Rapid progress in the research and development of solid-state lighting (SSL) has resulted in the advent of LED for many general lighting applications. The benefit of SSL to the environment is enormous. The US Department of Energy estimated that by 2025, SSL could cut the US energy consumption by 29%, reduce the amount of electricity used for lighting globally by 50% and also eliminate 258 million metric tons of carbon emission (US Department of Energy, 2003).

The efficiency of electrical to light conversion, known as the overall luminous efficacy, is measured in lumen per watt (lm/W). The white LEDs currently available can produce 45-60 lm/W and are particularly useful in battery-powered devices. By comparison, typical incandescent lamp can only produce 10-20 lm/W whereas a florescent lamp can produce 60 lm/W. The xenon arc-lamp has an overall lumen efficacy of 30 lm/W (Schuda, 1998).

The use of LED is ubiquitous, including mobile phones, TV displays, torches, traffic lights, automobile headlights. LED devices are commercially available and are mechanically robust. They usually have an epoxy resin plastic lens to encase the tiny illuminating semiconductor chip, which is around $1mm^2$ in size. High power white LEDs are readily available at a low cost of less than US$10 each and have a long life-span of over 10,000-100,000 hours. Their relatively high electrical efficiency, coupled with low heat production, rugged long life and compact size make LEDs an ideal light source for MAS.

4.2.3 **Surgical use**

The widespread applications of LEDs have led to their use in the operating room in various forms, such as the capsule endoscope for close-range illumination of mucosal surfaces (Iddan et al., 2000) and the new generation of main operating lights, using 184 LEDs to create 160,000 lux of illumination (Anonymous, 2006a). Research work has also been done on LEDs integrated into medical goggles worn by surgeons to provide illumination in open surgery (Shimada et al., 2001).

4.3 The LED endo-illuminator

A novel endoscopic illumination rod for MAS was developed in conjunction with other research groups within Imperial College London, namely the Photonics Group (led by Dr Mark Neil) of the Department of Physics and the Surgical Graphics and Computing Group (led by Dr Fernando Bello) of the Department of Biosurgery and Surgical Technology.

4.3.1 Aims

The aim of this part of the project was to develop a working prototype for endoscopic illumination using white LEDs that are currently available.

4.3.2 Methods

4.3.2.1 Design considerations

The new endoscopic illumination system was designed to fulfill the following requirements:

i) To provide illumination to the whole endoscopic workspace;

ii) To act as a separate light source to cast shadows without clattering cables;

iii) To be powered by a convenient and inexpensive power supply; and

iv) To be easy and cheap to produce.

4.3.2.2 Method of light delivery to target

There are three possible routes to transmit light from a novel non-arc lamp source to the target endoscopic operative workspace. The first method is by using the existing illumination fibre-optics of the endoscope as in conventional endoscopic surgery

with the novel light source. The second method is by using the imaging optics of an endoscope for illumination, and therefore results in the need for the light source to share the same space with the imaging camera at the proximal end of the endoscope. Both methods transmit co-axial illumination and therefore do not produce shadows. Furthermore, preliminary tests with these methods showed significant light loss of up to 90% (Kumar, 2004). The third method is by direct illumination through a separate light source, uncoupled from the imaging optical axis. As the illumination source can be placed at an angle from the optical axis of the imaging optics, this would allow the casting of shadows.

The third method, direct illumination separate from the imaging endoscope was chosen as the method of light delivery to the endoscopic field in the project.

4.3.2.3 **Components of the LED endo-illuminator**

4.3.2.3.1 *LED illumination rod*

A prototype, the LED endo-illuminator, was developed at the Imperial College London. An one watt (W) InGaN white LED device (LXHL-MW1D, Luxeon Star Hex, Philips Lumileds, San Jose, CA, USA) that is commercially available was chosen based on a previous Master degree project by Sunil Kumar, which involved the testing of a number of LED devices with potential to supply the projected amount of optical power needed as compared to the distal end of an arc-lamp endoscope (Kumar, 2004). This LED device can produce a typical luminous flux of 45 lumens with a colour temperature of 5500K at 350mA with an overall luminous efficacy of about 38lm/W. It provides a lambertian radiation pattern which covers a total included angle of 160°, over which 90% of the total luminous flux is emitted (Anonymous, 2006b). For ease of handling, the LED device was mounted at the end

of a steel rod of 10mm in diameter and 405mm in length, similar to the instruments used in MAS (Figure 11). A copper heat-sink was constructed within the rod at the distal end. The electrical wires were placed within the rod and connected to a BNC connector in the proximal end for connection directly to a power supply (Figure 11 and Figure 12).

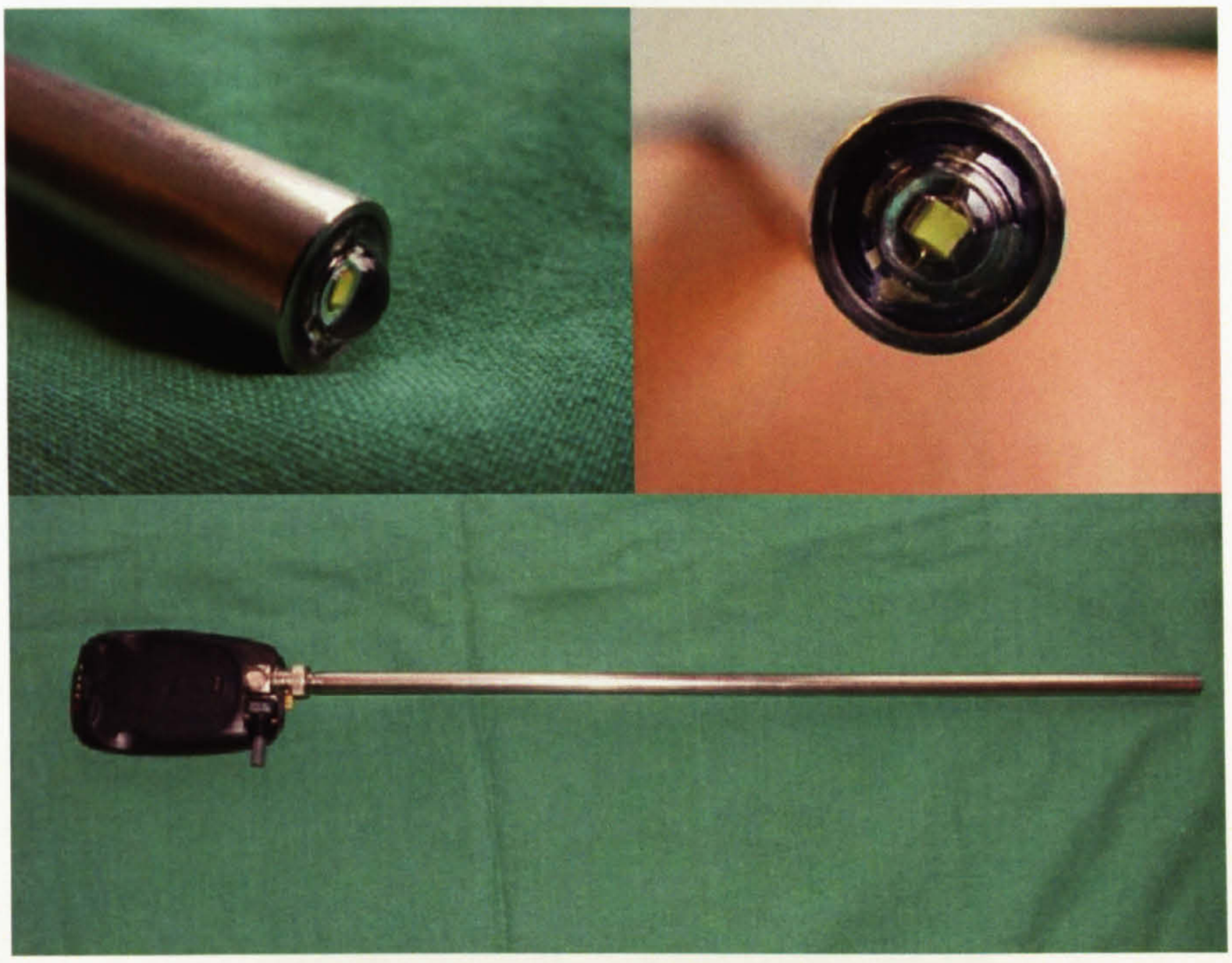

Figure 11 Oblique (upper left photo) and end (upper right photo) views of the LED mounted at the distal tip of the rod. Endo-illuminator with the battery unit attached to the proximal end (lower photo).

4.3.2.3.2 *Power Supply*

Two power supplies were used in the experiments. A bespoke battery unit was developed by Dr Fernando Bello and Adolfo Santa Fe of the Surgical Graphics and Computing Group by using a conventional mobile phone battery and charger (Figure 12 upper photo). The custom-made electronic circuitry which controlled the amount of current and voltage supplied to the LED was housed within a battery recharger

(DCH133BSE, Samsung, Korea) measuring 100mm x 60mm x 20mm with five indicators showing the remaining battery power. A BNC connector was used for connection to the LED endo-illuminator. The Li-ion battery (BST3078BE, Samsung) measuring 70mm x 45mm x 5mm can be recharged by a separate desktop recharger. The combined weight of the battery unit was 80g. Each fully charged battery can last up to 60 minutes at preliminary testing.

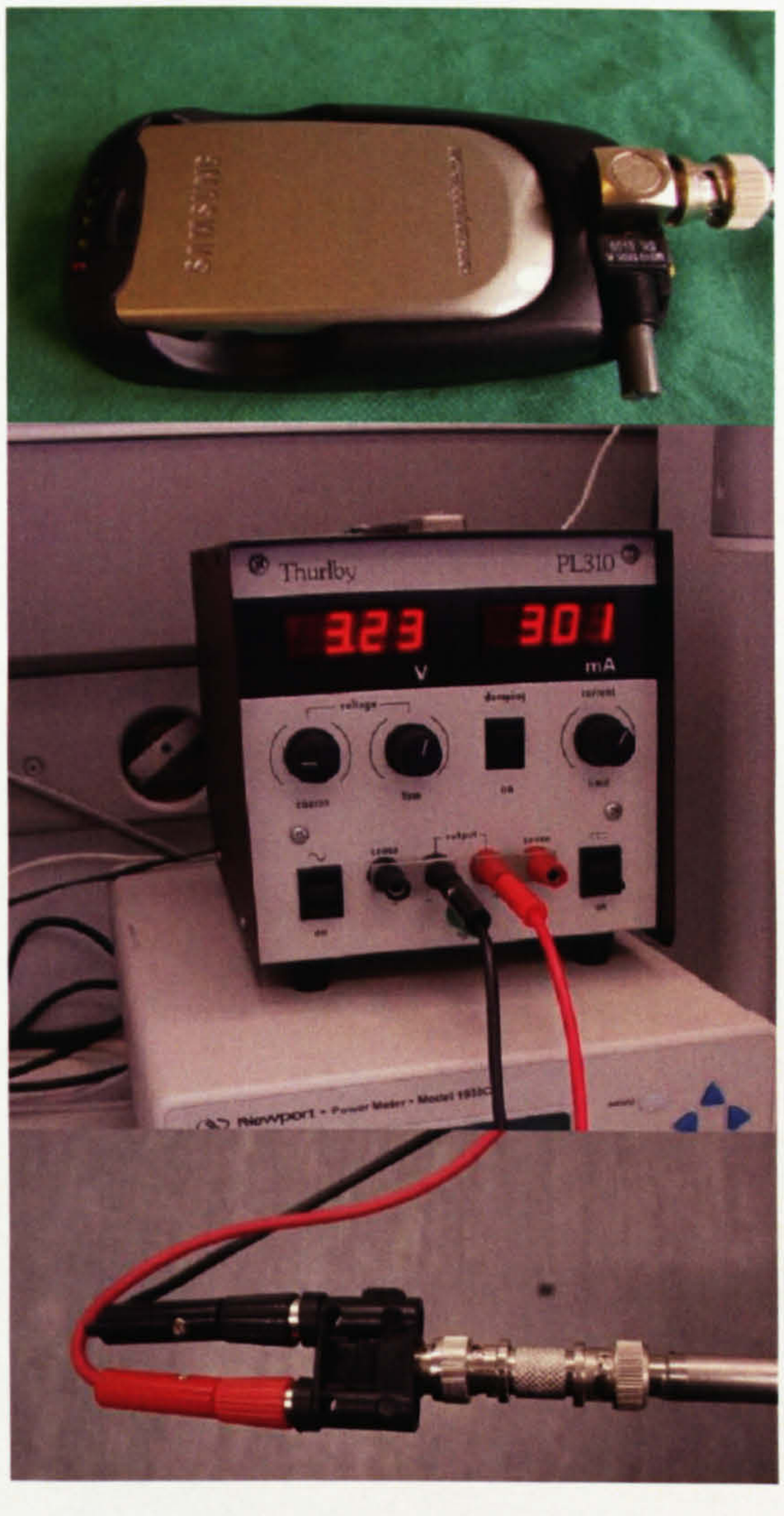

Figure 12 Power supply to the LED endo-illuminator. Mobile phone battery in the battery holder (upper photo). Alternatively a power supply unit (PSU) can be used to supply the LED via electrical wires (middle and lower photo).

Alternatively, the LED endo-illuminator was connected to a bench top DC power supply unit (PSU) (PL310, Thurlby Thandar Instruments Ltd., Huntingdon, UK) via long thin electrical cables (Figure 12). The PSU was set in constant current mode.

4.3.3 **Results**

The LED endo-illuminator can be inserted through a standard 10mm port and used as a secondary light source to provide illumination to the whole endoscopic field (Figure 13). Cable cluttering in the external operative field was absent when the battery unit was used. The temperature at the tip reached up to 50°C after 30 minutes of use at 350mA which cooled down rapidly when the LED was switched off. This lower temperature compares favourably with the temperature at the tip of conventional 10mm endoscopes which can reach up to 95°C (Hensman et al., 1998).

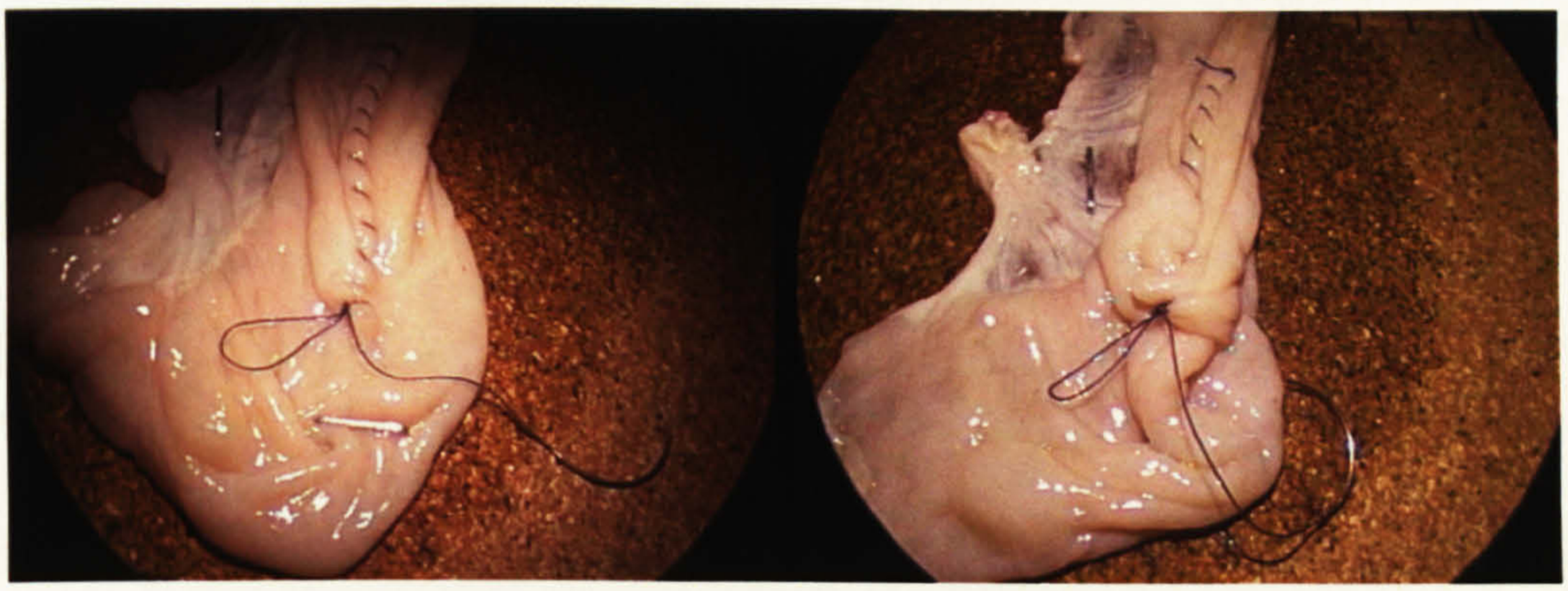

Figure 13 Endoscopic illumination with conventional arc-lamp light source (left photo) and LED endo-illuminator (right photo).

4.4 User testing of the LED endo-illuminator

4.4.1 Aim

The objectives of this section of the project were:

(1) To assess feasibility of using the LED endo-illuminator within an endoscopic operative workspace.

(2) To investigate the influence of the additional endoscopic shadow, from the LED endo-illuminator or arc-lamp source, on task performance and visual comfort for users. The experiment was designed to test the hypothesis that the LED illumination is a better additional light for shadow producing illumination.

4.4.2 Methods

4.4.2.1 Subjects

Six healthy subjects (median age 29.5 years and range 27-33 years) took part in the study. They included 3 non-medical and 3 junior surgical trainees (with minimal clinical experience in MAS). They had normal or corrected eyesight, and were not aware of the hypotheses of the experiment. Informed consent was obtained from the subjects to participate in the study.

4.4.2.2 Task

The performance of two endoscopic tasks under different illumination conditions was examined. The non-surgical tasks resemble common operative manoeuvres which are often in used in clinical practice in MAS.

i) Looping task. The task rig consisted of a wooden block with a surface area of 75x150mm angulated at 30° from the horizontal plane and covered with a non-reflecting cloth. Four metallic ring screws, with internal diameter of 10mm, were

inserted onto the surface at a distance of 50mm from each other (Figure 14). The subject was instructed to pass a 30mm silicone tubing of 10 French size through the four rings twice in a counter-clockwise direction, starting from the lower right ring, using two endoscopic graspers. The objective was to complete the task in the shortest period of time without dropping the tube from the jaws of the instrument. The task was repeated three times under each illumination condition.

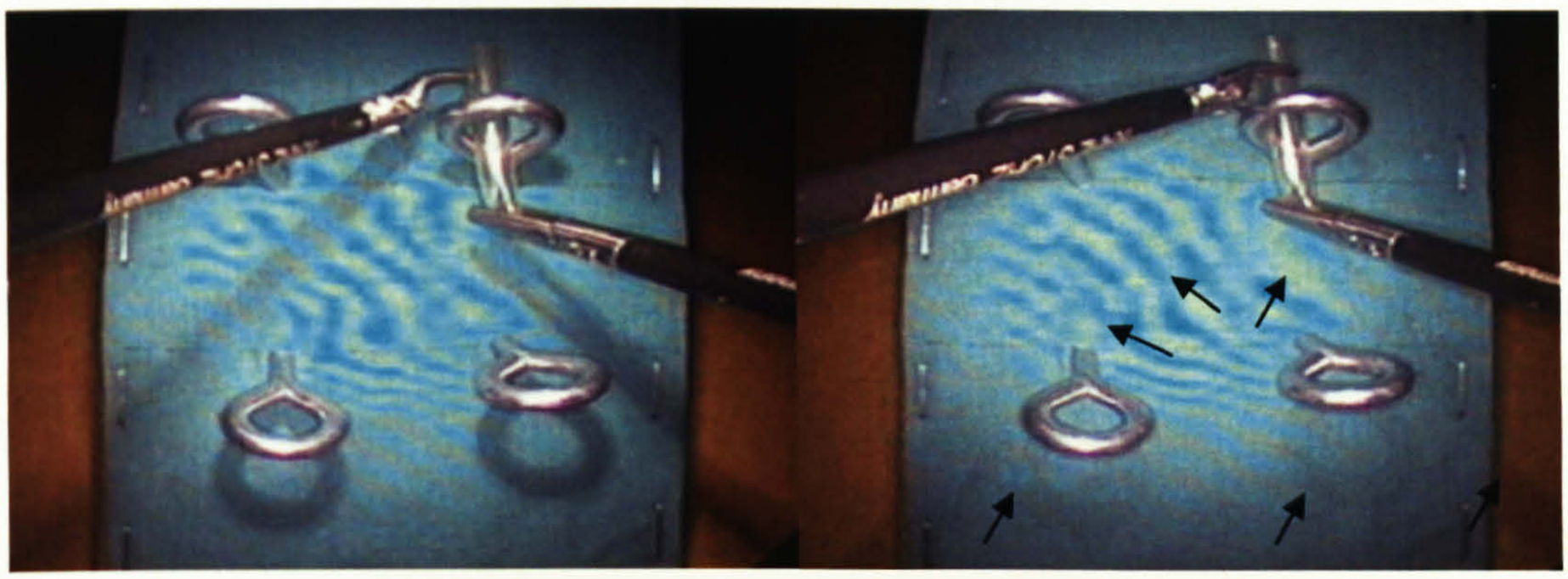

Figure 14 Looping task. Additional illumination using arc-lamp source (left photo) and LED endo-illuminator (right photo). The additional shadows from the LED illumination (arrows) were more evident when the moving images were displayed on screen.

ii) Cutting task. The task rig consisted of a wooden block which is the same as the one used in the looping task. A latex glove was stretch-mounted onto the four rings so that the front and back layers of the glove were against each other. A circle, which was 3mm thick and with an outer diameter of 40mm, was drawn on the front layer with a black felt-tip pen. The subject was instructed to cut out the circle from the front layer of the stretched glove within the thickness of the line and to avoid cutting the back layer (Figure 15).

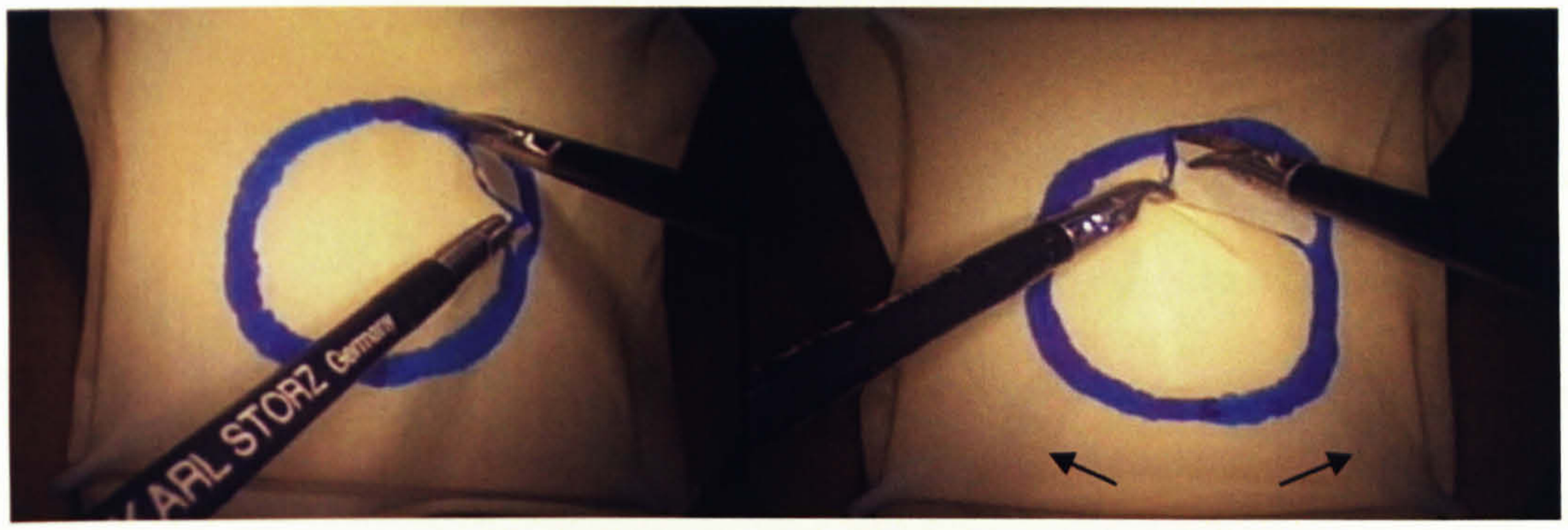

Figure 15 Cutting task. Additional illumination using arc-lamp source (left photo) and LED endo-illuminator (right photo). The additional shadows from the LED illumination (arrows) were more evident when the moving images were displayed on screen.

4.4.2.3 **Video-endoscopic set-up**

The following equipment was used in the video-endoscopic set up:

Endoscope: Forward viewing 0° endoscope (model 26003AA) of 10mm in diameter was used for the imaging and as the main co-axial illumination source.

Main light source: The xenon arc-lamp source (Nova model 20131520) was used and a 4.8mm light cable (model 495NCS) was used to connect the light source to the imaging endoscope as the main co-axial illumination.

Camera and monitor: The Storz Image 1 3-chip camera system (model 22210030 and model 22200020) and 20-inch high-resolution monitor (Model PVM-2053MD, Sony, Tokyo, Japan) were used.

Endoscopic instruments: Laparoscopic graspers (model 33321MD and model 33321MH) and scissors (model 34321MW) of 5mm in diameter and 360mm in length were used in the experiments.

4.4.2.4 **Illumination conditions and experimental design**

All subjects started with the task under direct vision with open ambient illumination using open surgical instruments (dissecting forceps and Metzenbaum scissors) for familiarisation of the task. This served as a baseline for comparison. The subjects then performed the task under the following three experimental endoscopic illumination conditions (Figure 16):

(1) Conventional co-axial illumination through the viewing endoscope;

(2) Conventional co-axial illumination with an additional endoscopic illumination, powered by a 175W xenon arc-lamp source (model 20132020). The 10mm 0° endoscope (model 26033AP, Storz) was placed at 30° anterior to the optical axis and 80mm from the centre of the task surface; and

(3) Conventional co-axial illumination with additional illumination via the LED endo-illuminator, powered by the mobile battery as described in the previous section. It was placed at 30° anterior to the optical axis and 80mm from the centre of the task surface.

A within subject repeated measure design was used to examine the difference in performance between the three illumination conditions set out above.

Each experimental task was performed in a counter-balanced order of the illumination conditions, based on a randomised complete block design, in order to counteract practice effects.

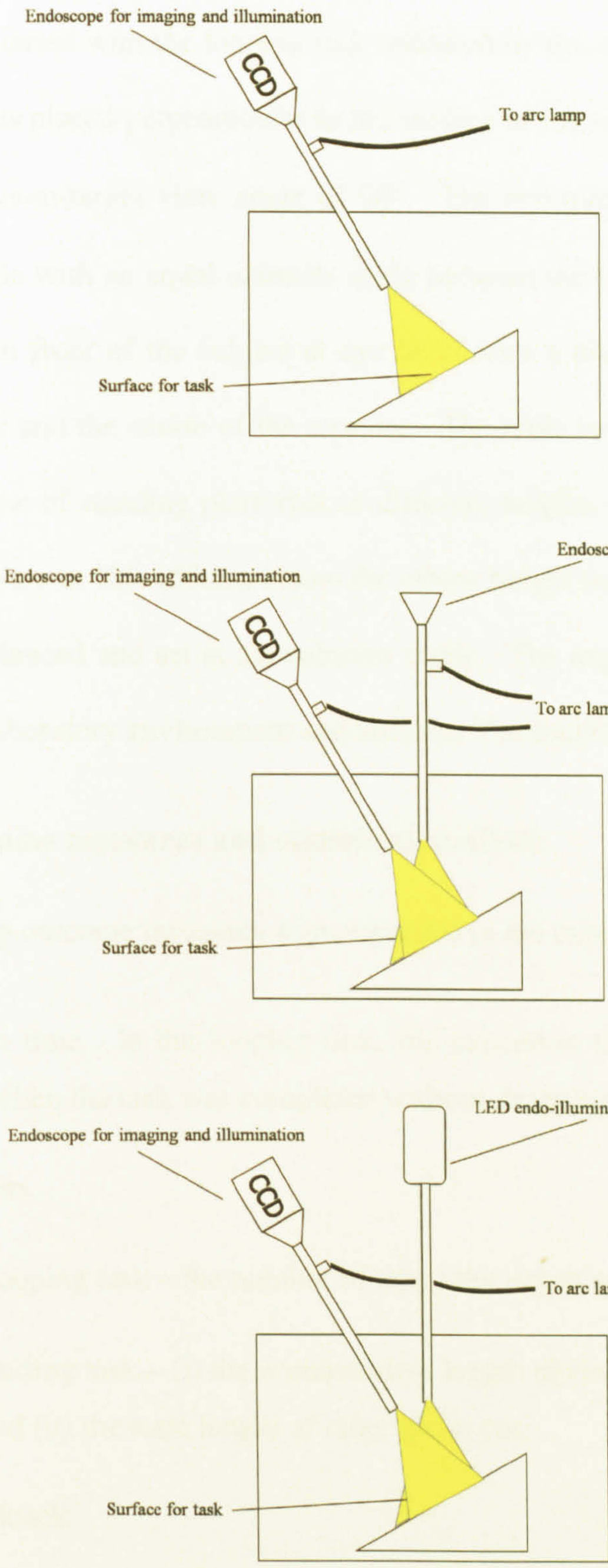

Figure 16 Experimental set-up for the three endoscopic illumination conditions. Co-axial endoscopic illumination (upper diagram), coaxial illumination and additional endoscopic illumination (middle diagram), and co-axial illumination with additional LED illumination (lower diagram).

4.4.2.5 **Control measures**

All subjects started with the looping task followed by the cutting task. The imaging endoscope was placed perpendicular to the surface of the task rig in order to achieve an optical axis-to-target view angle of 90°. The instruments were inserted at 60° elevation angle with an equal azimuth angle between the instruments. The monitor was located in front of the subject at eye level with a distance of 1m between the subject's eyes and the centre of the monitor. The table height was adjusted with or without the use of standing platforms of different heights so that the handles of the instruments were at 100-150mm below the elbow height from the floor. The camera was white balanced and set at auto-shutter mode. The experiments were conducted in the same laboratory environment and ambient illumination conditions.

4.4.2.6 **Outcome measures and statistical analysis**

The following outcome measures were recorded in the experiments:

(1) Execution time. In the looping task, the execution time was only used in the analysis when the task was completed without dropping the tube.

(2) Total errors

a. Looping task – the number of times the object was dropped;

b. Cutting task – (i) the accumulative length deviated from the intended line; and (ii) the total length of inner glove cut.

(3) User feedback

a. Self-report visual analogue score for visual discomfort on a 100mm line – At the end of each task, the subjects were asked to record a score to indicate the level of visual discomfort where zero mm represents no discomfort whereas 100mm represents maximal discomfort; and

b. General user free-text comments.

Non-parametric Friedman ANOVA test was used for statistical testing of the execution time and number of errors under the different endoscopic illumination conditions. Significance level was set at 5%.

4.4.3 **Results**

There were no significant differences in the execution time to complete the looping and cutting tasks between the three endoscopic illumination conditions. The execution time required to complete both tasks were significantly shorter under open illumination and direct viewing (Figure 17 and Figure 18).

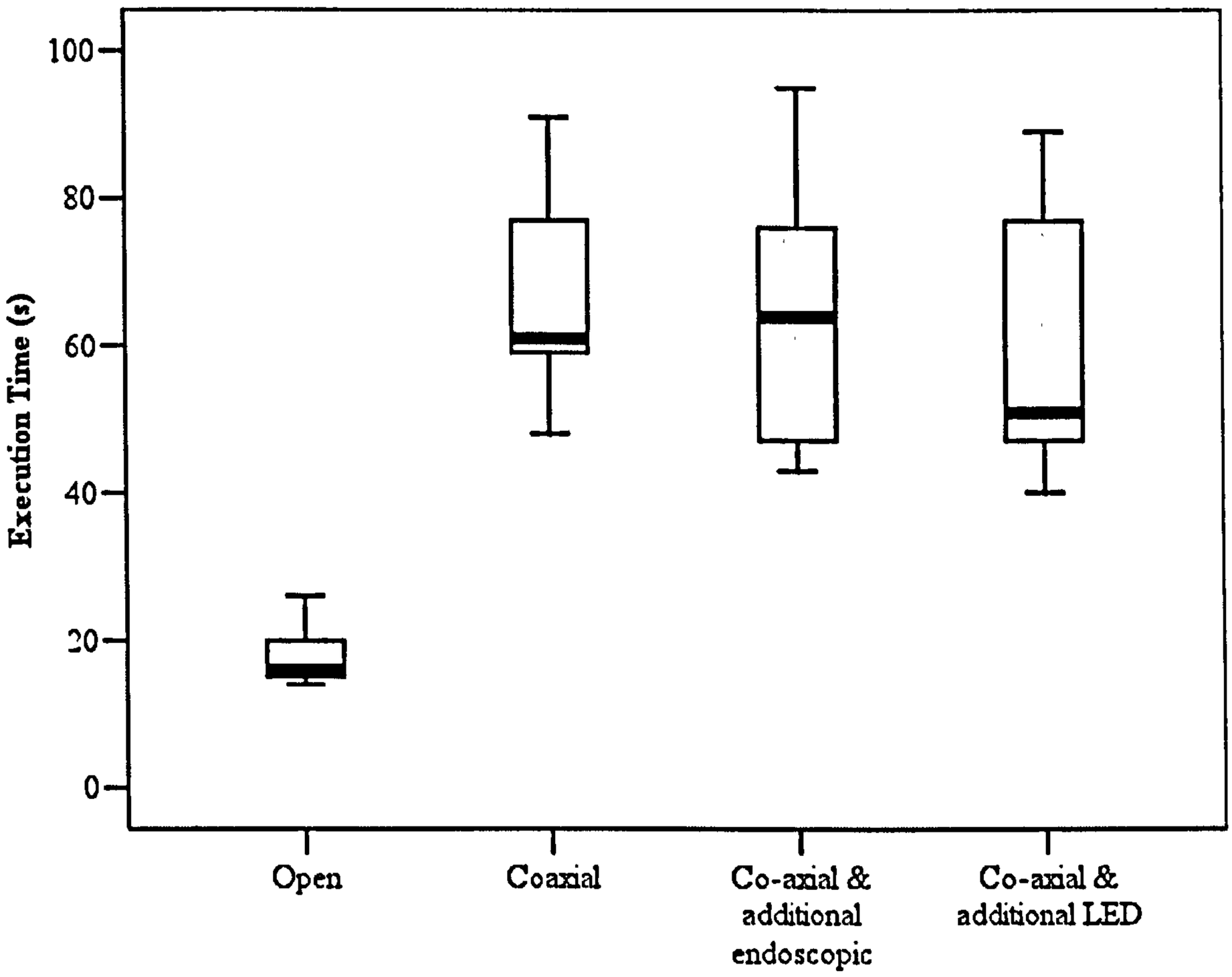

Figure 17 The execution time of the looping task completed under the four different illumination conditions.

(1) Open illumination with direct viewing, (2) co-axial endoscopic illumination, (3) co-axial endoscopic illumination with additional off-axis endoscopic illumination and (4) co-axial endoscopic illumination with additional off-axis LED illumination. Data shown as median and interquartile range. (Friedman test, (1)-(4) $p<0.01$; (2)-(4) $p=0.179$)

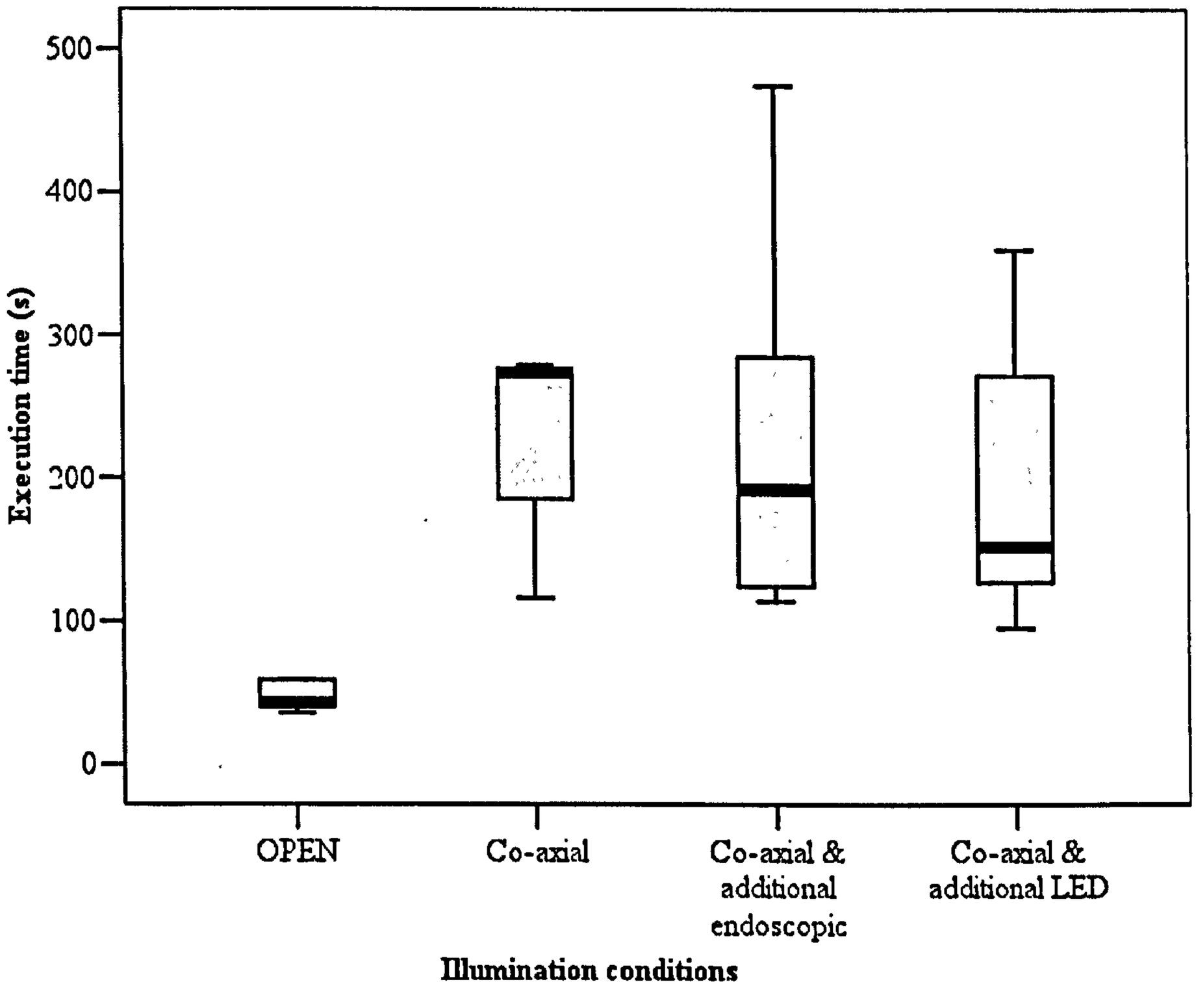

Figure 18 The execution time of the cutting task under the four different illumination conditions.

(1) Open illumination with direct viewing, (2) co-axial endoscopic illumination, (3) co-axial endoscopic illumination with additional off-axis endoscopic illumination and (4) co-axial endoscopic illumination with additional off-axis LED illumination. Data shown as median and interquartile range. (Friedman test, (1)-(4) $p<0.001$; (2)-(4) $p=0.568$)

During the looping task, none of the subjects dropped the tube under the open illumination condition. The tube was dropped on five occasions in total under the endoscopic illumination conditions but the numbers were too small for comparative analysis (Table 7).

Subject	Set-up whereupon the tube was dropped
1 – Medical	Co-axial and LED illumination
2 – Medical	None
3 – Non-medical	Co-axial illumination
4 – Medical	Co-axial and LED illumination
5 – Non-medical	Co-axial and endoscopic illumination (on two occasions)
6 – Non-medical	None

Table 7 Illumination set-up when the tube was dropped during the looping task by each subject.

The differences in the number of errors occurred during the cutting task, both in terms of the accumulative length deviated from intended line (Figure 19) and the total length of inner glove cut (Figure 20), were insignificant between the different endoscopic conditions. The differences were also insignificant under the open illumination and direct viewing condition.

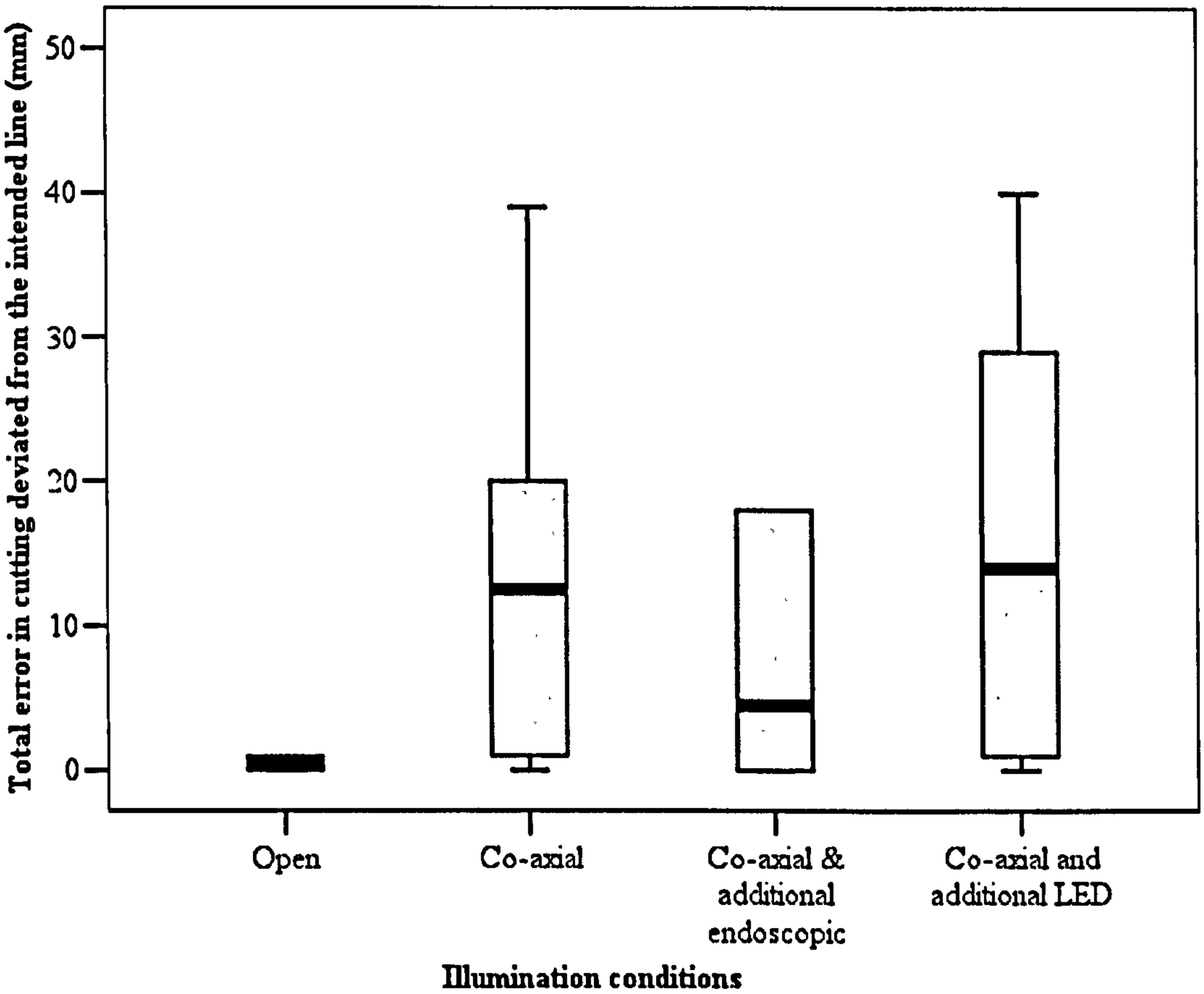

Figure 19 The accumulative length of cutting of the front layer deviated from the intended line under different illumination conditions.

(1) Open illumination with direct viewing, (2) co-axial endoscopic illumination, (3) co-axial endoscopic illumination with additional off-axis endoscopic illumination and (4) co-axial endoscopic illumination with additional off-axis LED illumination. Data shown as median and interquartile range. (Friedman test, (1)-(4) p=0.115; (2)-(4) p=0.465)

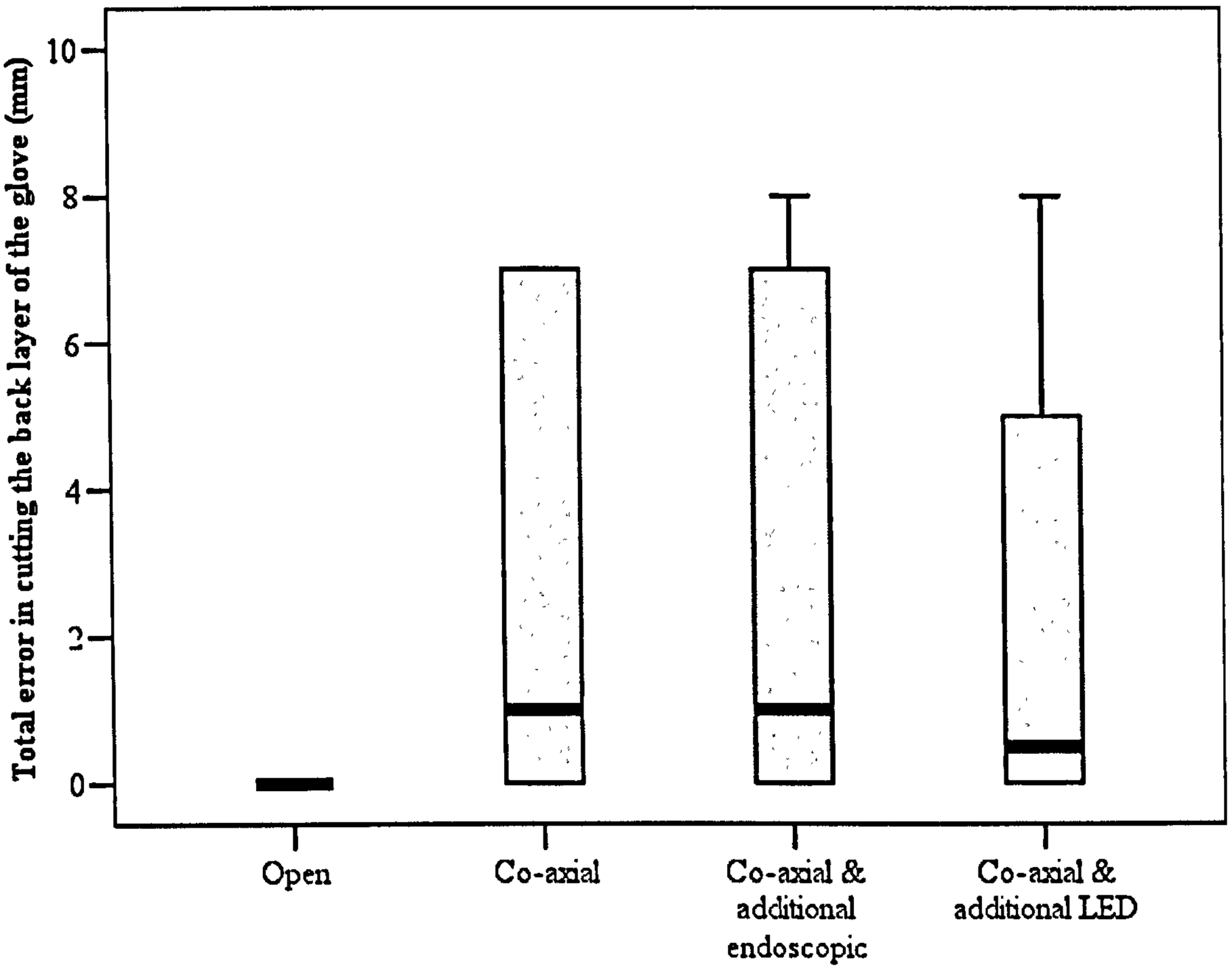

Figure 20 Total error in cutting the back layer of the stretched glove under different illumination conditions.

(1) Open illumination with direct viewing, (2) co-axial endoscopic illumination, (3) co-axial endoscopic illumination with additional off-axis endoscopic illumination and (4) co-axial endoscopic illumination with additional off-axis LED illumination. Data shown as median and interquartile range. (Friedman test, (1)-(4) p=0.450; (2)-(4) p=0.678)

There were no significant differences in visual discomfort between the three endoscopic illumination conditions as indicated by the VAS scores (Figure 21 and Figure 22). Direct viewing with open illumination was more comfortable compared to the endoscopic illumination in both tasks.

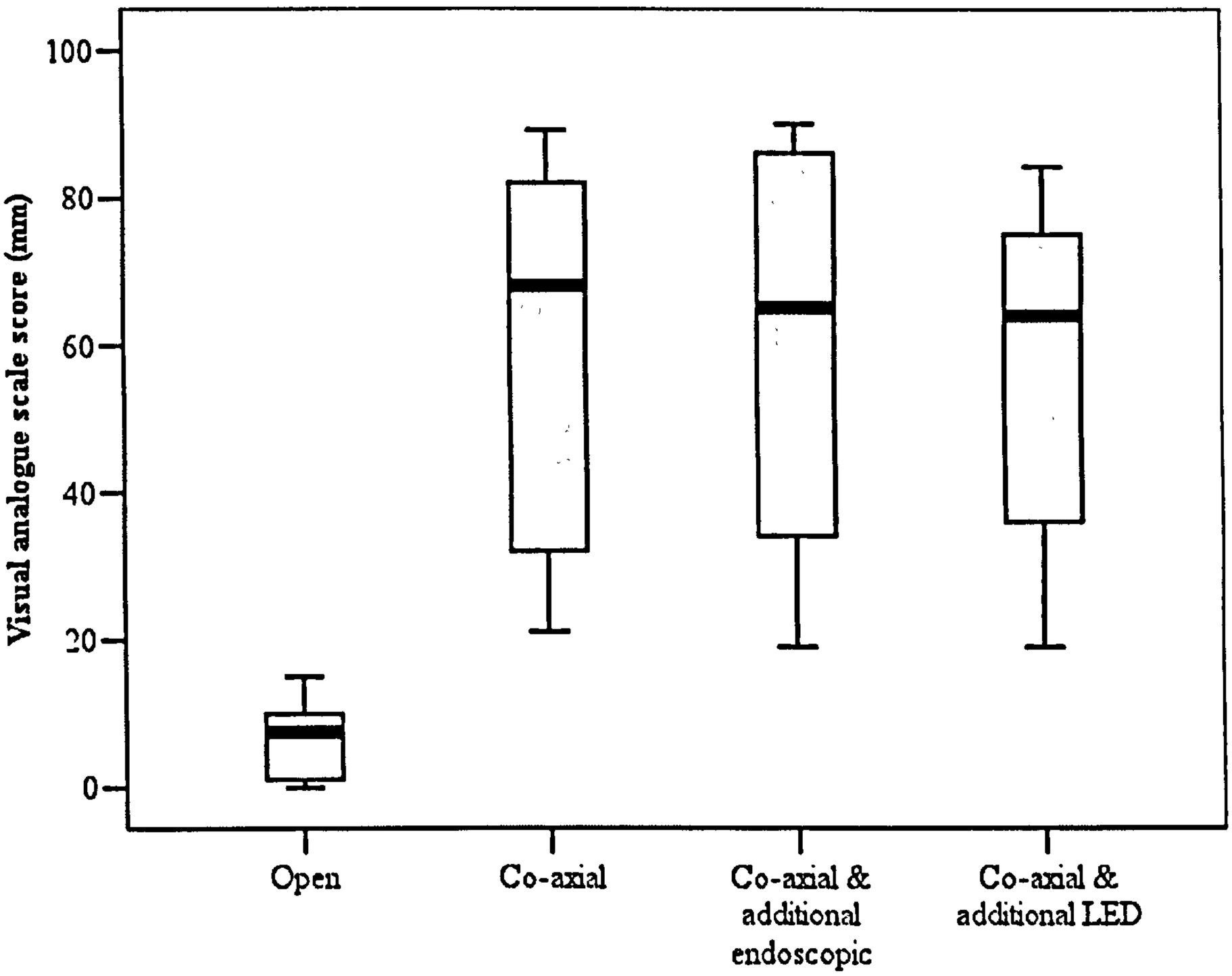

Figure 21 Visual discomfort for looping task under different illumination conditions.
(1) Open illumination with direct viewing, (2) co-axial endoscopic illumination, (3) co-axial endoscopic illumination with additional off-axis endoscopic illumination and (4) co-axial endoscopic illumination with additional off-axis LED illumination. Data shown as median and interquartile range. (Friedman test, (1)-(4) p=0.012; (2)-(4) p=0.957)

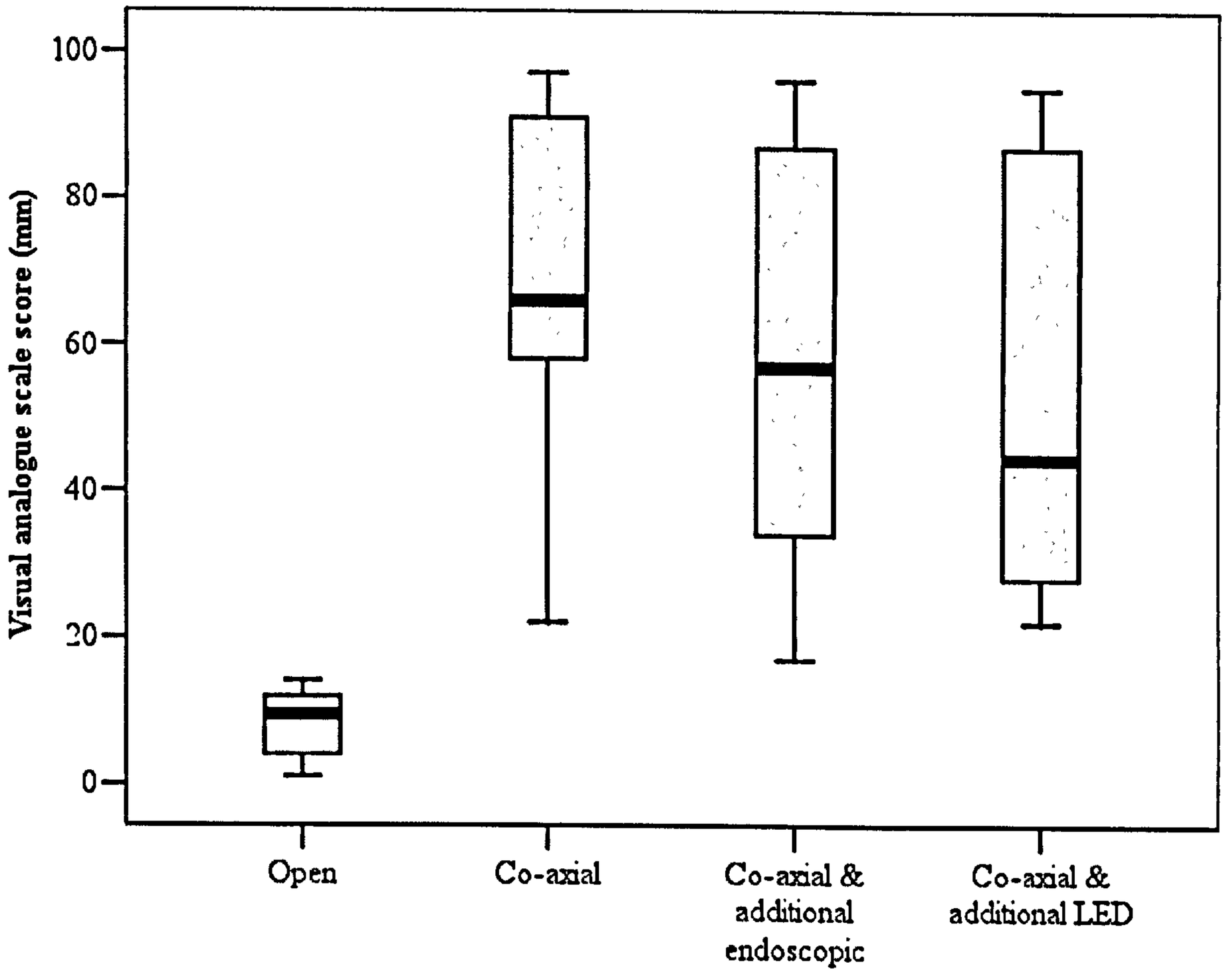

Figure 22 Visual discomfort for cutting task under different illumination conditions.

(1) Open illumination with direct viewing, (2) co-axial endoscopic illumination, (3) co-axial endoscopic illumination with additional off-axis endoscopic illumination and (4) co-axial endoscopic illumination with additional off-axis LED illumination. Data shown as median and interquartile range. (Friedman test, (1)-(4) $p<0.001$; (2)-(4) $p=0.179$)

All subjects reported difficulties in depth estimation during the endoscopic tasks and in coordination of the scissors and grasping forceps during the cutting task. Four subjects stated that the presence of shadow was useful in depth perception and two subjects reported that it might have helped. The distribution of preferences between medical and non-medical subjects were the same. One non-medical subject, however, pointed out that perception could be adversely affected if the shadows were too intense. All three medical subjects and one non-medical subject found that the addition of illumination from the LED endo-illuminator was helpful and in particular, one non-medical subject pointed out that the LED illumination had helped to locate the ring during the looping task. Most subjects reported that the LED was quite dim especially towards the end of the sessions.

4.5 Characteristics of the LED endo-illuminator

4.5.1 Aim

The aim of this part of the project was to investigate the optical and imaging characteristics of the LED endo-illuminator within an endoscopic workspace. The specific objectives were to study the illumination intensity, stability, uniformity and shadow sharpness from the LED endo-illuminator.

4.5.2 Materials and methods

4.5.2.1 Experimental set-up

The experimental data were obtained either by indirect analysis of captured endoscopic images or by direct measurements of the illumination source (Table 8).

Characteristic	Experimental method / analysis
Illumination intensity	Direct measurement and indirect image analysis
Illumination stability	Direct measurement
Illumination uniformity	Indirect image analysis
Shadow sharpness	Indirect image analysis

Table 8 Experimental methods used for investigating the different characteristics of the LED endo-illuminator.

4.5.2.1.1 *Illumination sources*

The following light sources were used:

(1) The LED endo-illuminator as described in previous sections. The bench top PSU was used in most experiments.

(2) The illumination optics of a 10mm endoscope (model 26033AP, Storz) (Figure 23) with the light supplied by a xenon arc-lamp light source (Nova 300W model 20131520 or 175W model 20132020, Storz).

(3) Co-axially through the imaging endoscope with a xenon arc-lamp light source as in conventional endoscopic illumination.

For (1) and (2), the light source was inserted into the box separately and positioned perpendicular to the target.

4.5.2.1.2 *Indirect image analysis*

The experimental video-endoscopic set-up for indirect image analysis (Figure 23) consisted of a 0° 10mm endoscope (model 26003AA, Storz, Tuttlingen, Germany), CCD camera head (Image 1 3-chip model 22210030, Storz) and camera control unit (model 22200020, Storz) and a DVD recorder (AIDA model 20204020, Storz). The viewing endoscope was placed at an optical axis-to-target view angle of 45° and at a distance of 4cm to produce an endoscopic field of 6cm in horizontal diameter. A piece of plain white photographic grade matte inkjet paper (S041569, Epson, Japan) was placed at the target endoscopic field within a darkened box. The camera was white-balanced with every change in light source and the shutter was set to automatic mode.

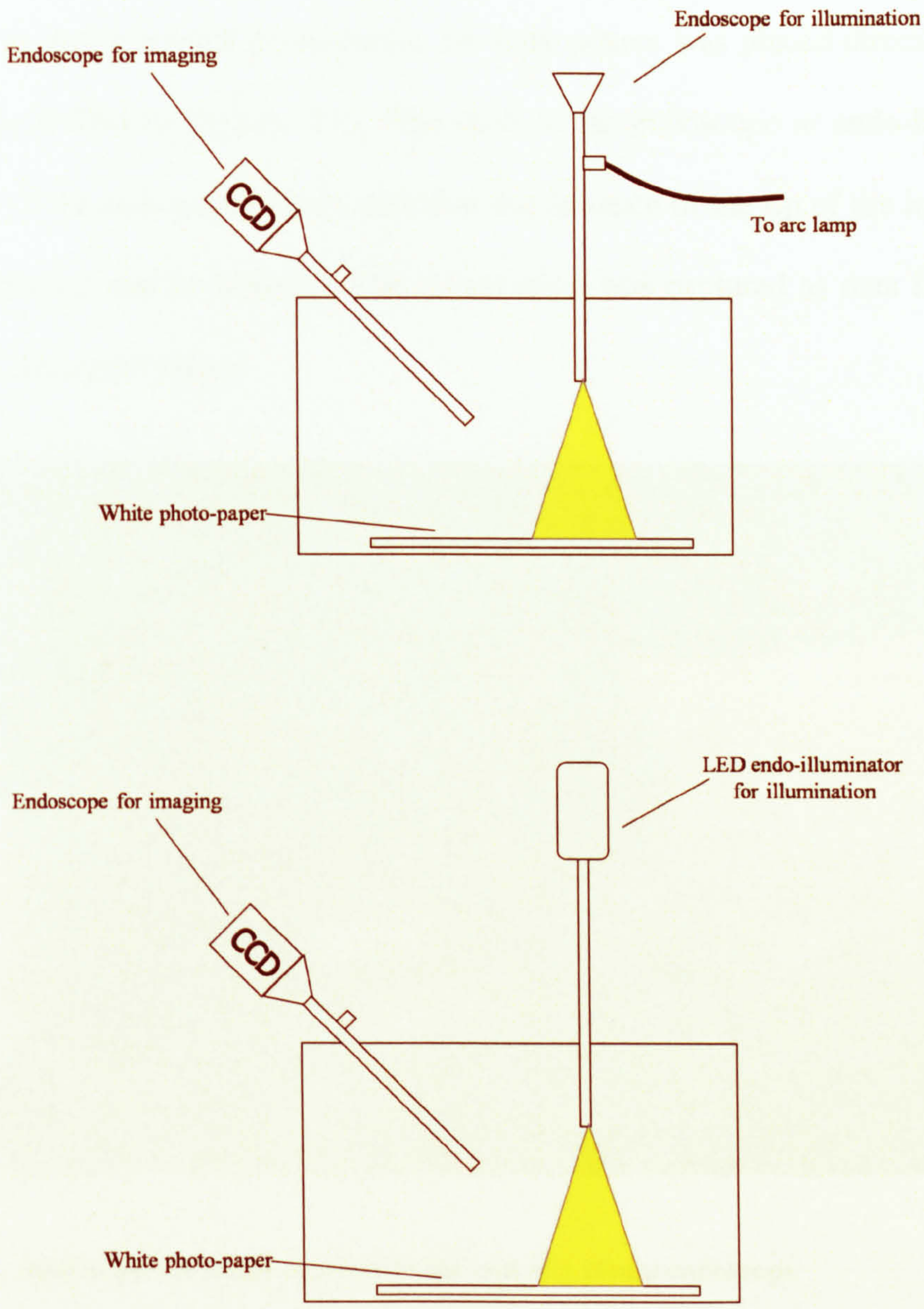

Figure 23 Experimental set-up. Arc-lamp based system (upper diagram). LED based system (lower diagram). The distance between the distal end of the illumination system to the target was compared at 4cm and 8cm.

Static digital images of the plain endoscopic field were taken and recorded in 24-bit high resolution JPEG format. Offline analysis was performed using a LabView based programme (Vision Assistant v.7.1.1, National Instruments, Austin TX, USA).

4.5.2.1.3 *Direct optical measurement*

In the direct measurement experiments, the light source was placed directly in front of the optical detector (Figure 24). The shaft of the endoscope or endo-illuminator was fixed on an endoscope clamp such that the distance of the tip of the light source and the detector can be adjusted. The information was captured as data files which were then analysed offline.

Figure 24 Optical power meter detector at the end of a 10mm endoscope

4.5.3 Illumination intensity

The illumination intensity was determined by indirect analysis of the captured images and by direct measurement of the optical power of the illumination sources.

4.5.3.1 Measurement of pixel intensity of the images

4.5.3.1.1 *Method*

Digital images were obtained with the above set-up with the target paper illuminated co-axially at 4cm, separately by the arc-lamp endoscopic light at 4cm or 8cm, or the LED endo-illuminator at 4cm or 8cm. The bench top power supply unit was used to supply power to the LED endo-illuminator. The power output from the arc-lamp light source was set at 50% and the camera was set to auto-shutter mode. In order to exclude the black peripheral rim at the corners, all images were cropped to the central 63% portion and there were 232,324 pixels for analysis in each image. The level of image brightness was determined by each pixel's luminance, graded from 0-255 arbitrary units. The mean pixel intensity of five images obtained under each illumination condition was calculated to indicate the overall brightness.

4.5.3.1.2 *Results*

When the LED endo-illuminator was used, the overall image brightness was highest, especially when it was placed 8cm from the target. Images taken using the separate arc-lamp endoscopic light source at 4cm have a lower mean pixel intensity compared to those taken using the co-axial illumination of the imaging endoscope. However, as the distance of the separate endoscopic light was increased to 8cm, the mean pixel intensity also increased (Figure 25).

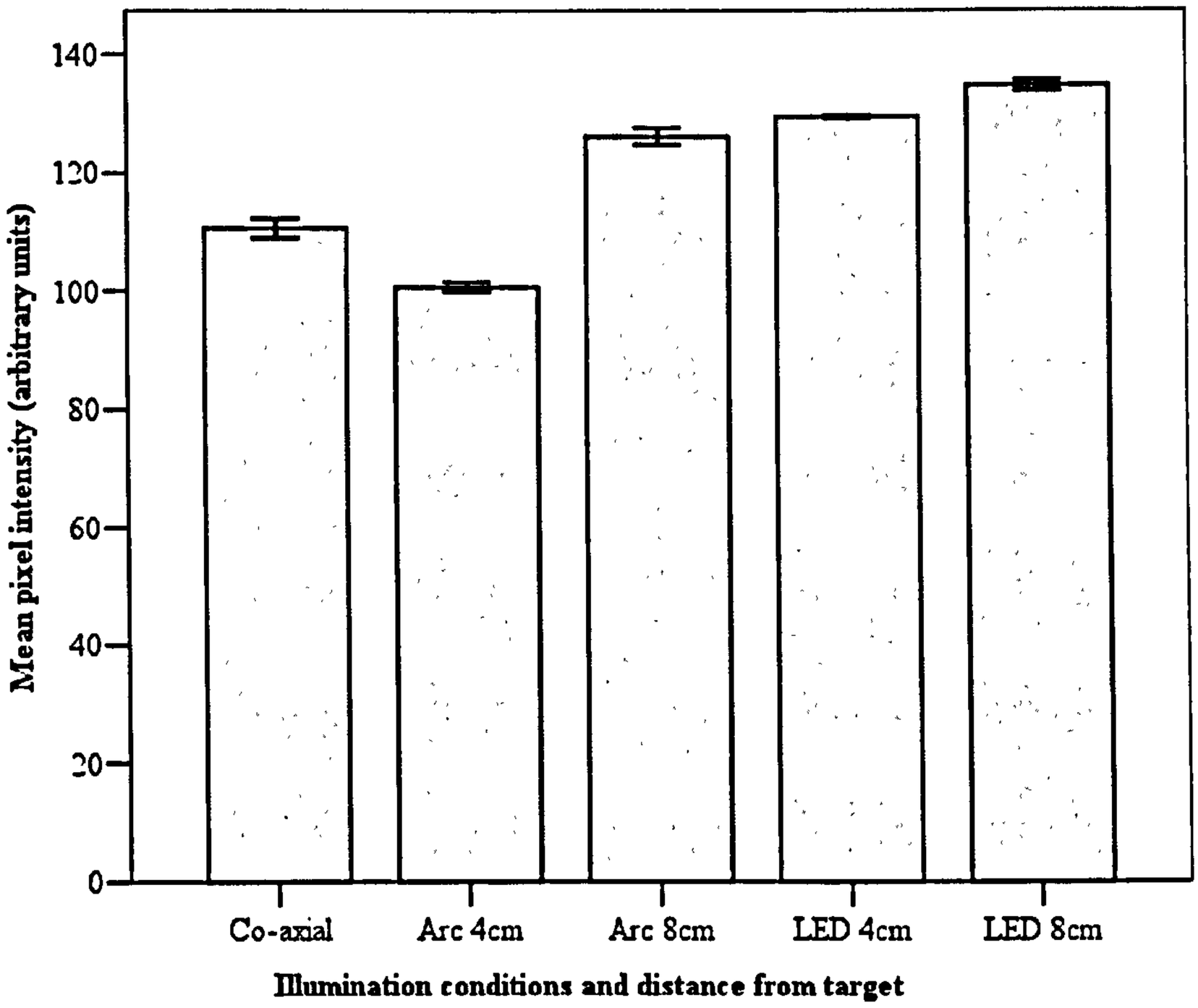

Figure 25 The mean pixel intensity of images taken under coaxial illumination, arc-lamp illumination at 4and 8 cm, and LED illumination at 4 and 8 cm. Mean pixel intensity (± 2 SD) is shown

4.5.3.2 Direct measurement of optical power

4.5.3.2.1 *Method*

An optical power meter (model 9130C with detector 918-UV, Newport, Irvine, CA, USA) was used to measure the optical radiometric power, at 555nm of the visible spectrum, directly in front of the light source. The background illumination within the darkened box was negligible (<0.5nW).

Using the optical power meter, the following properties of the illumination systems were examined:

(1) The driving current to the LED endo-illuminator. The LED manufacturer's recommended maximum DC forward current is 350mA. The effect on radiometric optical power from changing the input current from 60mA to 360mA to the LED endo-illuminator was recorded in three repetitions.

(2) The size of the light cable used in the arc-lamp light source. The endoscope manufacturer recommended that a 4.8mm light cable should be used in a 10mm endoscope and the 3.5mm light cable should be used in small scopes of 5mm or less in diameter (Figure 26). When a small endoscope is used, a cable that is larger in size will transmit more heat (but not light) and is also heavier. Conversely, when a large endoscope is used, a smaller light cable does not have enough fibre-optics to transmit sufficient light. In our laboratory, only the 4.8mm light cable (495NCS, Storz) was permanently available. In order to determine whether a small light cable was necessary, measurements were carried out using a 3.5mm light cable (495NAS, Storz) on loan from the main theatres. The radiometric optical power at the end of the light cables, supplied from a 175W xenon arc-lamp light source (model 20132020, Storz) at 100% output, with or without a 4mm or 10mm endoscopes (26009BA or 26003AP) were measured.

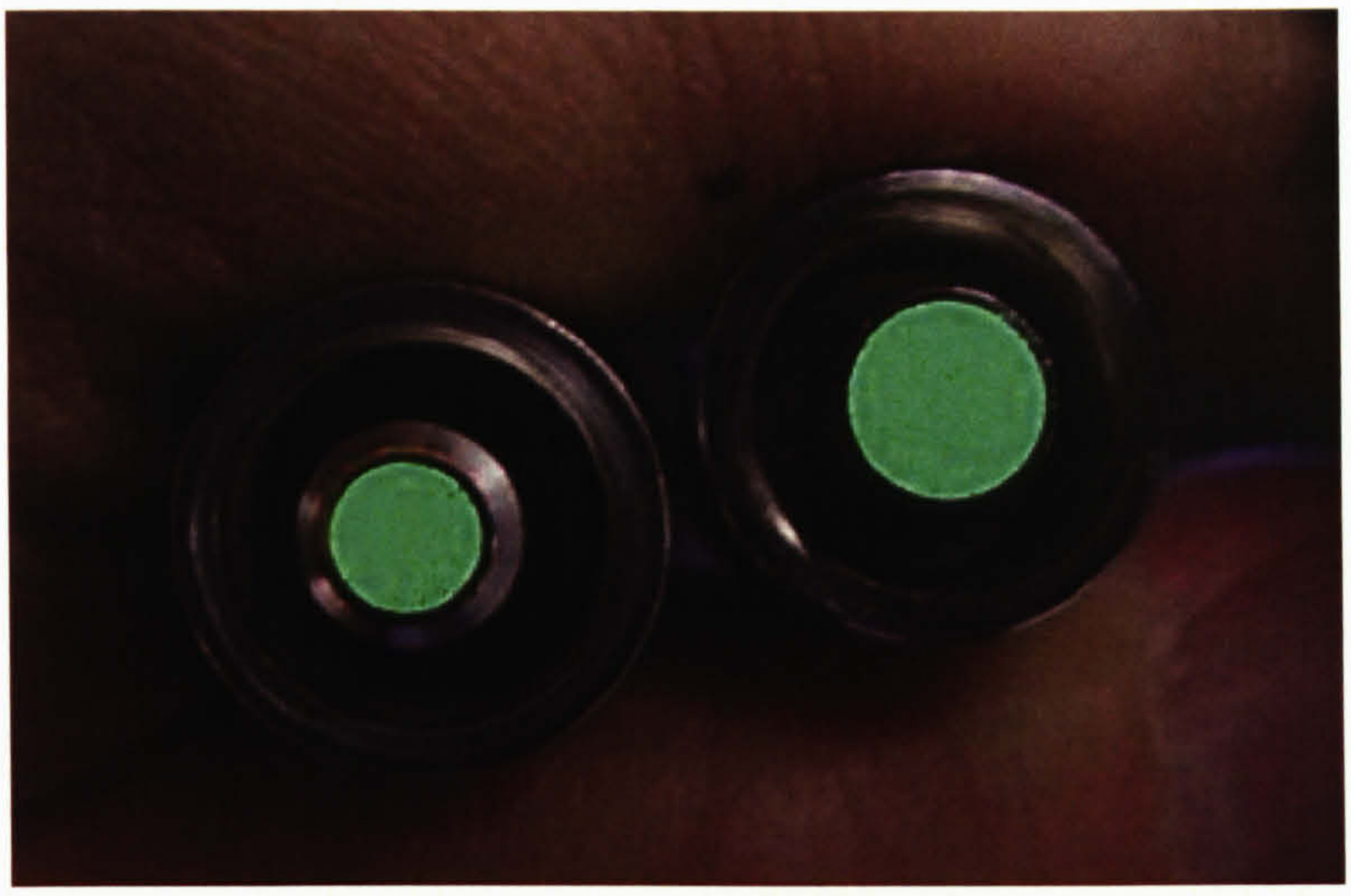

Figure 26 The proximal ends of the 3.5mm (495NAS) and 4.8mm (496NCS) fibre optic light cables showing the differences in area for illumination coupling.

(3) The output power of the LED endo-illuminator over 10 minutes when the battery or bench top PSU was used.

(4) Direct optical power measurements from the three illumination sources:

i) The 1W LED endo-illuminator powered by the battery unit or the bench top PSU at a constant current of 350mA.

ii) The 4mm (model 26009BA, Storz) endoscope powered by the 175W xenon arc-lamp light source with the output supply adjusted in 5% increments of its full power to the endoscope from 25% to 65%.

iii) The 10mm (model 26003AP, Storz) endoscope by the 175W xenon arc-lamp light source with the output supply adjusted in 5% increments of its full power to the endoscope from 5% to 50%.

Five measurements were taken under each illumination condition and the mean power in mW and standard deviation were determined.

4.5.3.2.2 *Results*

Figure 27 shows there is an almost linear relationship between the forward current input and the radiometric optical power intensity output from the LED endo-illuminator. The sub-linearity at the maximum current was most likely due to the increased temperature at this level which is known to reduce the efficiency of LED devices.

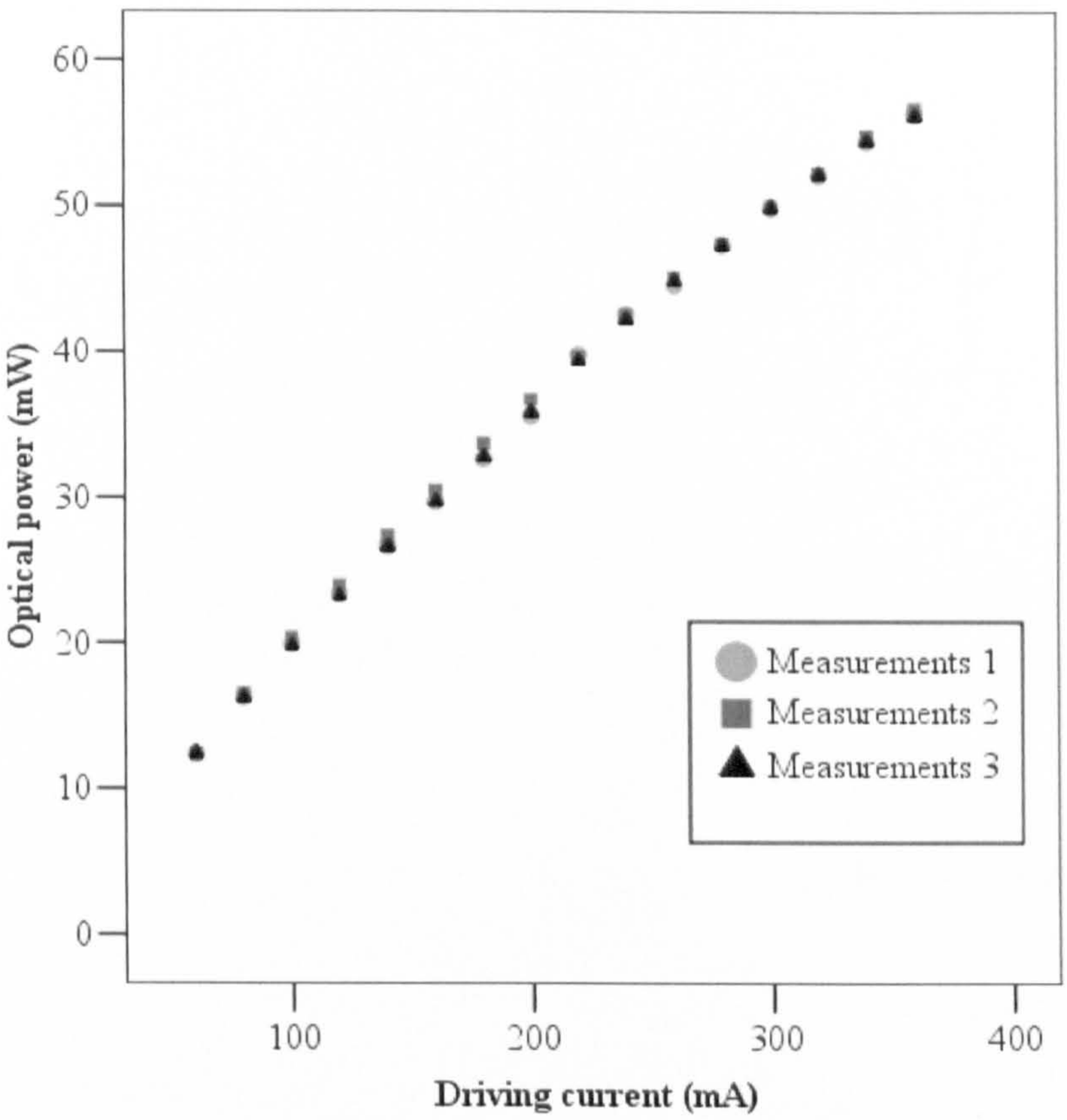

Figure 27 The output optical power of the LED endo-illuminator, as a function of the forward current in 3 repetitions, increases sub-linearly up to 360mA, just beyond the manufacturer's recommended maximum

The optical power output of the LED endo-illuminator decreased rapidly in the first 2-3 minutes of battery operation whereas the decrease was very gradual when powered by the PSU (Figure 28). This indicated that the reduction in the former case

was primarily due to the battery, which would explain the dim illumination towards the end of the user-testing sessions in Section 4.4.

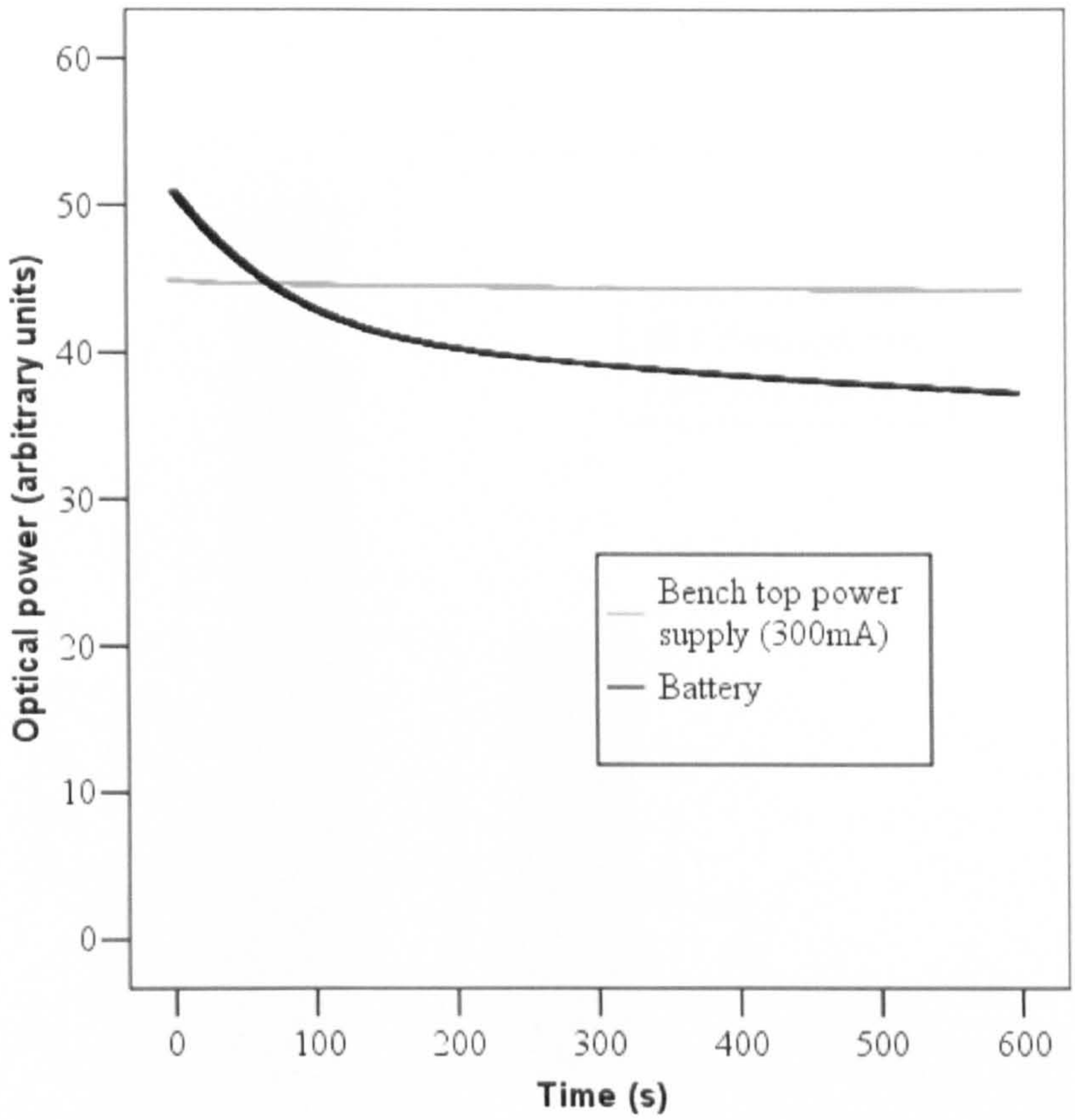

Figure 28 The decrease in optical power of the LED endo-illuminator was marked in the first 2-3 minutes when the battery was used (black line).

The radiometric optical power at the distal end of the 4.8mm (495NCS) and the 3.5mm (495NAS) light cables with or without the attachment of the 4mm endoscope and 10mm endoscope are shown in Figure 29. The use of the larger light cable resulted in twice the radiometric power at the end of the cable compared to the 3.5mm (495NAS) light cable. When the 10mm and 4mm endoscopes were attached, the additional radiometric power with the larger light cable were 2.5x and 1.4x respectively. Since there was no reduction in the optical power when the 4.8mm

cable was used with the 4mm endoscope, it was appropriate to use this light cable with the paediatric endoscope for the purpose of the experiments in this thesis.

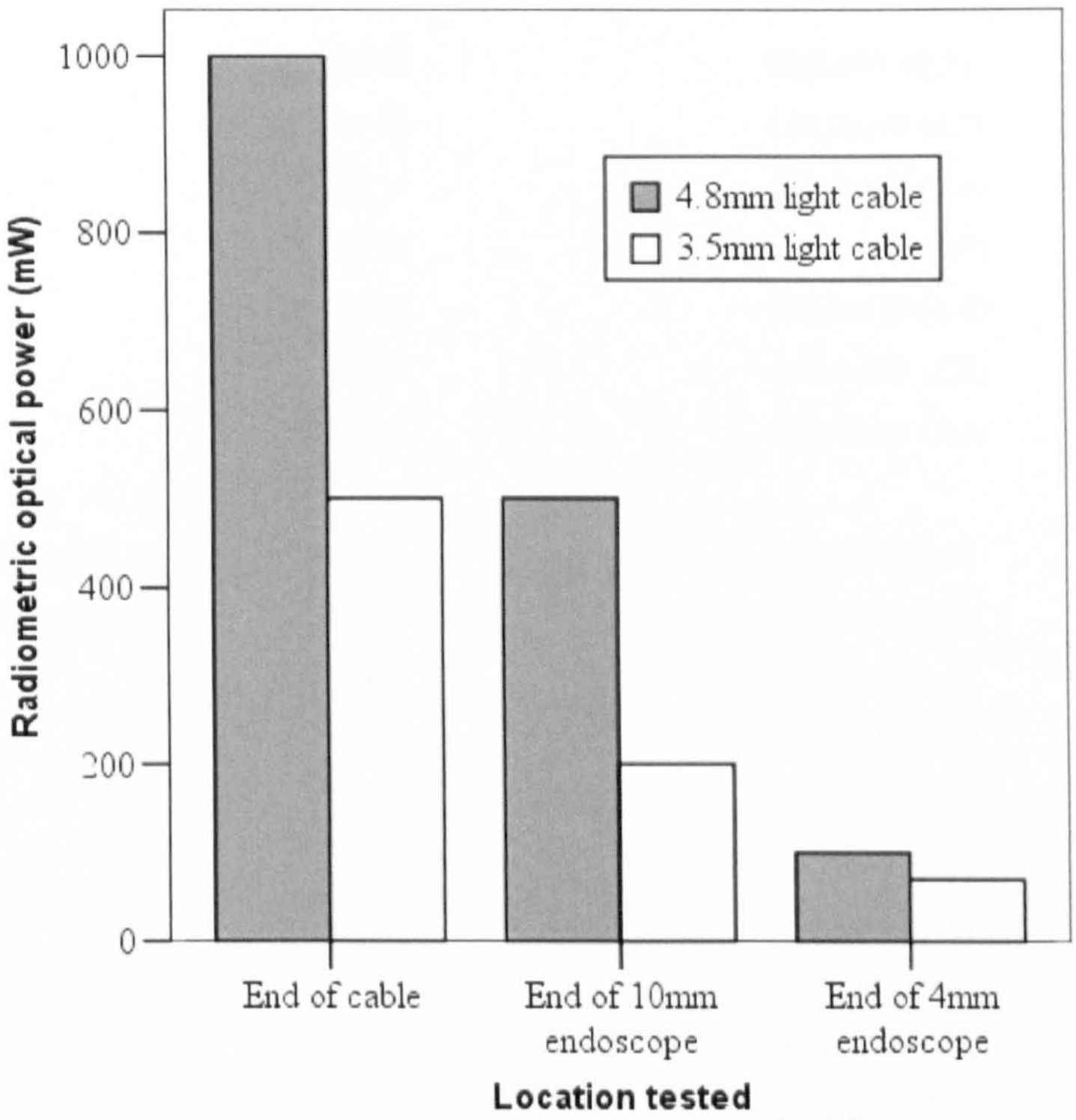

Figure 29 Comparison of the output of the optical power using the 4.8mm and 3.5mm light cables on its own, attached to a 10mm endoscope and attached to a 4mm endoscope.

The mean radiometric power immediately in front of the LED was 42mW (SD 0.84) when powered by the mobile phone battery and 47mW (SD 0.84) when powered by the bench top power supply at 350mA. Comparable magnitudes of radiometric power were obtained using the 10mm endoscope at 10% power and the 4mm endoscope at 60% power from the arc-lamp (Table 9).

	Input power setting	Optical power
LED endo-illuminator	**Phone battery**	**41.8mW (0.8)**
	350mA	**47.2mW (0.8)**
Arc-lamp with	**5%**	**22.8mW (0.5)**
10mm endoscope	**10%**	**42.4mW (0.6)**
	15%	**64.8mW (0.5)**
	20%	**88.8mW (0.5)**
	25%	**114.0mW (0.7)**
	30%	**139.4mW (0.6)**
	35%	**165.2mW (0.8)**
	40%	**191.0mW (1.4)**
	45%	**216.6mW (1.8)**
	50%	**232.6mW (1.5)**
Arc-lamp with	**25%**	**21.8mW (0.5)**
4mm endoscope	**30%**	**26.6mW (0.6)**
	35%	**31.4mW (0.6)**
	40%	**35.8mW (0.5)**
	45%	**40.6mW (0.6)**
	50%	**44.2mW (0.5)**
	55%	**43.0mW (0.00)**
	60%	**45.6mW (0.6)**
	65%	**48.2mW (0.5)**
	70%	**55.4mW (1.1)**

Table 9 Direct optical power measurements of LED and arc-lamp endoscopic illumination at different levels of power immediately in front of the optical power meter. Values expressed as mean (SD).

4.5.4 Illumination stability

The illumination stability or flickering of the LED endo-illuminator and 300W xenon arc-lamp was examined by direct measurements.

4.5.4.1 Low frequency sampling

4.5.4.1.1 *Method*

The optical power meter (model 9130C with detector 918-UV, Newport) was used to measure the optical radiometric power at 555nm directly in front of the light source continuously over 30 minutes. The background illumination was negligible (<0.001mW). The data was captured on a personal computer at a sampling rate of 3-4Hz.

4.5.4.1.2 *Results*

At this slow sampling rate of 3-4Hz, it was not possible to determine the exact fluctuation of the optical power from the arc-lamp source which was shown as dots forming the thicker line in Figure 30. On the other hand, the optical power from the LED appeared more stable in the sampled data. However, there was a gradual decay in the optical power over the sampling period of 30 minutes which was not seen with the arc-lamp. This is different from the decay seen when the battery was used as shown in (Figure 28).

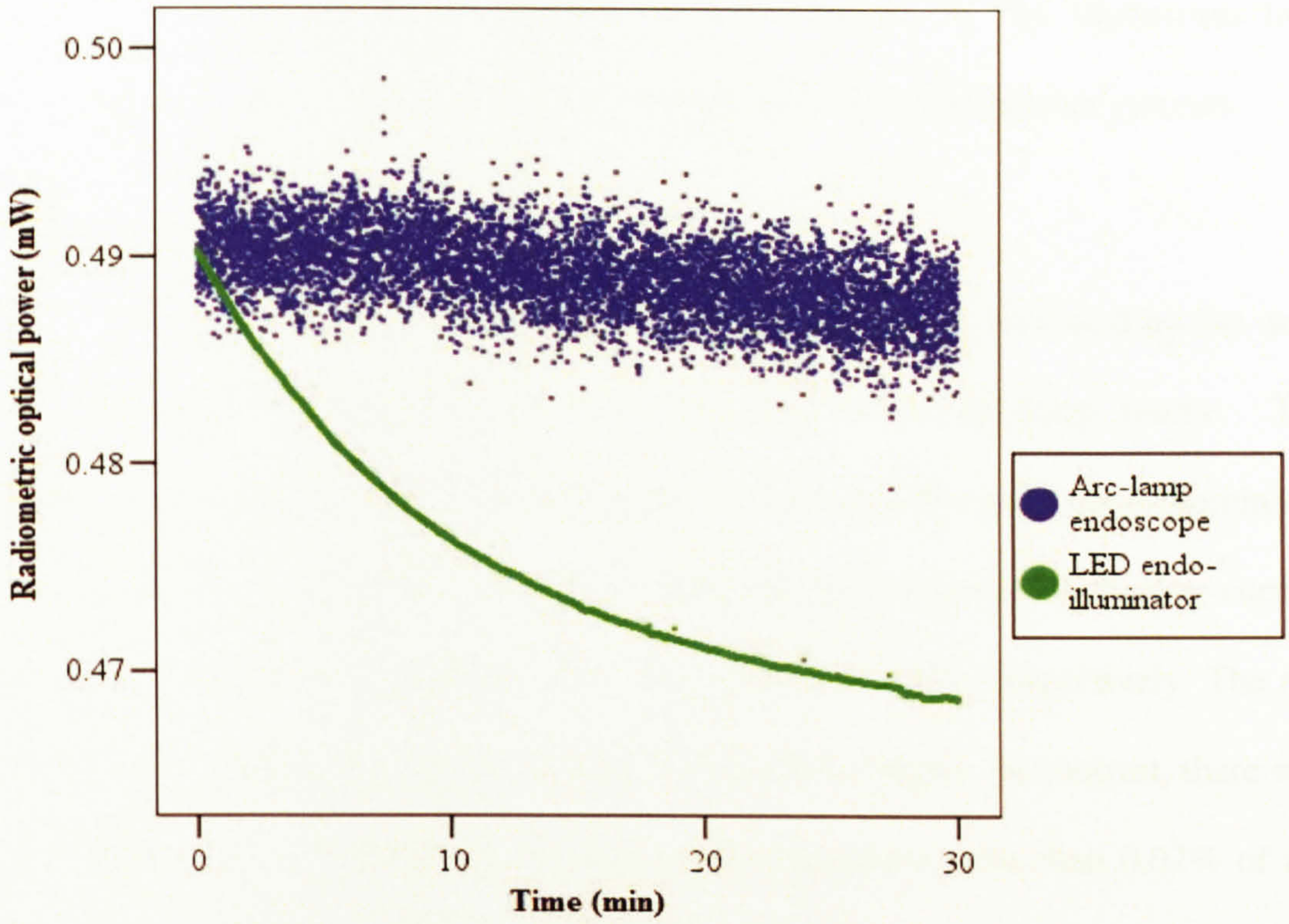

Figure 30 Lower frequency sampling of optical power over 30 minutes. Illumination instability of the arc-lamp source is indicated by the blue dots. The LED data was more stable (green dots) but showed a gradual decay over time. The Y-axis scale was truncated to illustrate the instability of the arc-lamp source.

4.5.4.2 **High frequency sampling**

4.5.4.2.1 *Method*

As a result of the findings in the previous section on low frequency direct sampling of flickering, a measuring system capable of more rapid data capturing was required. A photodiode (model SM05PD1, Thorlabs Inc., Newton, NJ, USA) combined with an oscilloscope (model TDS3052B, Tektronix Richardson, TX , USA) was used to measure the relative brightness intensity of the 300W xeon arc-lamp light source and the LED endo-illuminator at 2.5kHz with five repetitions. Discrete Fourier

Transforms were used in the Matlab software (version 7.0, The Mathworks Inc., MA, USA) to determine the magnitude spectra of the two illumination systems.

4.5.4.2.2 *Results*

The variation in optical power of the LED endo-illuminator, indicated by the non-oscillating line in Figure 31, was less than that of the arc-lamp source. The magnitude spectra of the arc-lamp (Figure 32 left) and the LED endo-illuminator (Figure 32 right) showed that the former light system has strong alternating current (AC) components at 36Hz and smaller ones at 2 Hz and 72Hz respectively The AC components represented around 5% of the total power output. In contrast, there was virtually no AC component for the LED endo-illuminator (less than 0.02% of the total power) compared to the dominant DC component.

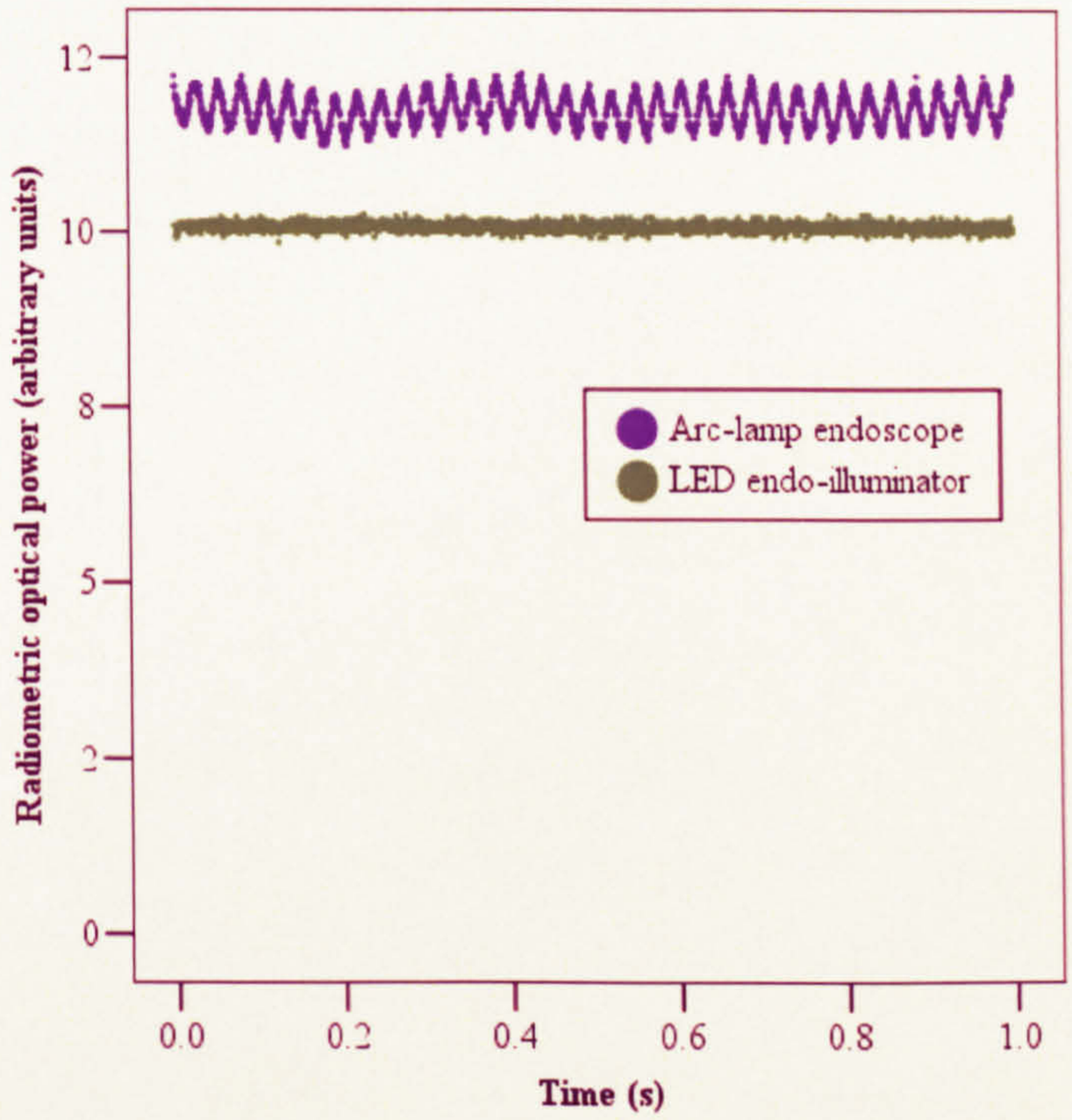

Figure 31 Illustrative examples of the time responses showing the oscillating signal from the arc-lamp source compared to the steady signal from the LED endo-illuminator with the data sampled at 2500Hz.

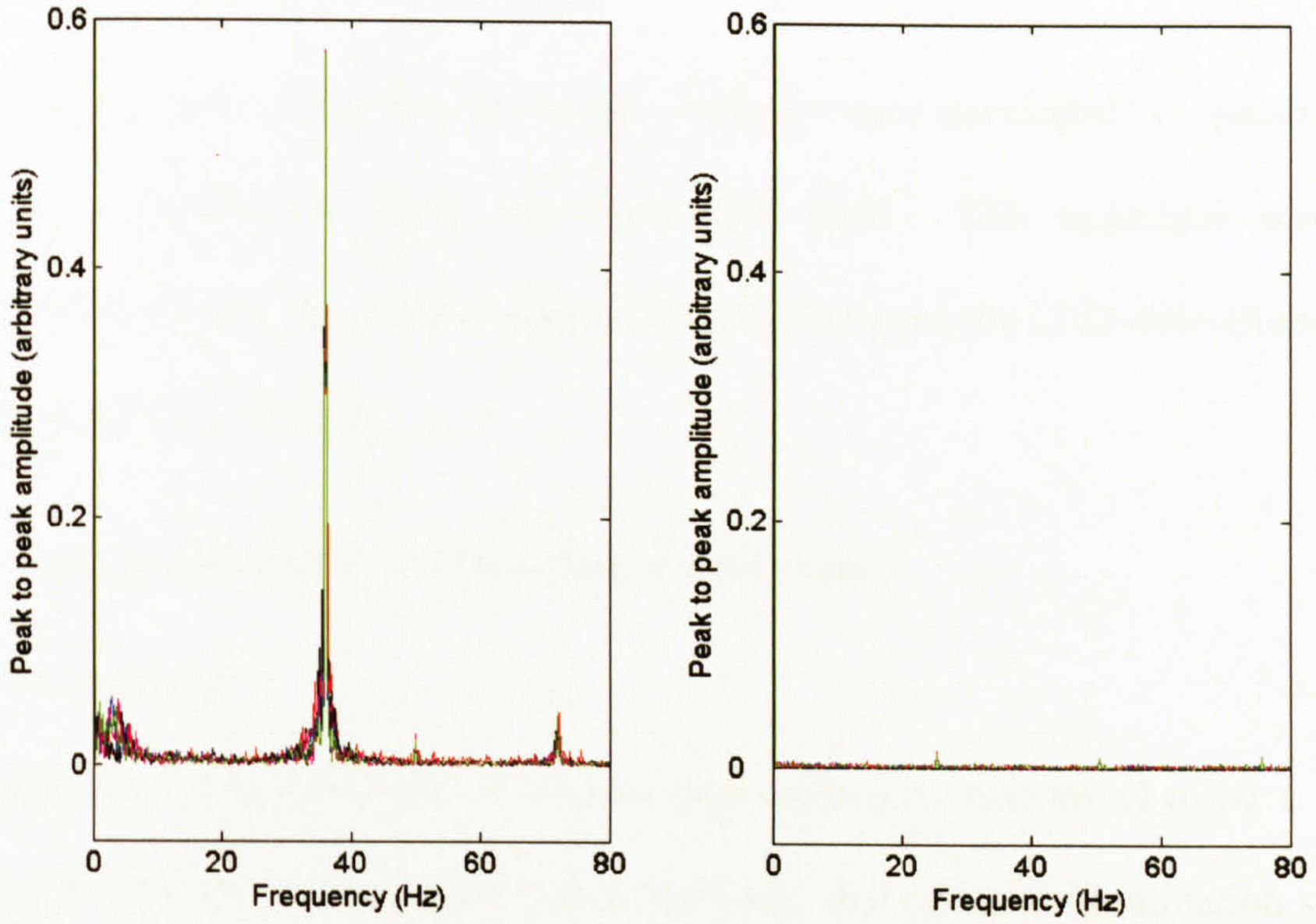

Figure 32 Magnitude spectra of the arc-lamp (left) and the LED endo-illuminator (right). The maximum amplitudes of the dominant DC components at zero Hz are not shown.

4.5.5 Illumination uniformity

A simple method using indirect image analysis was developed to quantify the illumination uniformity across the endoscopic field. This technique was then employed to compare the illumination uniformity between the LED endo-illuminator and arc-lamp light sources.

4.5.5.1 Image analysis for estimation of uniformity

4.5.5.1.1 *Method*

The method of image analysis on illumination uniformity was tested using a 10mm endoscope powered by the 300W xenon arc-lamp as a co-axial illumination source. The shutter was set to automatic. Four setting/position variables were examined:

(1) The output light power was adjusted on the power output dial of the arc-lamp source to 0/6, 1/6, 2/6, 3/6, 4/6, 5/6, and full power at 6/6. The endoscope was placed at 90°, at a distance of 24mm from the target and at the widest zoom of 1.0x.

(2) Side-way tilting of the separate illumination endoscope so that the illumination was at 90°, 60°, 45° and 30° to the target. The endoscope was placed at a distance of 24mm from the target, at the widest zoom of 1.0x and power output adjusted to 4/6 of full power.

(3) Distance of the illumination source to target was adjusted to 50mm, 36mm, 24mm and 14mm. The endoscope was placed at 90° from the target, at the widest zoom of 1.0x and power output adjusted to 4/6 of full power.

(4) Zooming by the camera to approximately 1.0x, 1.5x and 2.0x as measured by the magnification on the screen. The endoscope was placed at 90°, at a distance of 24mm from the target and power output adjusted to 4/6 of full power.

Five images were taken at each setting and position. The central portion of the image was cropped to enable consistent comparisons between images. The luminance plane of each image was extracted and the point of highest average intensity, the centroid, was determined by the Vision Assistant software (Figure 33). The pixel intensity was measured along a horizontal line drawn at the level of the centroid. The pixel intensity distribution, in arbitrary units from 0 to 255, was then plotted against the pixel position which was 447 pixels in length in the cropped images (Figure 33).

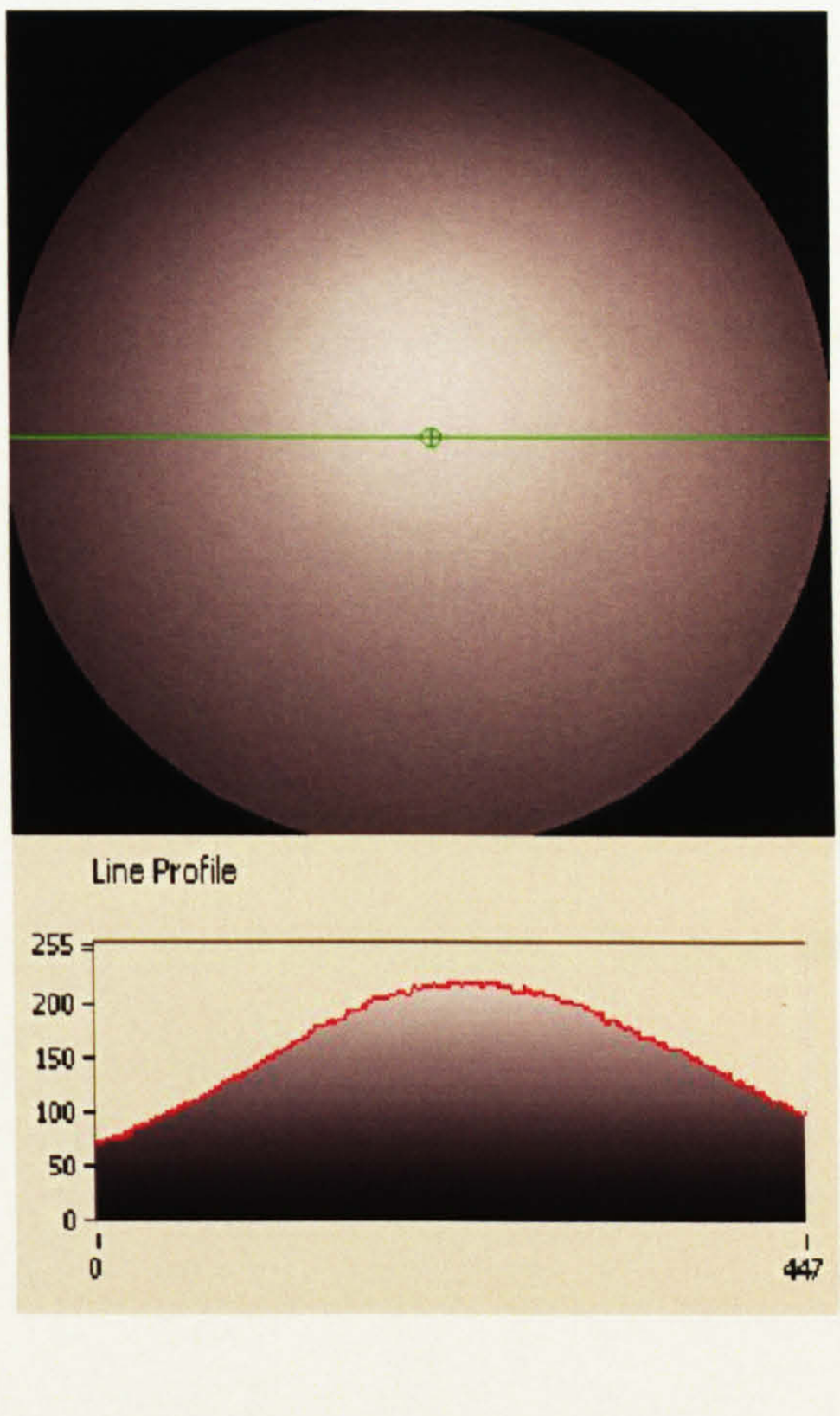

Figure 33 Line profile across the illuminated field at the level of the centroid.

A trend-line using a 2nd order polynomial curve was fitted to each data set:

$$y = ax^2 + bx + c$$

In order to estimate the parameters a, b and c, a minimum variance unbiased estimation approach was employed (Kay, 1993). This method ensured the variances of the estimators were minimised and thus high confidence levels of the estimated parameters could be achieved. Cross-correlation coefficients (R^2) were calculated for the fit of the data to the curves. These parameters were obtained from the data and exported to a Microsoft Excel spreadsheet where the trend line was applied.

The second order derivative, which represents the convexity of the curve, was calculated:

$$\frac{d^2y}{dx^2} = 2a$$

This represented the change in illumination intensity from the periphery to the centre of each image, with a higher convexity magnitude (2a) indicating a less uniform illuminated field. The mean values were compared.

4.5.5.1.2 *Results*

The spatial variation in intensity across an image reduced from the brightest central part to the dimmer peripheral part of the image. The pixel intensity data fit closely to the 2nd order polynomial curves (R^2 >0.94).

The convexity was not affected by changes in the power of the light source within the usual range used (1/6 to 5/6). At full power 6/6, there was a drop in convexity due to the artefactual effect of oversaturation at the centre of the image (Figure 34).

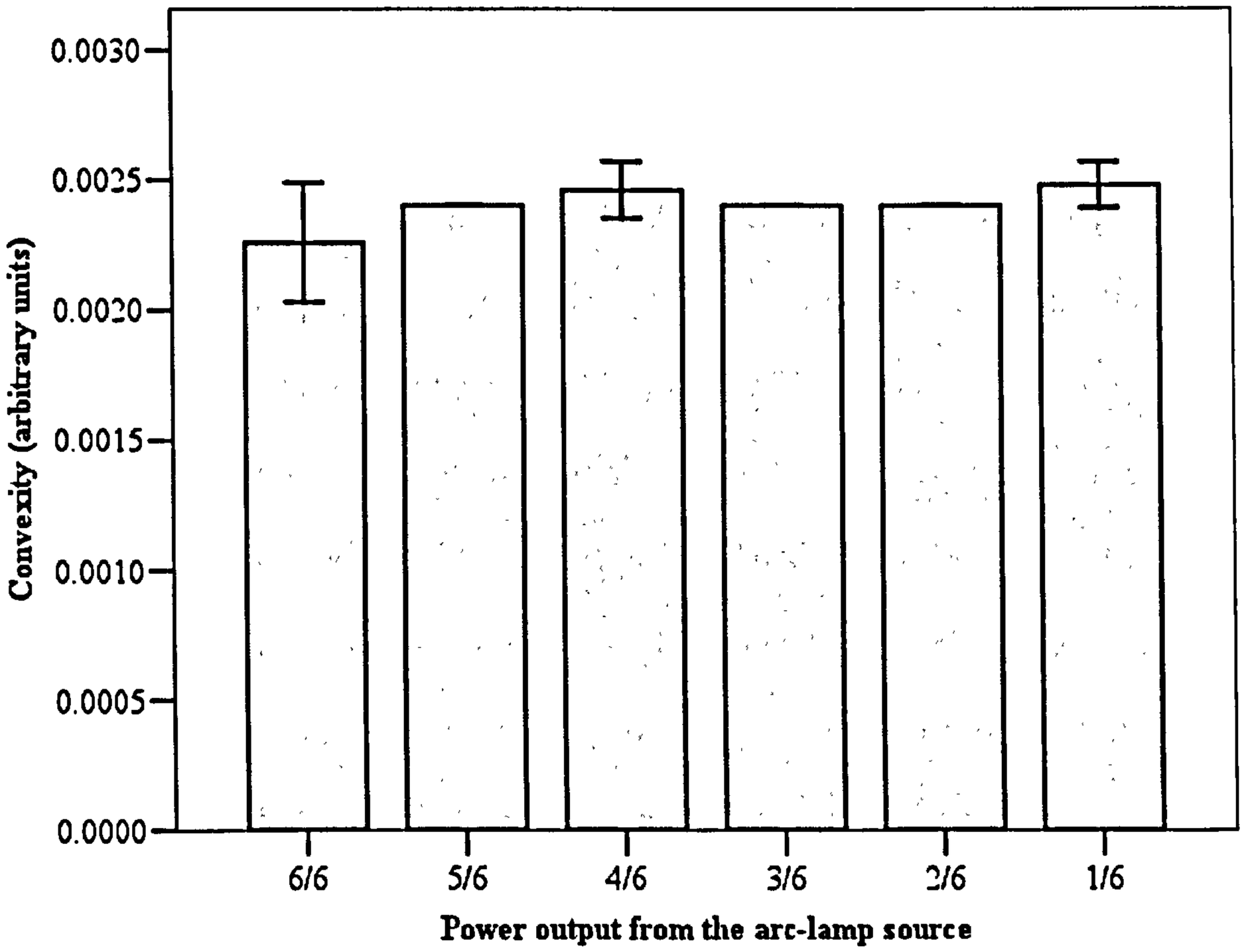

Figure 34 Effect of output power on illumination uniformity. The magnitude of the second derivatives ($\frac{d^2y}{dx^2} = 2a$) representing the convexity of the curves, and hence uniformity. The convexity of the illumination curves are similar when the output from the arc-lamp source was set at 1/6 to 5/6. Mean convexity (± 2 SD) shown.

Tilting of the endoscope from 90° to 60° did not change the convexity of the curve. However at 45° and 30°, the reduction in curve convexity was significant (Figure 35).

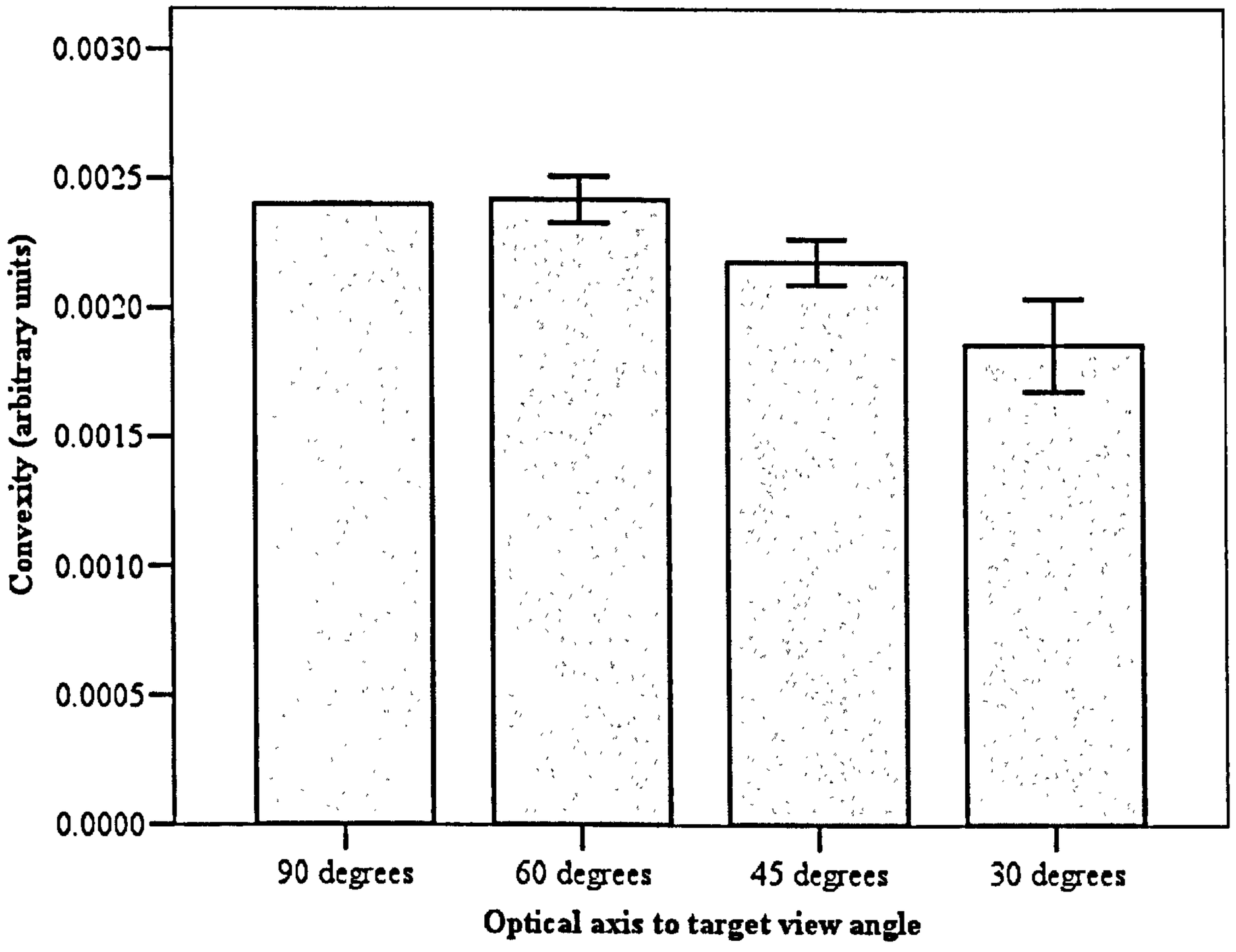

Figure 35 Effect of angle of direction of illumination on illumination uniformity. Tilting of the illumination by 30° did not cause changes. Mean convexity (± 2 SD) shown.

The effect of changes in the illumination source-to-target distance on the convexity was small. The exception is where the light source was very close at 14mm, the convexity was reduced due to the artefactual effect of oversaturation at this close distance (Figure 36).

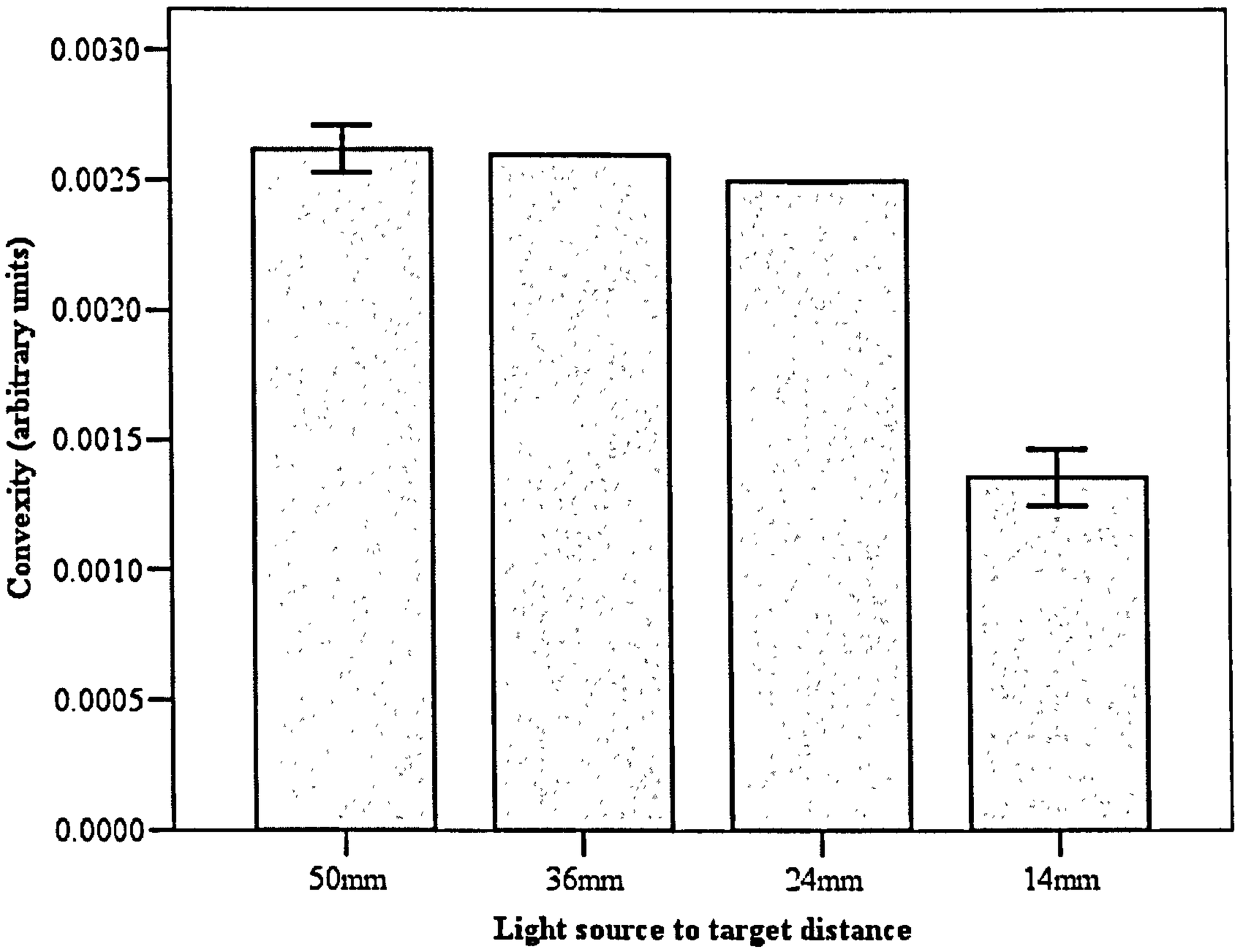

Figure 36 Effect of distance of illumination on illumination uniformity. Reduction of convexity was an artefactual effect due to central white-out when the illumination was at close distance of 14mm. Mean convexity (± 2 SD) shown.

Camera zooming resulted in significant changes in the convexity of the curves with the illumination in the image appearing more uniform when zoomed into the target (Figure 37).

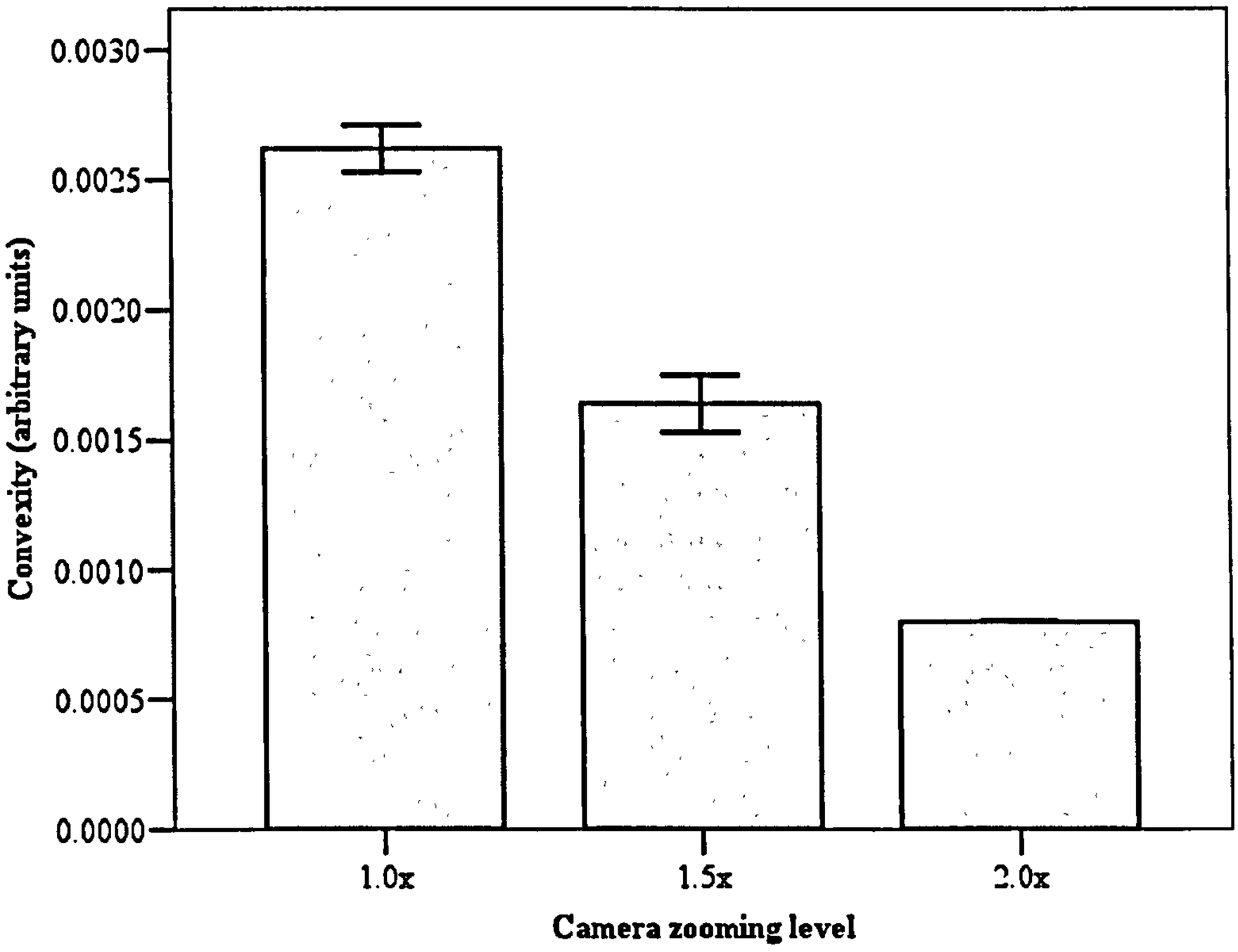

Figure 37 Effect of zooming on illumination uniformity. The convexity reduced when the image was zoomed in. Mean convexity (± 2 SD) shown.

4.5.5.2 Comparison of LED endo-illuminator and arc-lamp source

4.5.5.2.1 *Method*

The illumination uniformity across the endoscopic field under the following illumination conditions was studied:

(1) co-axial illumination by the viewing endoscope at 6cm;

(2) separate illumination by the 10mm endoscope at 4cm;

(3) separate illumination by the 10mm endoscope at 8cm;

(4) separate illumination by the LED endo-illuminator at 4cm; and

(5) separate illumination by the LED endo-illuminator at 8cm.

Five images were taken under each of the above illumination conditions and the mean values were compared.

4.5.5.2.2 *Results*

The curves from the LED endo-illuminator were flat with a low convexity magnitude indicating uniform illumination (Figure 38). In contrast, the curves from the arc-lamp endoscopic illumination were much more convex, especially at 4cm, which was similar to the co-axial illumination. The illumination became more uniform by a factor of three when the light-to-target distance was increased to 8cm. The change in uniformity was more noticeable with the arc-lamp compared to the LED endo-illuminator (Figure 38).

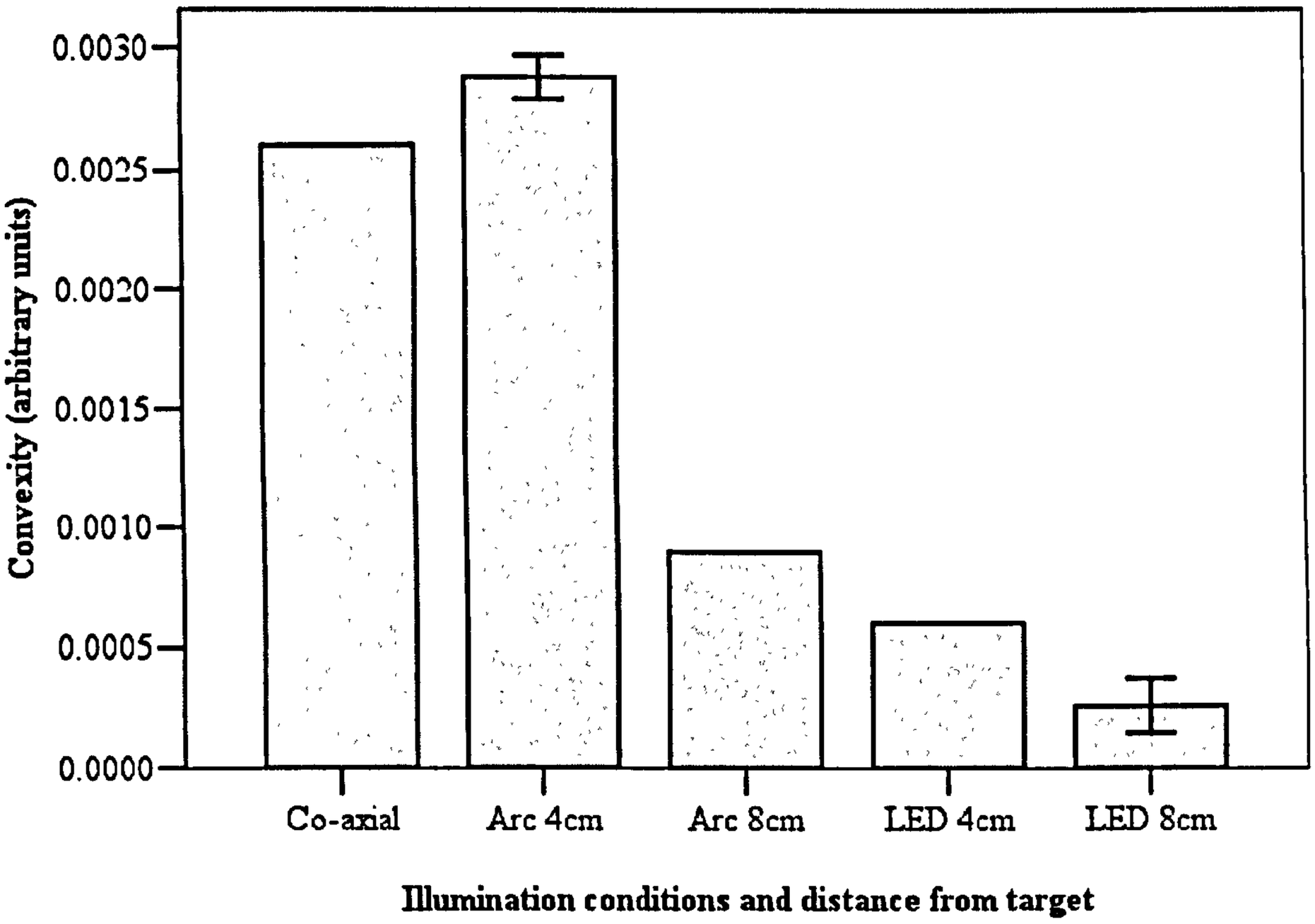

Figure 38 The magnitude of the second derivatives ($\frac{d^2y}{dx^2} = 2a$) representing the convexity of the curves, and hence uniformity from co-axial illumination, arc-lamp illumination at 4cm and 8 cm, and LED illumination at 4cm and 8cm. Mean convexity (± 2 SD) shown.

4.5.6 Shadow sharpness

4.5.6.1 Edge strength analysis

The edge strength of the cast shadow determines its sharpness, which was defined in the experiment as the magnitude of intensity gradient at each pixel position. The edge strength profile was measured within a pre-determined line drawn across the shadow.

There were two shadow edges on a cast shadow of a narrow object; one was the switch from the bright region to the dark region and the other was vice versa. Two threshold values were set – Tb for the bright region and Td for the dark region. For the first shadow edge which represents the switch from the bright region to the dark region, the pixel intensity decreased. The starting point of the first shadow edge was defined as the point where all consecutive gradient points were negative with the value of the starting pixel greater than Tb. The end point of the shadow edge was defined as the location where all consecutive gradient points were negative with the last pixel value smaller than Td. For the second shadow edge which represents the switch from the dark region to the bright region, the pixel intensity increased. The gradient of this edge was positive and the starting pixel value was below Td. The starting point of the edge was defined as the location where all consecutive gradient points were positive with the value of the starting pixel smaller than Td. Similarly, if all consecutive gradient points were positive with the last pixel value greater than Tb, this location was defined as the end point of the second shadow edge.

The width of the shadow edge was estimated from the starting and ending positions of the shadow edges as described above. Distinct narrow peaks represented sharp

shadows, and on the other hand, wide peaks represented background noise of the wide penumbra of blurred shadows (Jain, 1989).

4.5.6.2 Shadow sharpness with the LED endo-illuminator and the arc-lamp

4.5.6.2.1 *Method*

Images were taken as in the set-up described in the previous section with the addition of a 5mm laparoscopic scissors inserted into the field from the left side to cast a shadow.

Five images were taken under each of the following illumination conditions:

(1) separate illumination by the 10mm endoscope at 4cm;

(2) separate illumination by the 10mm endoscope at 8cm;

(3) separate illumination by the LED endo-illuminator at 4cm; and

(4) separate illumination by the LED endo-illuminator at 8cm.

A pre-determined line was drawn across the shadow of the instrument and the edge strength profiles were analysed. Edge I was the switch from the bright region to the dark region and vice versa for Edge II.

4.5.6.2.2 *Results*

The edge strength profile of cast shadows from the LED endo-illuminator (Figure 39 right) showed narrower, hence sharper, shadow edges compared to the arc-lamp endoscopic illumination (Figure 39 left), due to the blurring of the shadow penumbra of the latter. The shadows were sharper when the distance of either illumination sources were at 8cm compared to at 4cm from the target (Figure 40and Figure 41).

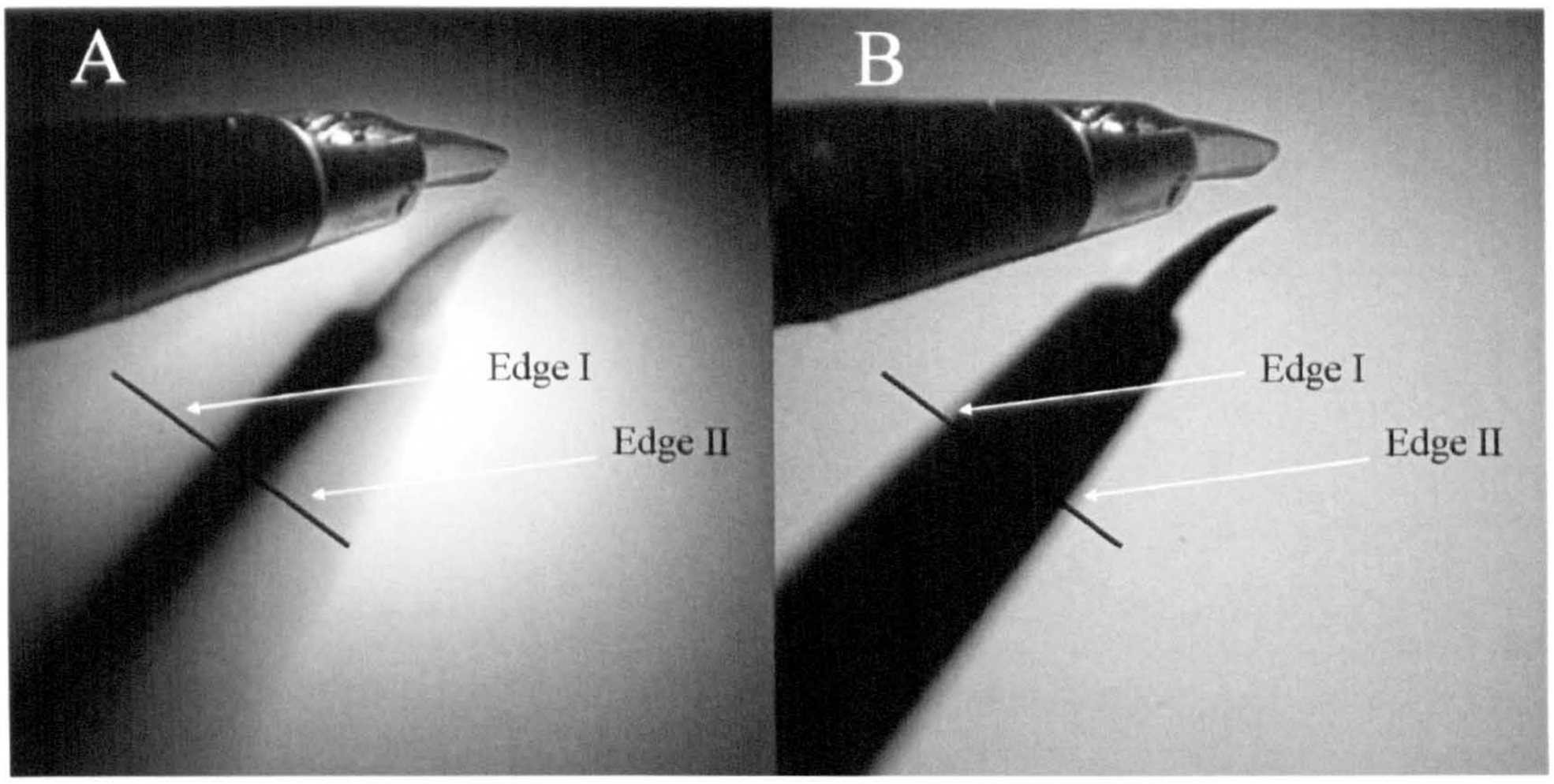

Figure 39 Cast shadows of an instrument using arc-lamp based illumination (A) and LED endo-illuminator (B) placed at 4cm from the target. Edges I and II were estimated for shadow sharpness.

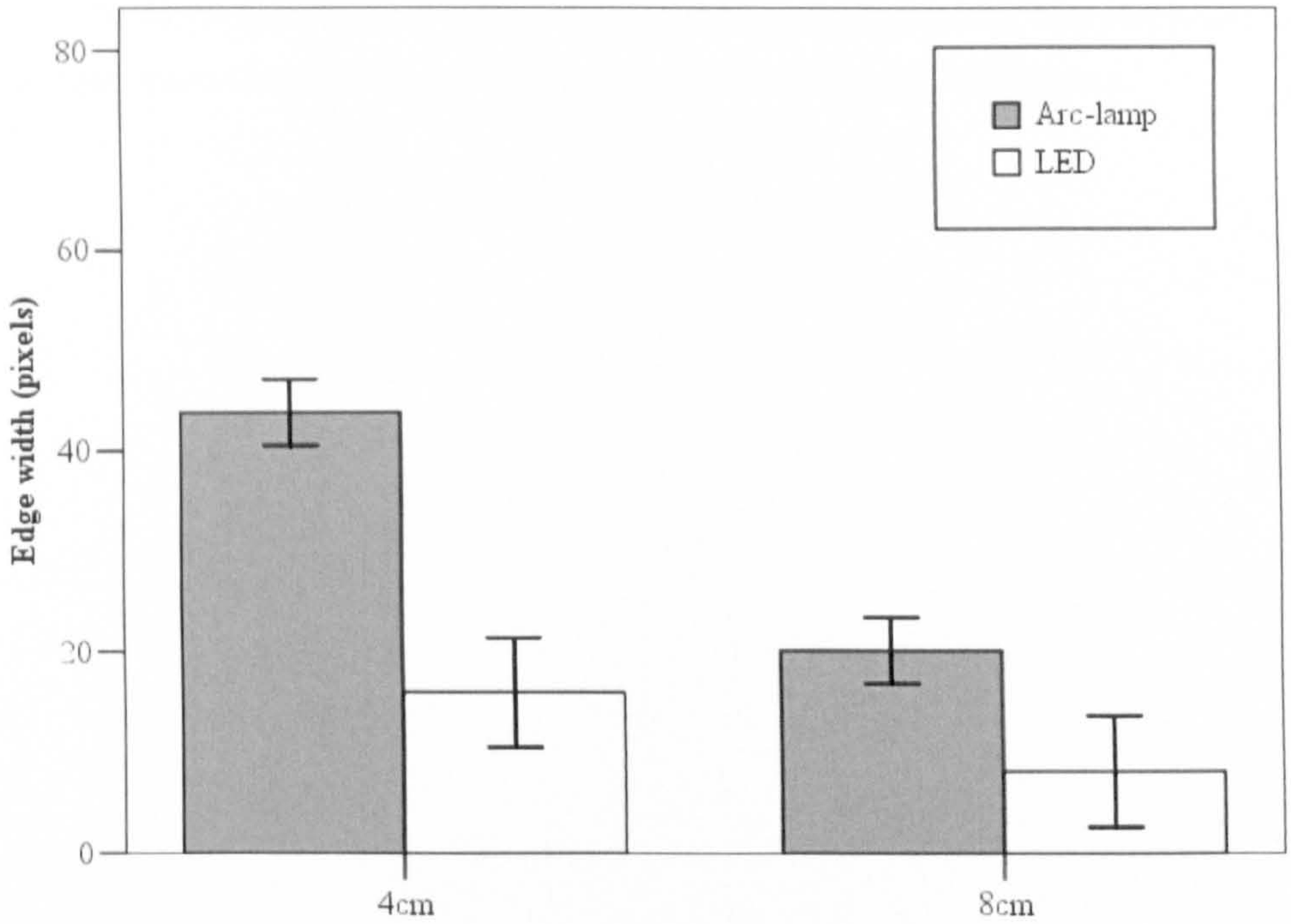

Figure 40 Shadow edge widths of Edge I with illumination distance of 4cm and 8cm from the arc-lamp light source and LED endo-illuminator. Mean values (+/- 2SD) shown.

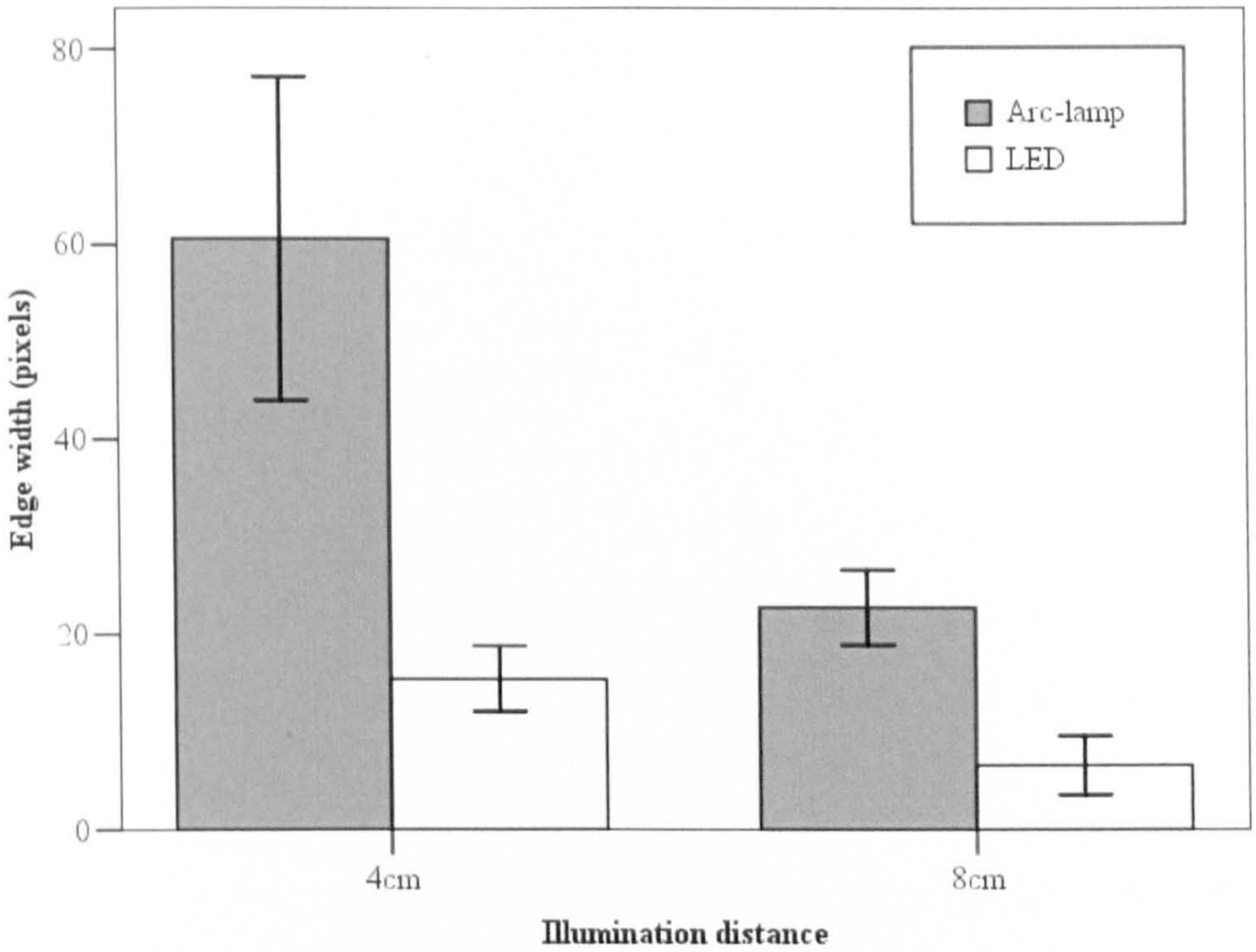

Figure 41 Shadow edge widths of Edge II with illumination distance of 4cm and 8cm from the arc-lamp light source and LED endo-illuminator. Mean values (+/- 2SD) shown.

4.6 Peripheral endoscopic perception with the LED endo-illuminator

4.6.1 Aim

The aim for this part of the project was to investigate the visual perception of the peripheral endoscopic field under different illumination conditions, using conventional co-axial illumination, separate illumination with arc-lamp light source and separate illumination with the LED endo-illuminator as described in the previous section. The study was designed to test the hypothesis that fine details discrimination in the peripheral endoscopic field is better under the LED illumination.

4.6.2 Methods

4.6.2.1 Subjects

Thirteen healthy subjects (4 male and 9 female) with a median age of 33 years (range 26-44 years) took part in the study. Initially 14 subjects was planned for the experiment However, one of the subjects had not brought his glasses and therefore was excluded. All tested subjects reported they were of good general health with normal or corrected vision. Four of the subjects were surgical trainees and the remaining were non-medical professionals.

4.6.2.2 Experimental set-up

The experimental video-endoscopic set-up was similar to Figure 23 in Section 4.5.2.1.2 and consisted of a direct viewing 10mm endoscope (model 26003AA, Storz), CCD camera head (Image 1 3-chip, model 22210030, Storz) and camera

control unit (model 22200020, Storz). The viewing endoscope was placed at an optical-to-target axis angle of 60° and 10cm from the target.

The target consisted of a piece of A4 white paper with a central horizontal black line and 3 pre-printed rows of 32 Landolt C letters (black and in font size 6) at the top one-third of the paper. Landolt C is an optotype and used as a standardised symbol for visual acuity testing (Chen et al., 2005). It consists of a broken circle, the gap of which has the same width as the thickness of the line which is one-fifth of the diameter of the circle (Figure 42).

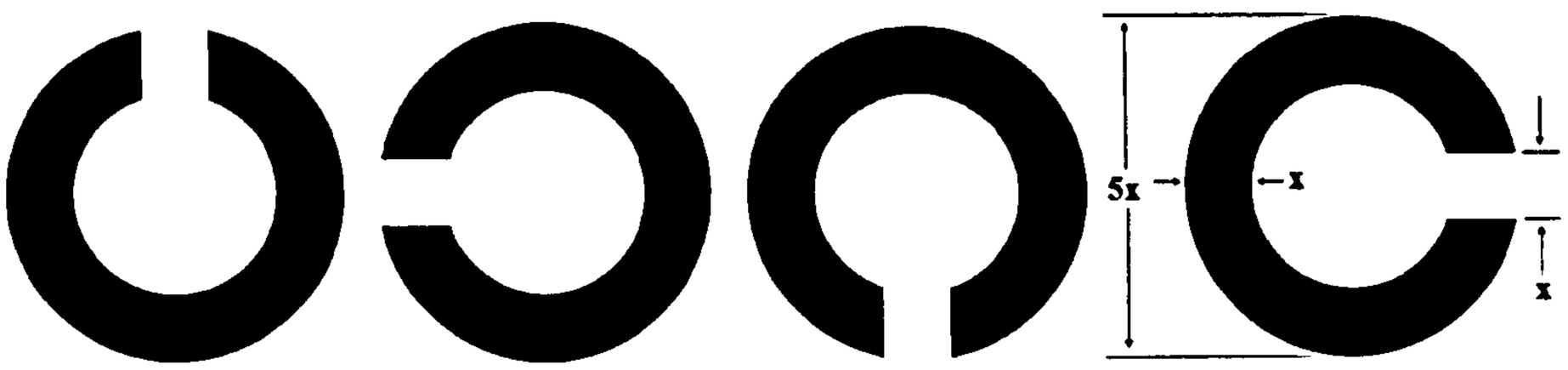

Figure 42 Landolt C optotypes.

In this experiment, the printed Landolt C has a diameter of 2mm and the gap width was 0.4mm. The orientation of the gap was at one of four positions (left, right, up or down) and eight letters of each orientation were randomly placed in each of the 3 rows which were located at the distal periphery of the endoscopic field.

The three illumination tested were 1) conventional co-axial endoscopic arc-lamp light via the direct viewing endoscope placed at an optical-to-target axis angle of 60° and 10cm from the target; 2) separate arc-lamp endoscopic light placed at 10cm perpendicular to the target; and 3) separate LED endo-illuminator, also placed at 10cm perpendicular to the target .

To avoid white-out at the centre of the image, a manual shutter was used and the light intensity from the arc-lamp source was adjusted until the central black line in the centre of the paper can be seen without over-saturation. The LED endo-illuminator was powered by the PSU and the current was set at 350mA. There was no over-saturation at this illumination level (Figure 43).

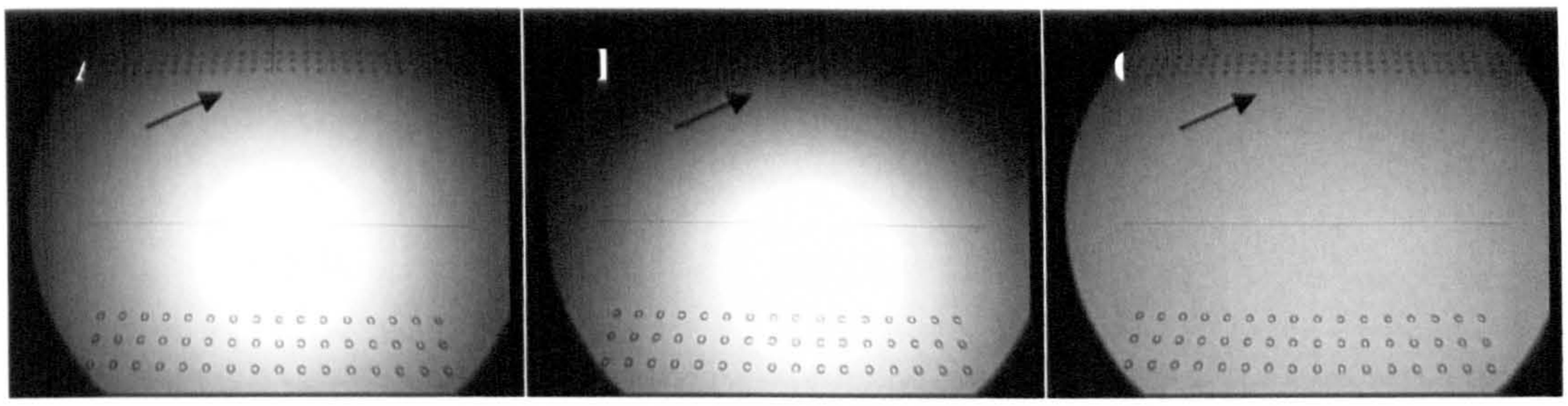

Figure 43 Perception of the orientation of the printed Landolt C letters at the peripheral endoscopic field (arrow) under 3 illumination conditions, A) co-axial arc-lamp source, B) separate arc-lamp source and C) separate LED endo-illuminator. The central black line was for adjustment of the arc-lamp source output to prevent over-saturation. The letters in the proximal field were for alignment of the target.

The endoscopic images were recorded by the DVD recorder (AIDA model 20204020, Storz) at 25fps as MPEG video-clips of 30 seconds durations.

4.6.2.3 **Procedure**

The video clips were played to the subjects on a laptop computer with a 14.1-inch screen (PCG-Z1XSP, Sony Corporation, Japan) using Microsoft Windows Media Player at full screen. The subjects were allowed to adjust their viewing position during the experiment. The order of video-clips of the three illumination conditions was counter-balanced by block randomisation. The subject read out his/her interpretation of the orientation of the Landolt C letters row by row and the responses were recorded by the experimenter. The video-clip was played repeatedly

until all responses were obtained and the same procedure was then applied to the next video-clip. Three marks were given for every correct response and one mark was deducted for every incorrect response. In total, 18 videos were shown and for each video, the maximum possible score was 288.

4.6.2.4 **Statistical analysis**

The data was not normally distributed and was expressed as median score and interquartile range. Friedman's ANOVA was used to compare the three illumination conditions and Wilcoxon signed rank test was used for post hoc testing with Bonferroni correction for multiple tests. Statistical significance level was set at 5%.

4.6.3 **Results**

The experiment was completed by all subjects. The best visual perception with the highest median score of 237 (I.Q.R. 37) was achieved when the LED endo-illuminator was used as the illumination source. The worst median score of 157 (I.Q.R. 36) was obtained when the illumination was from the arc-lamp endoscopic light placed perpendicular to the target. When the co-axially placed the arc-lamp endoscopic light source was used the median score was 219 (I.Q.R. 45). The scores were significantly different ($\chi 2=129$, d.f.=2, $p<0.001$) and post hoc comparisons also showed significant differences between 1) co-axial endoscopic arc-lamp light and separate endoscopic arc-lamp light ($z=-7.614$, $p<0.001$); 2) co-axial endoscopic arc-lamp light and separate LED endo-illuminator light ($z=-5.308$, $p<0.001$); and 3) separate endoscopic arc-lamp light and separate LED endo-illuminator light ($z=-7.673$, $p<0.001$) (Figure 44).

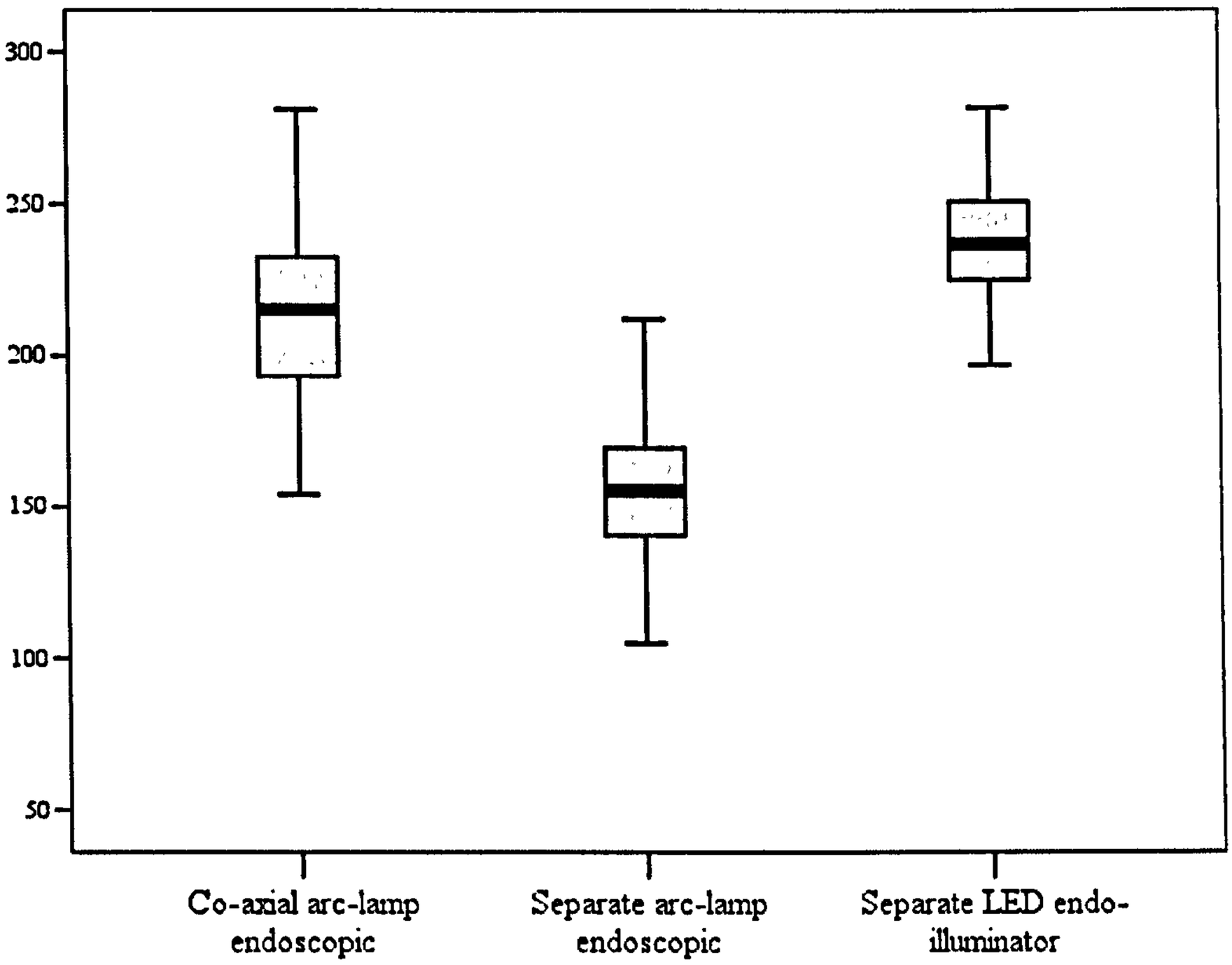

Figure 44 Accuracy in the perception of the peripheral endoscopic field under 3 illumination conditions showing subjects obtained the highest score with the LED endo-illuminator. Friedman's ANOVA $p<0.001$

4.7 Distance estimation with endoscopic shadows

4.7.1 Aims

The aim of the study was to compare the ability of subjects in distance estimation under different endoscopic illumination conditions.

In this study, we tested the hypotheses that 1) distance estimation is easier in the presence of a shadow; and 2) the illumination provided by the LED endo-illuminator produces shadows that are useful for distance estimation.

4.7.2 Methods

4.7.2.1 Subjects

Twenty-four healthy subjects consisted of 8 surgeons and 12 non-medical professionals with normal or corrected eyesight and good self-reported general health took part in the study. There were 12 male and 12 female subjects with a median age of 31 years (range 26 to 44 years). The subjects were not aware of the hypotheses of the study.

4.7.2.2 Experimental set-up

The same video-endoscopic equipment as described previously in Section 4.5.2.1.2 was used and the viewing endoscope was placed at an optical-to-target axis angle of 60° and 8cm from the target. Video-clips were similarly recorded under the three lighting conditions, 1) conventional co-axial endoscopic arc-lamp light via the direct viewing endoscope placed at an optical-to-target axis angle of 60° and 8cm from the target; 2) separate arc-lamp endoscopic light placed at 8cm perpendicular to the

target; and 3) separate LED endo-illuminator, also placed at 8cm perpendicular to the target. The imaging equipment was white-balanced before each recording.

The background consisted of simulated gall bladder and adjacent viscera made up of silicone materials. A red pin head of 3mm diameter was inserted into the simulated gall bladder. A 5mm laparoscopic grasper was introduced into the endoscopic field from the left so that the tip of the instrument was at one of the following six actual distances (A) from the red pin-head: 1) 5mm, 2) 7mm, 3) 12mm, 4) 20mm, 5) 29mm and 6) 40mm. None of the instruments moved during the video recording.

The recordings were obtained for each of the six instrument positions under the three illumination conditions and were saved as MPEG movie files, each with a duration of 30 seconds (Figure 45).

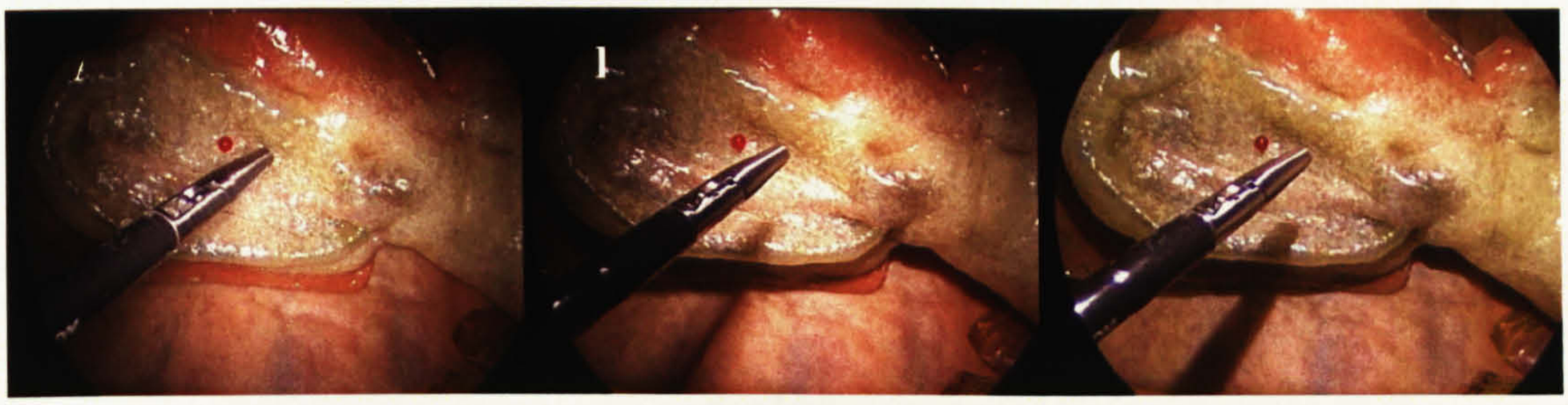

Figure 45 Snap shots of video recordings of the static instrument with its tip at 20mm from the red pin head and the operative field illuminated by A) co-axial endoscopic arc-lamp source, B) separate endoscopic arc-lamp source, C) separate LED endo-illuminator.

4.7.2.3 **Procedure**

As in Section 4.6, the video clips were played to the subjects on a laptop computer with a 14.1-inch screen using Microsoft Windows Media Player at full screen. The subjects were allowed to adjust their viewing position during the experiment.

The 18 video-clips were shown to the subjects in a counter-balanced sequence. The subjects were asked to estimate the distance between the tip of the instrument and the red dot. To facilitate their estimation, the true scale of the instrument, the red pin head and the tape measure were shown on the data collection sheet and they were asked to mark their estimation of distance on the tape measure on the data collection sheet.

4.7.2.4 Error score calculation

An error score calculation was developed in this part of the research to account for the variability in distance estimation in general. The method was endorsed by a psychologist experienced in experimental research methodologies.

At the start of the experiment, each subject was asked to estimate the length of 20mm on a line drawn on a piece of paper. This estimation (L) was divided by 20mm to give a ratio (R) to account for the error in the subject's estimation of length:

$$R = \left(\frac{L}{20}\right)$$

The subjects' estimated distances in each video-clip as marked on the data collection sheet were measured (D). In order to account for the variability in distance estimation between subjects in general, D was divided by R to derive the adjusted estimated distance. The absolute difference between the actual distance (A) and the estimated distance $\left(\frac{D}{R}\right)$ was then calculated. Hence:

$$Error\,Score = \left|\left(\frac{D}{R}\right) - A\right|$$

4.7.2.5 **Statistical analysis**

The error scores were expressed as median (IQR). Statistical analysis was carried out using Friedman's ANOVA test for each actual distance and comparison was made between the three illumination conditions. Wilcoxon signed rank test with Bonferroni correction was used as a post-hoc test when the Friedman's ANOVA showed a significant result. Significance level was set at 5%.

4.7.3 **Results**

The median of the subjects' estimated distance of the 20mm (L) was 19mm (SEM 0.467; range 14 to 25mm). The error scores were not significantly different under the three illumination conditions, except in the case where the actual distance was 29mm (Friedman's ANOVA test, p=0.006), the error score under illumination by the LED endo-illuminator was significantly lower than the error score when under co-axial endoscopic illumination (Wilcoxon signed rank test, p=0.003) (Figure 46).

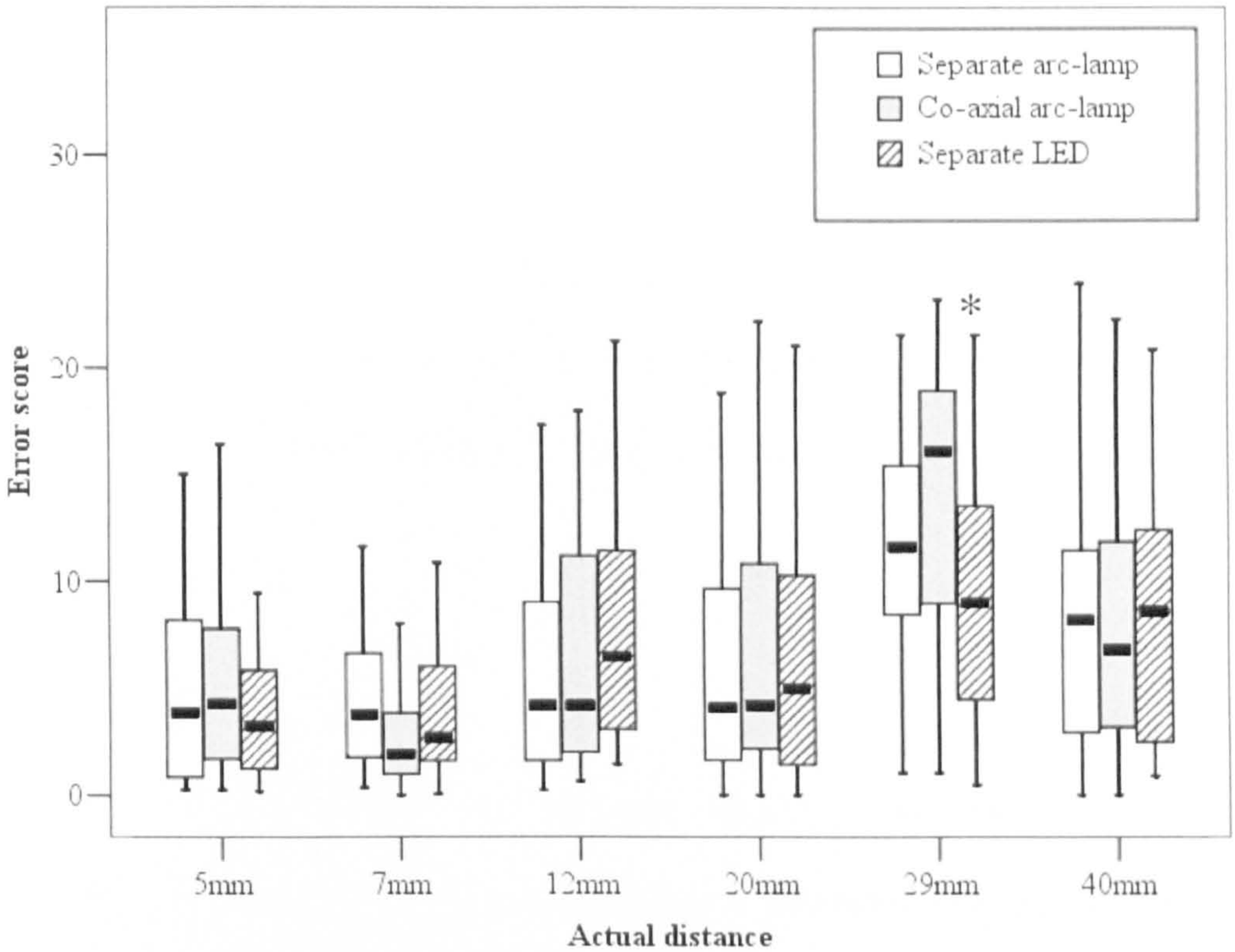

Figure 46 Box plot showing the error scores of different distances under the 3 illumination conditions. *The only significant difference was noted when the actual distance was 29mm (Friedman's ANOVA, p=0.006) and was due to the difference between the lower error score when the LED endo-illuminator was used compared to co-axial arc-lamp illumination (Wilcoxon signed rank test, p=0.003).

4.8 Moving shadows

4.8.1 Aims

In this experimental study, we tested the hypotheses that I) viewers assume shadow movement is due to object movement; and II) it is more difficult to determine the source of shadow movement when the light is moving.

4.8.2 Methods

4.8.2.1 Subjects

Thirty six healthy subjects (13 surgeons and 23 non-medical professionals) participated in this study. They had normal or corrected eyesight, and were not aware of the hypotheses of the experiment.

4.8.2.2 Experimental set up

Standard endoscopic equipment was used to obtain video recordings of moving shadow against four different backgrounds. The image was captured with a 10mm zero degree endoscope attached to a camera mounted on a clamp and the illumination was delivered using a second 10mm endoscope placed perpendicular to the background. An endoscopic instrument was placed between the illumination endoscope and background such that only the shadow was within the endoscopic view (Figure 47).

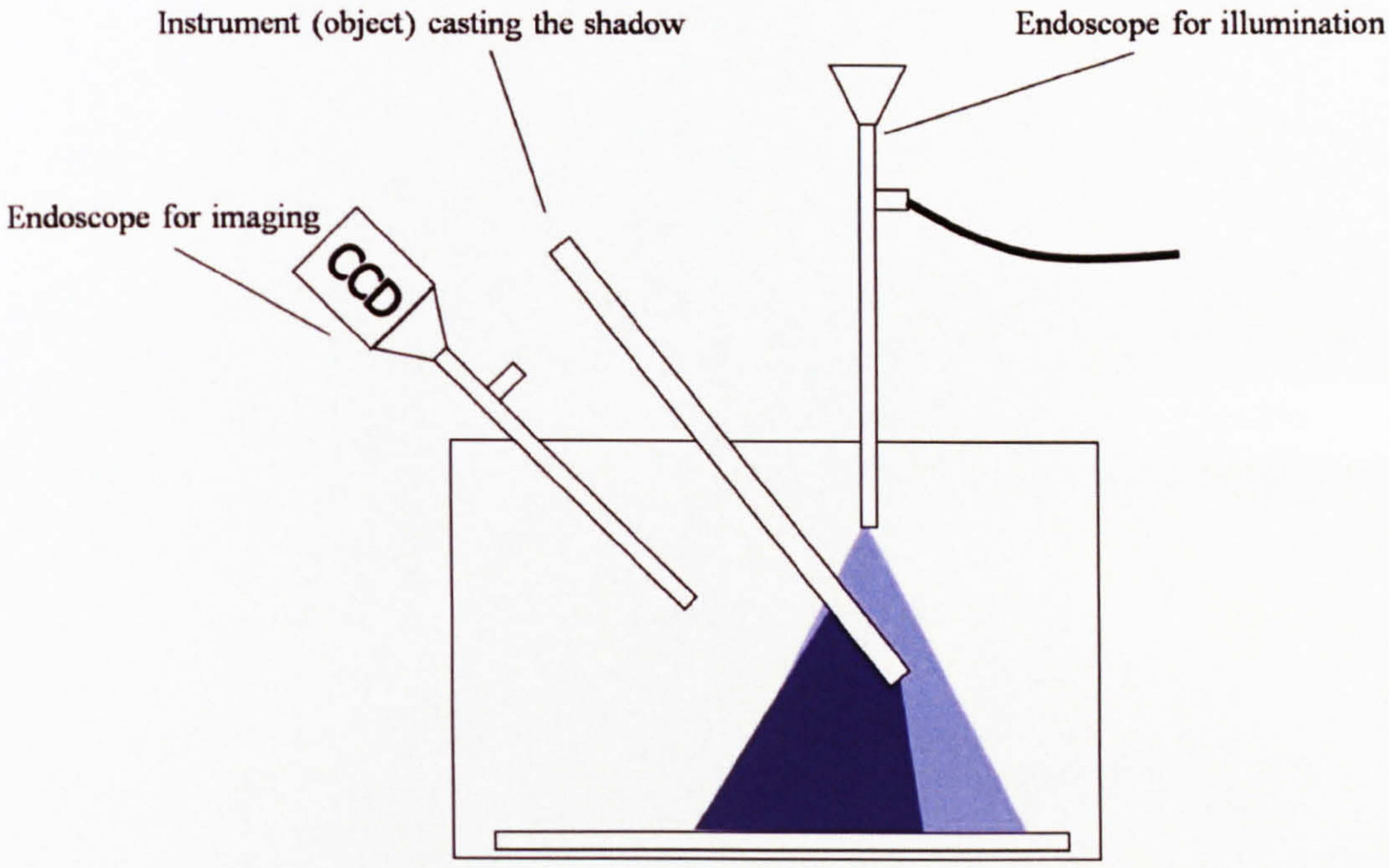

Figure 47 Schematic representation of experimental set up for the video recording. An instrument was introduced from the left side to cast the shadow onto the background surfaces.

All videos were edited to a duration of 5 seconds each. The backgrounds were: (i) plain white background; (ii) grid paper with 1mm squares; (iii) textured background of simulated visceral tissue; and (iv) undulating background consisted of simulated gall bladder and bowel loop made of silicone materials. These backgrounds have increasing complexity in terms of pattern and three-dimensional appearance (Figure 48).

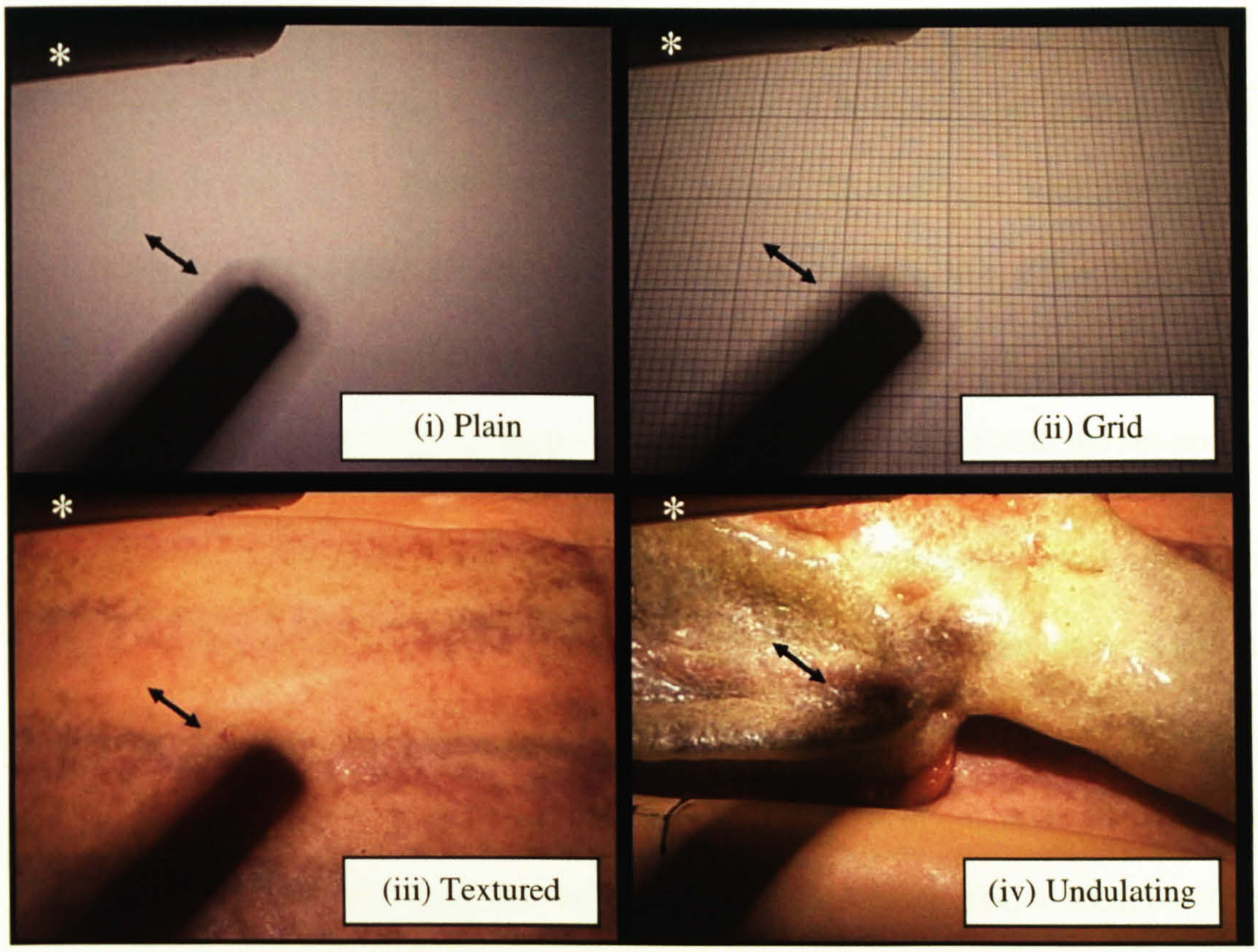

Figure 48 Moving cast shadow of the instrument (↔) onto four background surfaces. The instrument in the left upper corner (*) was included only in Experiment I.

In Experiment I, four videos were taken with the light source moving horizontally by 5-10mm. The endoscopic view also included the shaft of the stationary instrument in the upper left corner of the video image as an extra clue that the instrument was not moving (Figure 48). In Experiment II, four videos were obtained with a moving light source and another four videos were also prepared with the light source held static and the instrument moving horizontally by 3-5mm. Only the shadow was captured within the endoscopic video image in the second experiment.

4.8.2.3 **Procedure**

The endoscopic set-up, specifically, the relationship between the light source, the instrument and viewing endoscope, was explained to all subjects using a diagram

(Figure 47). The images were shown to the subject as video clips within a Microsoft PowerPoint slide show using a laptop computer placed in front of the subject with a magnification ratio of 2:1 in the centre of the screen. The subjects were allowed to view the videos in the most comfortable position. Before each task, a familiarisation video with no movements of the instrument or light source with the grid paper background was shown to the subjects to allow them to familiarise with the set-up.

In Experiment I, the four video clips were shown in a counterbalanced sequence allocated randomly by a computer and each video was repeated three times to give a total of 12 viewings per subject. Each subject was asked beforehand to indicate the estimated "maximum horizontal movement of the instrument" as seen in the video clip with the choices of (i) 0mm (i.e. no movement), (ii) 1-3mm, (iii) 4-6mm and (iv) 7mm or more. In Experiment II, the eight video clips were shown in a partially counterbalanced sequence. The subjects were asked whether they thought it was the light or the instrument that was moving in each video clip. At the end of Experiment II, all subjects were asked if they would be surprised if they were told that the instrument was stationary in all the videos in Experiment I, and whether they noticed the stationary instrument in the upper left corner.

4.8.2.4 **Analysis**

The endpoints were the correct distance of instrument movement (0mm) in Experiment I and the number of correct responses in relation to the source of moving shadows in Experiment II. Pearson's chi-square test was used to investigate the differences in the proportions of correct responses for each of the source of shadow movement (i.e. the instrument or light source), and the differences in the proportions

of correct responses between medical and non-medical subjects. Significance level was set at 5%.

4.8.3 Results

4.8.3.1 Experiment I

The distances of the "instrument movement" estimated by all subjects are shown in Figure 49. Ninety eight percent of responses given indicated that the instrument has moved despite the presence of the stationary instrument at the upper left corner of the image. Three subjects (one surgeon and two non-medical subjects) noted the instrument was stationary in eight viewings (six correct answers with the textured background and two with the grid background).

All subjects were surprised when they were told that the instrument did not move in any of the video clips in Experiment I. Also, none of the subjects noted the stationary instrument included in the corner of the image in Experiment I.

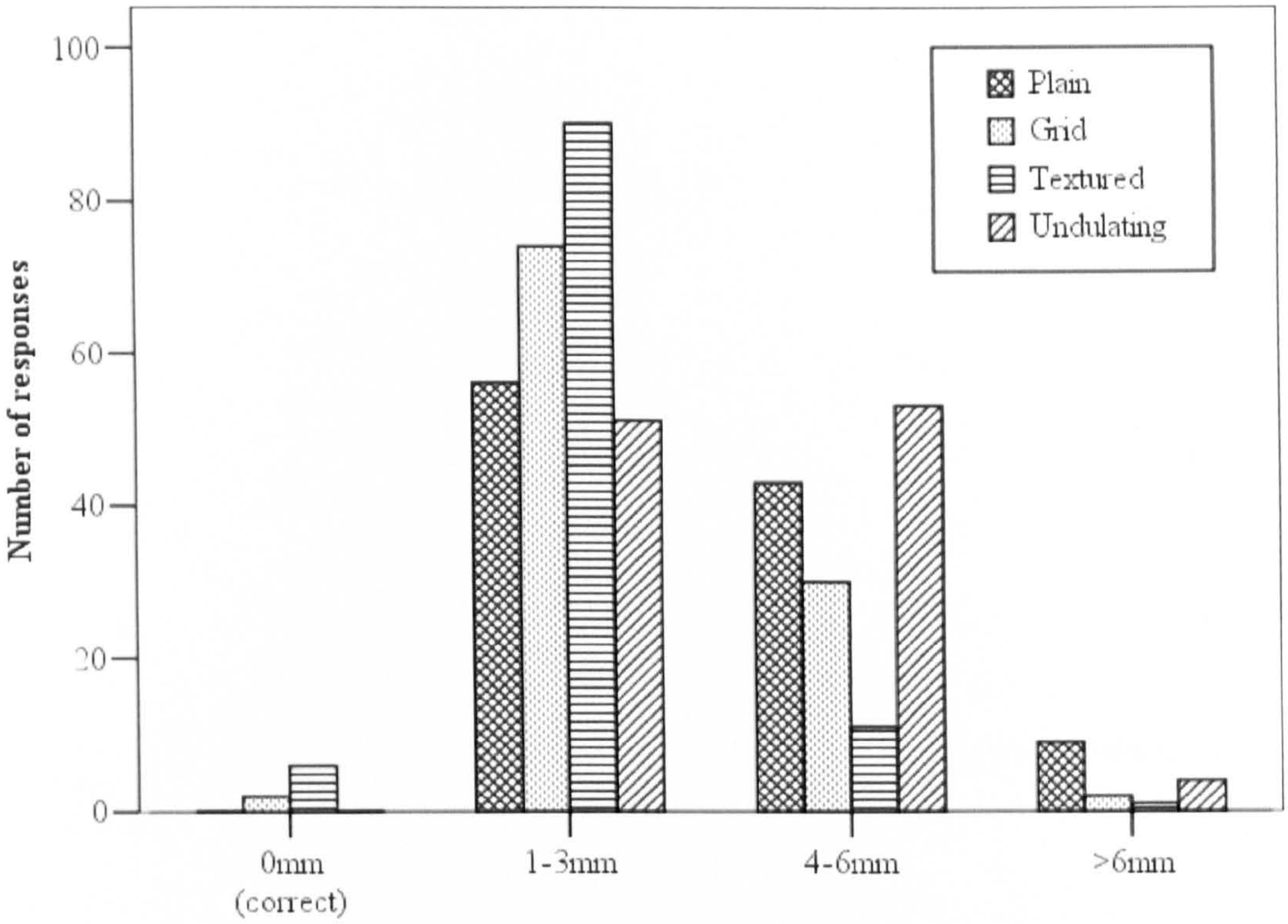

Figure 49 Results of experiment I. Subjects' estimated distance of movement by the instrument. 0mm was the correct answer as the instrument did not move in any of the videos.

4.8.3.2 **Experiment II**

Overall 186 out of 288 (65%) responses given were correct (Table 10). When the light was moving only 67 out of 144 responses (47%) were correct, whereas when the instrument was moving 119 out of 144 (83%) were correct ($\chi 2 = 41.05$, $p = <0.001$). The lower proportion of correct responses when the light was moving was due to more incorrect interpretations when the grid and textured backgrounds were used, where only 25% and 33% of the responses were correct respectively. There was no significant difference in the proportion of correct responses given by the surgeons compared to that given by the non-medical professionals (63% vs. 68%, $\chi 2 = 0.62$, $p = 0.43$).

Background	Light moving		Instrument moving	
	Correct	Incorrect	Correct	Incorrect
Plain	25	11	31	5
Grid	9	27	30	6
Textured	12	24	32	4
Undulating	21	15	26	10
Total	**67**	**77**	**119**	**25**

Table 10 Results of experiment II. Responses on the source of shadow movement (a) when the light was moving and (b) when the instrument was moving.

4.9 Laser diode illumination

The term "laser" is an acronym for Light Amplification by Stimulated Emission of Radiation. Laser is emitted when a current passes through a laser diode.

The use of blue laser diode in optoelectronic devices has recently attracted a lot of attention especially with the development of the optical storage media format known as the Blu-ray disc. This uses the blue laser at 405nm for reading and writing DVDs for high definition video and data with storage capacities of up to 50 gigabyte. The use of laser diode as an illumination source has not been previously explored.

4.9.1 Aim

As an extension of the development of the LED endo-illuminator, the feasibility of using a blue laser diode to generate endoscopic illumination was examined.

4.9.2 Methods

The laser illumination system prototype was constructed at the Physics department with the help from Dr Dan Elson of the Institute of Biomedical Engineering who assisted in data collection.

The laser was generated by a temperature stablised solid state blue laser diode (DFBL-9050, Suwtech, Shanghai, China) and power supply (LDC-2500, Suwtech) with an output power of up to 50mW at a wavelength of 473nm. The laser generator is classified as a Class 3B laser and appropriate laser safety precautions were required. The raw laser beam, either directly or through its reflections, has sufficient power to cause retinal injury. In the prototype, the laser generator and the proximal

part of the fibre were therefore encased within a custom-made metal box to prevent accidental reflection of the raw laser beam (Figure 50).

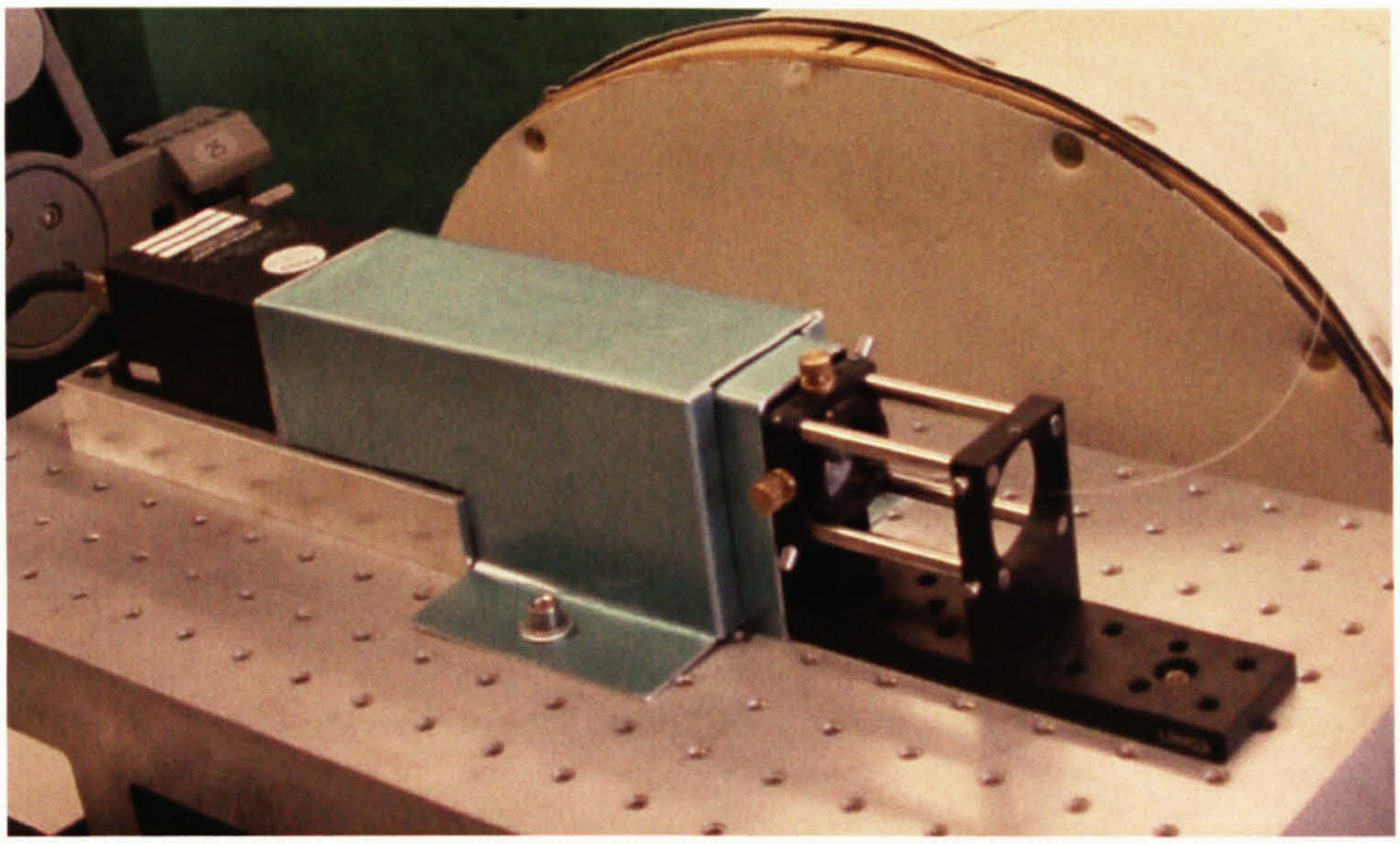

Figure 50 Metal box (in light green colour) encasing the laser generator

The transmission of the laser beam to the working space for illumination was by means of a multimode graded index optical fibre. This consists of a 50 micron core of optical glass which is surrounded by a light-reflective layer, the cladding, with an outer diameter of 125 microns. A layer of plastic coating, the buffer, provides protection to the optical fibre. The fibre has a diameter which was small enough to be inserted into a 22 gauge spinal needle and its length can be of many metres without transmission loss. The laser beam was directed to the proximal end of the optical fibre which needs to be in precise alignment. The distal polished end of the fibre was inserted into a blunt needle with a hollow centre (Figure 51). The tip was covered with a yellow phosphor which consisted of cerium doped yttrium aluminium garnet (Ce^{3+}:YAG) (QMJ58, Phosphor Technology, Stevenage, UK) as in the white LED. The phosphor is insoluble in water and has a melting point of more than

1500°C (Anonymous, 2005). It converts the blue laser radiation into a broad spectrum white illumination.

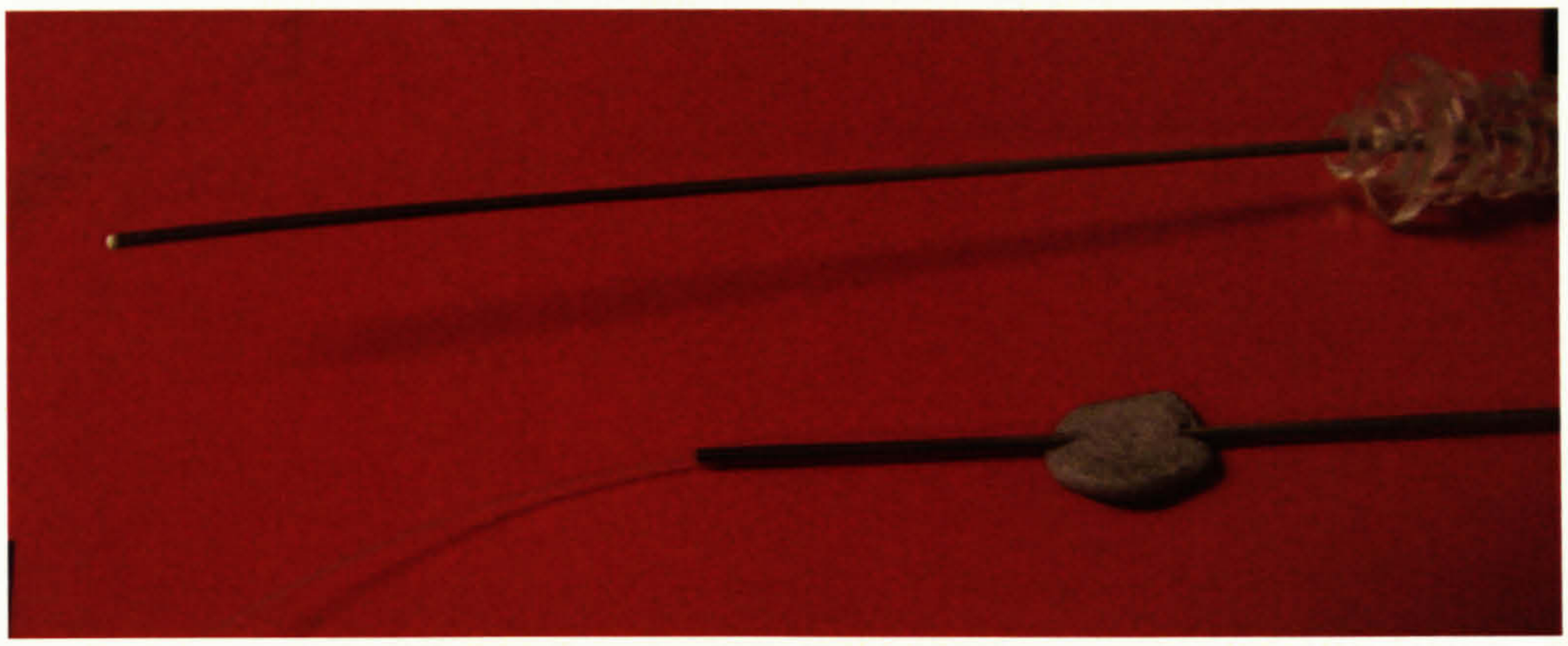

Figure 51 The end of a needle covered with phosphor (upper). The optical fibre was inserted into a needle (lower)

The small calibre fibre can be inserted into a body cavity scarlessly via a needle cannula to provide a potential alternative source of endoscopic illumination. It will have a similar potential as the LED endo-illuminator as previously described. For the purpose of the experiments, the distal end of the fibre (with the needle) was inserted into a 10mm tube with its tip protruding 5mm from the tube's end (Figure 52 and Figure 53).

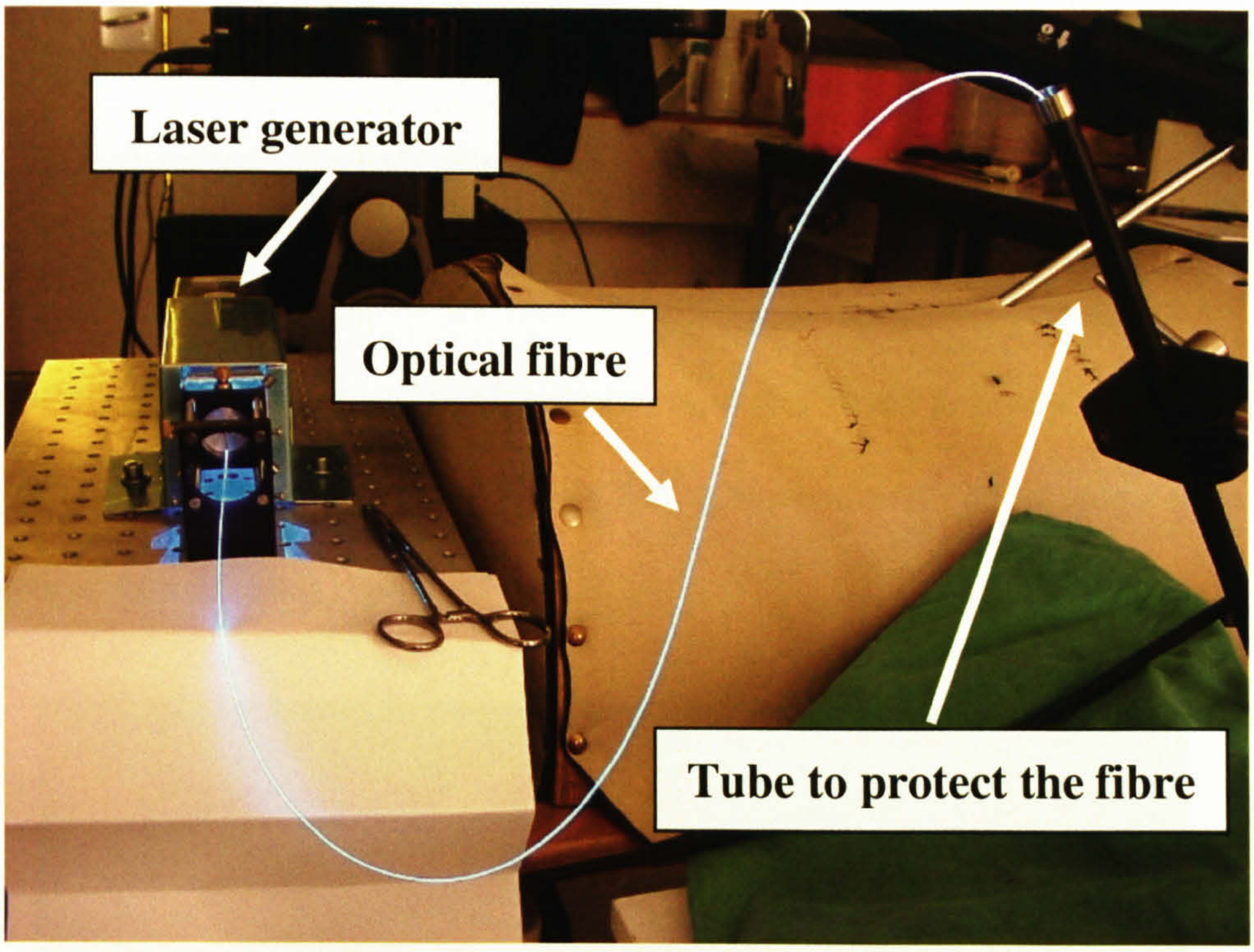

Figure 52 Flexible optical fibre from the laser generator to the 10mm protective tube for insertion. Note the blue colour of the fibre which will be converted to white light

Figure 53 Tip of the optical fibre (with yellow phosphor) protruding from the 10mm steel tube

4.9.3 Preliminary testing of the LED endo-illuminator and the laser illumination prototypes

4.9.3.1 Methods

The LED endo-illuminator and the laser prototype were used to produce illumination within the neonatal simulator box (Figure 54). Conventional endoscopic xenon arc-lamp source was used for comparison.

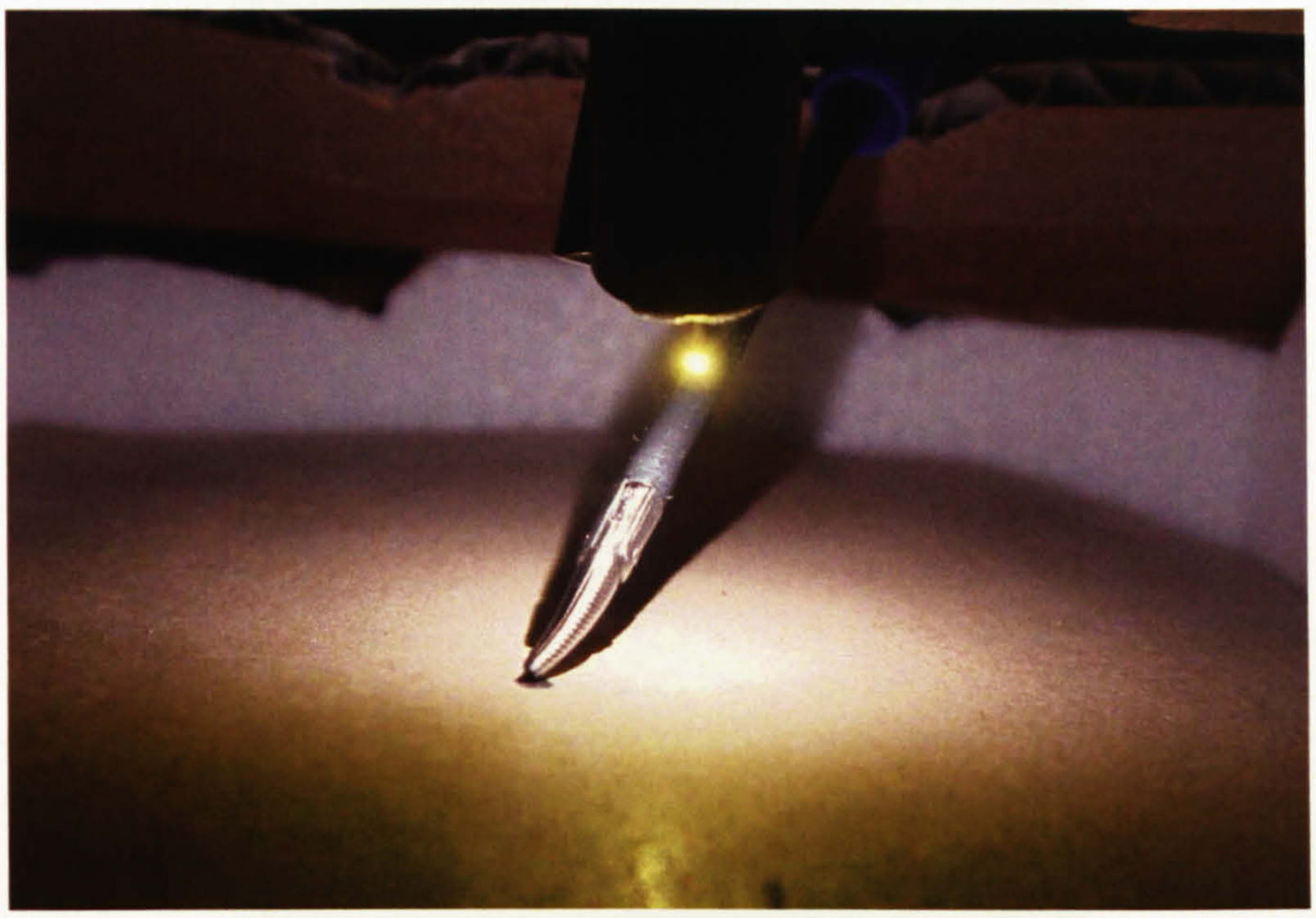

Figure 54 Laser white light illumination within the neonatal simulator box

Digital images were taken of the endoscopic field with a single light source placed at 30mm from the target and 30° anterior to the optical axis of the viewing 4mm endoscope (model 26009BA, Karl Storz). A pair of 3mm MAS scissors was inserted into the field thereby casting a shadow (Figure 55). The images were then analysed at each pixel position along a line in the lower third of the images to determine the illumination intensity.

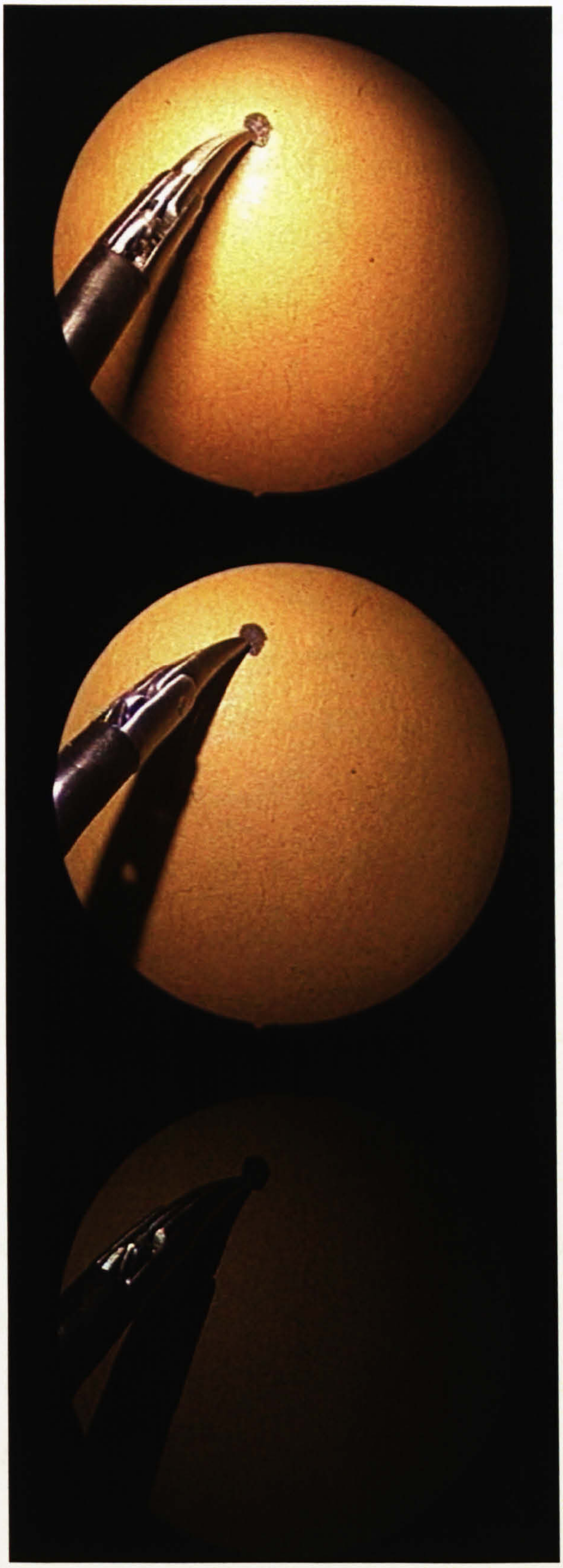

Figure 55 Arc-lamp endoscopic illumination (upper photo), LED endo-illuminator (middle photo) and laser illumination (lower photo) placed at 30mm from the target within the neonatal simulator

The spatial variation in intensity across the images where a shadow has been cast by the instrument was also determined qualitatively. An indication of the sharpness of the shadow can be determined by recording the steepness of the rising edges at either side of the shadow. The spectral pattern of the illumination sources was also measured using a spectrometer (Ocean Optics, Dunedin, FL, USA).

4.9.3.2 **Results**

The spatial variation in intensity across the images and the appearance of the endoscopic shadow from the illumination conditions are shown in Figure 56.

There is a reduction in intensity from the brightest central part (at pixel coordinate 300) to the dimmer peripheral part of the image (at pixel coordinate 550). The slope of the curve appear to be flatter with the laser illumination and LED endo-illuminator and steepest with the xenon arc-lamp light source indicating more uniform illumination with the laser and LED light sources.

Figure 56 also shows the shadow formed with the laser source was the sharpest (U-shape in the graph), followed by the LED endo-illuminator, with the conventional xenon arc-lamp illumination casting the most blurred shadow (V-shape in the graph). This was consistent with the visual observations of the images, and demonstrated an important advantage of the laser source. The sharper shadows from the LED and laser systems were due to the small size of the emitter and therefore it behaved much more like a point, rather than a less well defined extended source.

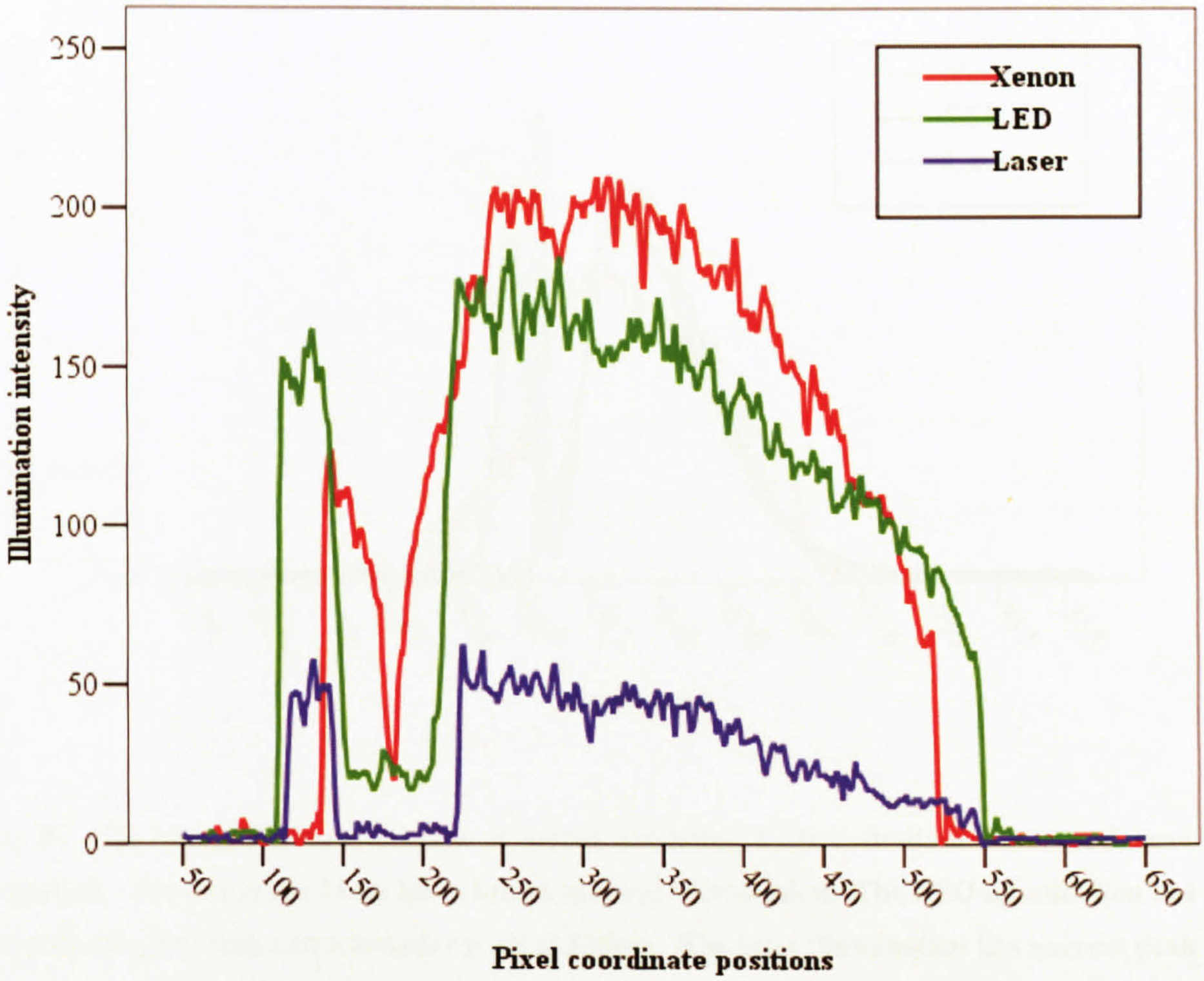

Figure 56 Spatial variation in illumination intensity across the lower third of the images illuminated by xenon arc-lamp, LED endo-illuminator and laser illumination (Figure 55). The shadows were located between pixel coordinate 140 and 230. Under the LED (green line) and laser illumination (blue line) there were steep drop and rise in intensities indicating sharp shadows whereas the change in xenon arc-lamp illumination (red line) is more gradual indicating a blurred shadow.

The spectral differences between the illumination sources are shown in Figure 57. The initial peak around 470nm for both laser and LED was due to the generated blue light. The excited phosphor then generated the yellow/green/red light. The arc-lamp source has a broader spectral illumination. The light emitted with longer wavelength was filtered by the infra-red filter. The LED and laser illumination systems have more blue light and less red light in the visible spectrum.

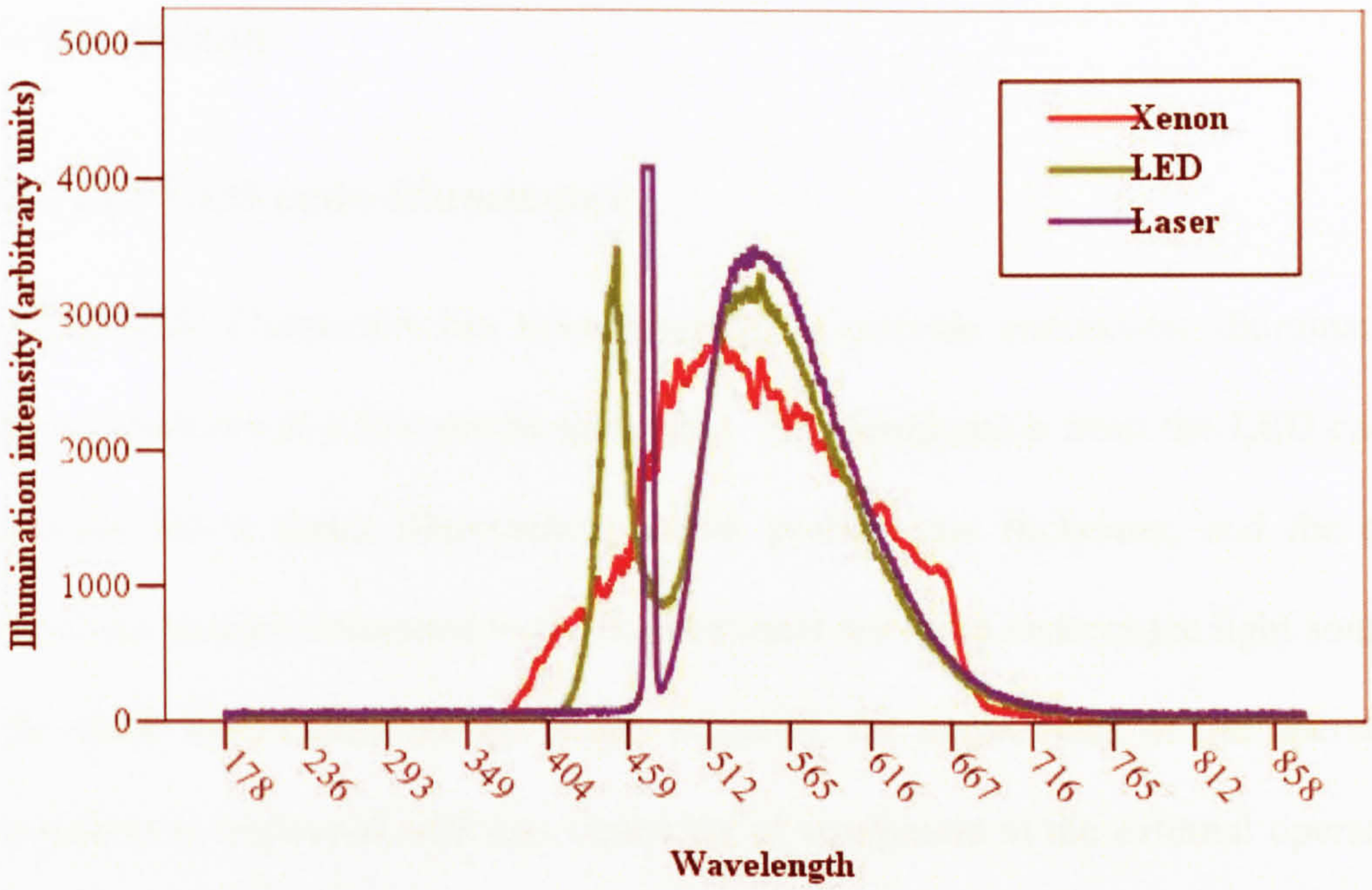

Figure 57 The spectral characteristics of xenon arc-lamp, LED endo-illuminator and laser illumination. The xenon arc-lamp has a broad spectral illumination. The LED illumination has a narrow peak at 453nm and a broader peak at 545nm. The laser illumination has narrow peak at 473nm and a broader second peak at 545nm.

Due to technical problems and fluctuations of the generated laser beam, it was difficult to measure the illumination power. We estimated that the power intensity of laser/phosphor was approximately ¼ that of the LED endo-illuminator. This was illustrated by the relative positions of the light sources in Figure 56, the laser being the lowest. However, this was only a rough estimation and more objective methods need to be developed for the measurement of intensity of the laser illumination.

4.10 Discussion

4.10.1 The LED endo-illuminator

The LED endo-illuminator has been designed to provide endoscopic illumination with cast shadows at a low production cost. The illumination from the LED endo-illuminator has a flatter illumination spatial profile, less flickering, and the cast shadows are sharper compared to the conventional arc-lamp endoscopic light source. As the thick light cables are no longer required, the ergonomics of the operative environment is improved with less cluttering of equipment at the external operative space.

An effective heat dissipation mechanism is essential because the performance and life-span of the LED largely depend on the operating temperature. Our design allowed efficient heat dissipation along the steel shaft with additional copper heat sink at the distal end of the steel rod attached to the back of the LED device at the tip to fulfill this requirement. The junction temperature can reach over 135°C which can lower the output efficiency. A different design which does not use the steel rod could be adopted as long as a heat dissipation mechanism is in place. The LED device of the LED endo-illuminator was mounted onto the steel rod also for the ease of handling, which could be held at different positions by a clamp during the experiments.

As the technology of solid state lighting (SSL) advances, the quality of LED devices continues to improve. Brighter and smaller devices are appearing in the market whilst the costs are becoming cheaper. The lower power requirement also allowed battery-based supply to be used as in our original design. However, as shown in our

experiments, the battery unit constructed was not powerful enough to maximise the potential of the LED device and the PSU was therefore used in the latter experiments. Nevertheless, using the connecting electrical wires is still better in terms of ergonomic layout compared to using the light cable as the connecting electrical wires are much thinner and can be connected to a PSU at a greater distance without the constraints from a light cable.

4.10.2 User testing of the LED endo-illuminator

Initial user testing showed that it was possible to use the LED endo-illuminator under endoscopic conditions to provide shadows for endoscopic tasks. The experiment was designed to assess the effect of an additional light on endoscopic task performance with the main illumination originated from the co-axial arc-lamp source. The experiments were carried out with the mobile phone battery supplying the LED endo-illuminator. The need for another light source, light cable or endoscope was eliminated and cluttering in the external work space was reduced.

The repeated measure design, with the experimental endoscopic illumination conditions counter-balanced, should minimise the effects of practice/fatigue of the subjects on performance outcome. All subjects performed the tasks under the open direct viewing condition before the experimental endoscopic illumination conditions. In all cases, the execution time was shortest under the open direct viewing session. The most plausible explanation was that the tasks were inherently easier to perform under open condition compared to the three endoscopic illumination conditions.

The addition of an extra endoscopic illumination source did not result in any significant differences in the performance of the looping and cutting tasks. This could be explained by the difficulty of the tasks for the subjects as basic endoscopic

skills, such as hand-eye coordination, were needed to perform the tasks. Although in the VAS scoring, the subjects were specifically asked to rate the level of visual comfort, the answers from some subjects would inherently be influenced by the physical difficulty and frustration in carrying out the tasks. There were no differences between medical and non-medical subjects. The error rates did not conform to any pattern in the comparisons and there were no statistical differences in execution time and VAS score. These were probably due to the small sampling size and the task difficulty which overcame the subtle differences in the pictorial cues. The outcome measurements were not sensitive enough to detect a difference between the illumination conditions. This was particularly true as the illumination sources were combined with conventional endoscopic illumination rather than compared in isolation (e.g. LED alone). Whilst a single illumination source used separately would produce shadows with strong contrast, it may cause perceptual confusion with the actual instrument. Furthermore, in practice, light from 2 sources used simultaneously would give better results, as highlighted by Mishra et al which stated that balanced shadows should ideally be between 22-42% and less than 65%, the level beyond which was associated with poorer performances (Mishra et al., 2004).

All subjects found it challenging to complete the cutting tasks due to the level of manual dexterity required. As a result, the shadow from the additional illumination source (whether from the second endoscope or from the LED endo-illuminator) and its characteristics were unlikely to influence the performance of the tasks.

Further perception experiments should evaluate the visual constraints to avoid confounding effects from the mechanical constraints.

4.10.3 **Characteristics of the LED endo-illuminator**

During the experiments, it was noted that when the LED endo-illuminator was powered by the battery alone, the illumination intensity became unsteady and too weak for prolonged experiments. Figure 28 shows that the power from the battery reduced quite rapidly, especially in the first 3 minutes. The PSU was therefore obtained and used for further testing of the LED characteristics in order to prevent confounding factors from the battery.

The illumination characteristics of the LED endo-illuminator were examined by direct measurements and indirect image analysis. The ability to provide an adequate brightness is a fundamentally important property of an illumination source. Although the direct measurements allowed the actual radiometric optical power to be determined directly from the illumination source, it was the processed image on the displaying monitor which ultimately provided information to the surgeon in MAS. Hence the indirect measurements of the intensity of the images would be more useful and relevant in clinical practice. Moreover, our optical power meter was only able to measure the radiometric power at a specific pre-determined wavelength, which may not represent the perceived brightness by the subject. In our experiments, the wavelength was set at 555nm, in the region of the visible spectrum to which humans are most sensitive.

The xenon arc-lamps used in the experiments were amongst the best MAS arc-lamp sources available in the market. They provided high luminous output, especially when compared to halogen light sources, but they have a considerably higher replacement cost. The current endo-illuminator uses a one watt LED and has radiometric power comparable to a 4mm endoscope at 60% power setting, or a

10mm endoscope at 10% power, supplied by the 175W xenon arc-lamp source. The measurements only included the total light detected with the photometer placed directly in front of the light source. During MAS, for a given distance between the light source and the target, there is a corresponding reduction in the light reaching the peripheral field due to the non-uniform illumination of the arc-lamp endoscope. In order to prevent over-saturation in the centre of the image, the shutter (automatic or manual) will limit the amount of light in the centre and the overall image brightness will thus be lowered. This would explain the lower average image pixel intensity values despite the higher direct radiometric power values of the arc-lamp endoscopes, especially at 4cm.

More powerful five watt LED devices, which became available recently, would provide higher luminance. Although the overall package size is identical, it has a larger active light emitting area compared to the one watt LED that we used. The size of the emitting semiconductor component in the one watt device is less than 1-2mm^2, with the epoxy and packaging for the connectors contributing to the bulk of the LED device. Along with the advancement in other electronic technologies, it is expected that LEDs will become smaller, brighter and cheaper. LED components which can produce up to 135 lumens of light output and achieve overall luminous efficacy of 129 lm/W are being developed by the LED manufacturers (Anonymous, 2007).

The optical power output is almost linearly proportional to the DC input. As the LED is able to switch on and off almost instantaneously, the current can be provided by using a high frequency (in kHz) pulsed driving current rather than a continuous current, at a rate which is invisible to the human eye. Our 1W LED allows a 500mA

pulsed current input, rather than a 350mA continuous current, which will result in higher output optical power and lower heat production (Anonymous, 2004, Anonymous, 2006b). Furthermore, brightness can be altered using the pulse width modulation technique by altering the duration of the "on" period, which results in a change in the brightness from the LED.

In addition, improvements in modern CCDs and camera systems have lowered the requirements of illumination intensity for adequate image exposure. Indeed, in normal clinical settings, mechanical light filters are usually used to reduce the light output at the external arc-lamp light source, which is commonly set at a power level of 50% or less with a new arc-lamp. In addition, the auto-shutter function, which is a common feature in current endoscopic imaging equipment, is usually activated in clinical practice. This would enhance viewing comfort by providing a more balanced overall luminance and preventing central white-out in the projected image, though at the expense of lowering the light levels in the periphery.

Visible flickering can just be seen with the naked eye in the arc-lamp but was absent in the LED. However, there was a gradual reduction in the optical power from the LED over a 30 minute period which was most probably due to the increasing junction temperature of the LED device. In order to capture all the information correctly, it was important to sample the data no less than twice its frequency. The Nyguist frequency was half of the sampling frequency. When the frequency of a signal was higher than the Nyguist frequency, the sampled signal will be converted to a lower frequency and resulted in data loss (known as aliasing). We were initially only able to collect the data at a low frequency (ie the Nyguist frequency was low) which resulted in data loss. The loaned photodiode allowed high-frequency

sampling at 2.5kHz, so that aliases would only occur above 1250Hz which was much higher than the frequency noticeable by human vision. The measurements from this equipment confirmed the flickering of the arc-lamp and the stability of the LED endo-illuminator. The fluctuation in the amplitude of the arc-lamp source was 5% of the main non-oscillating DC component. The instability of the xenon arc lamp was due to arc wander, flare or flutter and was previously noted to be in the region of 1% (Breeze and Ke, 1972). The high sampling rate of 2500Hz allowed us to have an accurate estimation of the flickering frequency which was found to be 36Hz. This was within the perceptual critical fusion frequency where the flicker will be visible to the user. Such flickering can cause discomfort such as eyestrain, reduce task performance and may even trigger migraine or epileptic seizures (Boyce, 2003, Pheasant, 1982). Indeed, changes in electro-retinograms have been reported at higher "invisible" flickering frequencies even though the flickering light may be perceived as fused (Berman et al., 1991).

We have used a LED device with diffuse lambertian radiating pattern in the LED endo-illuminator. The diffuse illumination enhanced visual perception by providing an excellent overall image resolution, whilst the central field was not over-illuminated as in the case of the arc-lamp illumination. LEDs with a batwing radiation pattern are also available, which may further increase peripheral illumination (Anonymous, 2006b). Diffuse overhead illumination is more intuitive to most people indoors (ceiling light) and outdoors (the sun) (Ramachandran, 1988), as opposed to the directional torch-like lighting at the endoscopic tip produced by an arc lamp coupled with fibre-optics. In endoscopic surgery, diffuse lighting is particularly useful for the inspection of unexpected pathologies. It is also useful in dissection and manoeuvering tasks which require precise movements whilst

maintaining attention in other areas of the field of view. The study also showed that the flat illumination uniformity profile of the LED endo-illuminator was not significantly affected by changing the target distance. This indicates that maintaining the position of the LED endo-illuminator is not essential in providing uniform illumination, whereas movements of the arc-lamp light source would cause obvious changes in the illuminated field.

An additional incision is required for the LED endo-illuminator to gain access into the cavity for shadow-forming illumination. The system may be modified by inserting the LED device without the shaft via one of the existing ports which is then anchored at the parietal side of the anterior abdominal wall. The thin electrical wires are directly introduced into the operative field and intra-corporally connected to the device. Alternatively, the LED can be placed within the abdomen via a flexible semi-rigid cable which can be inserted via the incision alongside with the optical port. This method of illumination will not be significantly affected by movements of the port.

Due to the small emitting surface of the LED device, the shadows formed from the endo-illuminator are sharper than those from an arc-lamp source. It is not known whether sharper shadows are beneficial or detrimental in endoscopic task performance. Sharp shadows may be useful in performing delicate endoscopic tasks involving pin-point accuracy within a small part of the operative field whereas softer shadows may be preferable in general endoscopic visualisation of the entire operative field. It is easier to increase the blurriness of images during image rendering and such image manipulation technique requires fast image computer processing and may be useful in future systems.

The low cost of LEDs allows the device to be used as a disposable piece of equipment. However, it is also possible for it to be used as a re-useable device due to its durability and ruggedness – the whole endo-illuminator rod may be autoclaved as a sealed unit. With further developments in light emitting semiconductor components, we believe that arc-lamps will soon be replaced by solid-state lighting technologies which have lower costs, produce less heat and provide better illumination for MAS.

4.10.4 **Peripheral endoscopic perception**

The LED endo-illuminator provided a more uniform illumination which was not significantly influenced by its position. This allowed better discrimination of fine details in the illuminated peripheral field as shown by the higher scores in the letter identification task.

The lambertian radiation of the light beam provided a wide angle of illumination, which resembled a room lit up by a ceiling light. In contrast, the light provided by the arc-lamp source through the endoscope was more analogous to a torch light, where light was only shown at the direction it was pointing to. As a result, the periphery endoscopic field was darkened. This was particularly apparent as the camera shutter also became faster automatically to prevent over-saturation in the centre. This results in an even more marked contrast between the bright centre and dark periphery.

The printed letters on a flat surface were used in the study in order to prevent effects of shadows confounding the main variable to be examined, i.e. the uniformity of illumination. The Landolt C print was chosen as it is a print type which is the least

ambiguous to distinguish, and in our study the crucial distinguishing feature was the 0.4mm gap which corresponds to the discrimination of very fine details.

Although in clinical practice, most operations are and should be performed in the centre of the endoscopic field, some procedural steps require manipulation at the periphery as well, e.g. for retraction of structures or knot tying tasks where the whole endoscopic field will be used, especially in the limited space of an infant during paediatric MAS. A wide illuminated field is also beneficial for the detection of unexpected findings which may be pathological or iatrogenic (e.g. bleeding), as it eliminates the need to move the illumination source which can cause confusion as will be discussed below.

4.10.5 Shadows in endoscopic illumination

Shadow-casting illumination from a separate overhead endoscopic light source provides extra depth cues. This has been shown to improve task performance especially with a balanced degree of illumination and shadow contrast (Hanna et al., 2002, Mishra et al., 2004). Overhead lighting is generally presumed to be static and cast shadows are expected to be found below objects in relation to the viewer's head position (Kersten et al., 1996, Ramachandran, 1988). Movements of shadows may give rise to the illusion that the shadow-casting object has moved even when it was actually the light source that has moved (Kersten et al., 1996). As the arc-lamp endoscopic illumination can only illuminate a small area, the light source will need to be moved to illuminate different areas and this may produce confusing shadow movements. On the other hand, the LED can be anchored in an immobile position, analogous to the fixed overhead lighting in a room, whilst providing uniform illumination across the field of view.

The LED endo-illuminator was designed to be use as an alternative source for shadow forming illumination. Previous studies have shown that task performance is improved in the presence of shadows in the endoscopic operative field. However, we were not able to replicate this finding in depth estimation and found no significant difference between illumination conditions with or without shadows. With the only exception when the distance was 29mm when there was a significant reduction in error score under shadow forming condition from the LED illuminator compared to the shadowless illumination from the co-axial arc-lamp source. Nicolaou et al using static images shown to 10 subjects with computer enhanced shadows images and also did not show significant difference compared to near invisible shadows produced from a secondary endoscopic light source. However, qualitative eye-tracking data suggested the apex of shadows provide direct cuing for depth perception (Nicolaou et al., 2005).

There are two possible explanations for the lack of difference observed in our study. Firstly, it is well known that length or distance estimation is not reliable even under normal 3-dimensional vision (Sharrack and Hughes, 1997). Our preliminary test showed wide variability of the 24 subjects in length estimation of a line of 20mm which ranged from 14mm to 25mm. A correction was therefore made for this error of each subject and the error score was calculated with this correction. In Nicolaou's study, a reference scale was placed within the endoscopic field and the subjects were noted to refer to this reference in the distance estimation (Nicolaou et al., 2005). In our study, a reference tape measure was provided in the data collection sheet to minimise subjective variation in the perception of length from memory. Secondly, the images were static even though there were viewed as video recordings. Static images were also used in Nicolaou's study whereas in others studies where shadows

were found to be useful, the outcome of dynamic endoscopic tasks were used as the endpoint (Hanna et al., 2002, Mishra et al., 2004, Shimotsu and Cao, 2007).

Our study therefore shows that shadow is not helpful for distance estimation in a static endoscopic environment, and its importance as a depth cue in endoscopic manipulation may only be useful during dynamic tasks.

4.10.6 **Moving shadows**

The experiments on the moving shadows have shown that most viewers generally assume the light source is stationary in their interpretation of the endoscopic operative field. A moving shadow as a result of the movement of the light source can be misleading and give the impression of instrument movement, as shown in Experiment I where 33 out of 36 subjects have not considered the instrument was stationary. Even when subjects were informed that the light source might be moving in Experiment II, a lower proportion of correct responses were obtained when the light was moving compared to when the instrument was moving. The stationary instrument included in the corner of the image in Experiment I was not noticed by any of the subjects even though this would have given a strong clue of its stationary nature. This may be due to the subjects' concentration on the centre of the image or a dominant effect of moving shadow on the subjects' perception.

The background surface where the shadow was cast also influenced the subjects' perception. In Experiment II where the light source was moving, more incorrect responses were given in the videos with the grid and textured backgrounds compared to the plain and undulating backgrounds. When viewing the video with the plain background, the subject could easily see the peripheral darkened area which also moved as the light was moving. Similarly in the video with the undulating

background, the cast shadows under the simulated gall bladder and bowel loop moved when the light source was moving. The 'five second' duration of the video clips was long enough for some subjects to search for these additional clues and determine their responses.

The ability to use shadows as a depth cue is developed at an early age. Yonas, et al showed that cast shadows can influence the judged depth and height of an object above a ground plane in three-year-old children (Yonas et al., 1978). Imura, et al showed that 6-7 months infants were able to discriminate the motion trajectory for moving cast shadows (Imura et al., 2006). The findings from our study are also consistent with the research on moving shadows created in computer graphics tested on adult subjects. Kersten, et al using a "ball-in-a-box" animation demonstrated that cast shadow motion causes a strong impression of the object moving in depth (Kersten et al., 1997). Their animation consisted of a ball and a cast shadow moving within a box with walls and a floor. A cast shadow moving diagonally in a motion to that of a ball produced the impression that the ball was receding in depth on the floor whereas a horizontal trajectory of a cast shadow produced the impression of the ball rising above the floor. When the shadow was given a non-linear trajectory in which it touched the ball then moved towards the front of the box, at mid-trajectory returned to touch the ball, and then swung to the front again, all subjects reported to see the ball was bouncing despite of the smooth straight diagonal trajectory. The robustness of the ball-in-a-box illusion may be attributed to the prior assumptions that the light source was stationary and the scene was viewed from a generic viewpoint (Kersten et al., 1997). The illusion from moving shadows was particularly strong when the light source was from above and the shadow edges blurred and

could override other conflicting pictorial cues such as size constancy (Kersten et al., 1996, Kersten et al., 1997).

We would therefore recommend that if shadows were to be introduced within the endoscopic view, the light source should be in a stationary position in order to maximise the benefit of shadow as a depth cue. This requires an off-axis light source which can be introduced into the operative filed via a single separate entry point or multiple fine entry points. Technologies employing fibre-optic light bundles within super-elastic diverging memory alloy can be used as multiple illumination points in the ceiling of the body cavity. Developments in solid state lighting using LED and laser illumination, as described in this thesis, have allowed alternative light sources to be explored. They are more versatile and unlike arc-lamp sources the LED illumination can be introduced directly into the body cavity without a thick light cable, while the laser beam can be transmitted via very fine fibre-optics small enough to pass through needle-sized entry points which leave minimal surgical scars. Multiple points of such light source would provide a wide field of shadow producing fixed illumination. Such technologies would be particularly useful with the development of intra-corporeal mobile camera systems as well as the increasingly adopted NOTES approach (Rentschler et al., 2007, Rentschler and Oleynikov, 2007).

In addition to instrument design, the study guides the ergonomics of handling instruments during surgical procedures. With NOTES, combined endoscopic and laparoscopic procedures and shadow-producing laparoscopic systems, the assistant should not move the illumination without prior communication with the surgical team to avoid confusion with instrument movement. By contrast, such precaution is not needed in shadow-less standard MAS where the camera driver works in harmony

with the principal surgeon to continuously adjust the target in the centre of endoscopic field.

In conclusion, people usually assume the light source is stationary, leading to the conclusion that the movements of shadows are attributed to movement of the casting object. When the light source moves, shadows can cause difficulty in the interpretation of the endoscopic scene and can give conflicting information to the viewer. Therefore if cast shadow is produced, the light source should be stationary.

4.10.7 **Laser illumination**

The laser-based illumination prototype that has been developed to date is too dim for endoscopic illumination, especially in a large operative space where more optically powerful illumination is required. Therefore, laser-based illumination systems may first be applied in the smaller operative environment, such as in paediatric MAS where the light source will be placed close to the target due to the limited operative workspace. The need for precise alignment between the laser generator and optical fibre requires adjustments even with small changes to the set-up. This was not practical during user testing in the laboratory, not to mention in the operating theatre. On the other hand, the LED based system appears to have adequate optical power and its robustness in its construction makes it more suitable for user testing. The LED endo-illuminator was therefore used for the other experiments in this thesis.

The laser illumination was tested as a proof-of-concept and the prototype was in its early stages of development. The illumination system uses a similar principle as in the LED by producing white light from narrow spectral blue laser by means of Ce:YAG phosphor. The initial impression was positive in terms of the light and colour quality. However, the light intensity of the early prototype was too dim for

quantification. The laser at source is classified as a Class 3B laser and therefore laser safety precautions are necessary for the laser beam from the machine. The prototype was encased within a steel box to avoid accidental strayed laser beam causing retinal injury. Safety issues would also need to be considered regarding the phosphor used. The main advantage of the system was that the bore size of the fibreoptic fibre is very fine which allows the insertion through a small needle cannula and the signal can travel through long distances. It has great potential to be used within the small operative space in paediatric MAS.

5 CONCLUSIONS AND FUTURE WORK

5.1 Summary of the thesis

The project aimed to improve the physical and sensorial ergonomics of the small operative field in paediatric MAS. This was achieved by the experiments outlined in this thesis on physical and sensorial ergonomics, which are important aspects of ergonomics affecting the everyday practice of MAS.

For the first part of the project, the author set out to quantify the physical environment of the paediatric MAS operative field in neonates and infants and to investigate the influence of instrument size on paediatric intracorporeal knot tying within a small operative field similar to that encountered in neonatal MAS. As paediatric patients are smaller in size compared to adult patients, the operative environment in the younger patients, especially neonates and infants, would pose different ergonomic difficulties and considerations to the surgeon. The author obtained external anthropometric measurements from infants and neonates and the data were used to construct two simulator boxes for the ergonomic experiments in paediatric MAS. The author also sought to investigate the effect of instrument size on task performance of endoscopic knot tying within the small operative space. Suturing and knot tying are essential basic surgical skills for tissue approximation in most open surgical procedures. Intracorporeal endoscopic knot tying was chosen as the task to be measured in this experiment as it is an important MAS skill which many surgeons find difficult to perform efficiently and comfortably. The study showed that by using the smaller paediatric needle-holders in the neonatal simulator box, the task was performed faster while knot quality was maintained. Upper limb muscular recruitment was reduced resulting in less discomfort for the surgeon. This experiment has therefore shown that ergonomic benefits exist when smaller

paediatric needle-holders were used in the small endoscopic operative field, which supported the need for specific instruments for use in neonates and infants. Paediatric surgeons who practice MAS should no longer be complacent with the use of MAS instruments designed for adult patients, even though this is widely practiced in general hospitals where adult and paediatric specialties share common facilities and equipment.

During the experiment on endoscopic knot tying within the neonatal simulator box, many subjects reported difficulties in depth perception affecting their performance regardless of the instrument used. This prompted the author to look for changes in the video-endoscopic set-up to improve the visual ergonomics of the small endoscopic operative field. The author decided to specifically investigate the illumination systems and the role of shadows in MAS.

This leads to the second part of the project which dealt with the sensorial and cognitive aspects of ergonomics, with the aims of developing an alternative illumination system in MAS using the SSL technology and to investigate its characteristics and feasibility for future use in MAS. Using existing SSL technology with commercially available LED devices, the LED endo-illuminator was developed which has superior illumination characteristics compared to existing arc-lamp illumination used in MAS. Our experimental data has shown that illumination from the LED endo-illuminator, unlike a conventional arc-lamp source, is more uniform across the operative field and more stable with negligible flicker. This would enhance the visualisation of the operative field and provide more visual comfort to the surgeon. The favourable characteristics of the LED illumination led to an improvement in visual perception compared to conventional illumination systems as

shown in the study on peripheral endoscopic perception where the LED illumination was found to improve task performance in endoscopic peripheral discrimination.

However, the illumination intensity of the 1W LED device was only comparable to a 4mm paediatric endoscope and so its use is confined to the small operative field as in paediatric MAS where the target distance is short. Although the optical power of the LED endo-illuminator is relatively weak at present, brighter and more efficient devices are expected to appear in the market in the near future with the rapid growth of the SSL industry. For the SSL devices that are currently available, its use in infants should be adequate due to the short viewing distance in the relatively small operative field.

The author also investigated the role of shadows in MAS as previous literature has shown that shadows can improve endoscopic task performance in MAS. The shadow produced by the LED endo-illuminator is very sharp due to the small emitting surface of the LED. It is currently not known whether the sharp shadows produced confer ergonomic benefit. It may be useful during the performance of fine delicate tasks to aid depth perception in the endoscopic operative field. The author did not find significant differences in distance estimation with or without shadows though this was most likely due to the static nature of the images viewed. The use of shadows as a depth cue is more evident when the shadows are dynamic. However, if the light was being moved, this project has shown that the resultant moving shadows can be detrimental to the visual perception by causing confusion to the viewer as to the true nature of the movements. On the other hand, other peripheral stationary objects in the visual field may provide clues to whether the light or the object is moving. It is therefore important that when shadow-producing video-endoscopic

set-up is used, the assistant should not move the illumination without prior communication with the surgical team to avoid confusion with instrument movements. The potential misperception of moving shadows and the potential benefit of stationary visual cues to assist perception should be highlighted during technical skills training where the imaging camera and light sources are physically separated. The surgeon should be aware of the potential misperception with moving shadows and look for stationary visual cues to enable correct interpretation of the operating environment. Therefore if shadows are produced during MAS, the light source should be stationary. This also highlights the importance that changes in the ergonomics of the operative environment caused by the introduction of new illumination technology or techniques would require the surgeon to relearn the interpretation of previously familiar endoscopic images.

The laser-based illumination prototype also used SSL technology to produce endoscopic illumination. Preliminary testing has shown promising results. The very fine size of the optical fibres used to transmit the illumination would allow such illumination to be introduced into the body cavity via fine needle cannula. This would enable healing without scars. Therefore, this laser-based illumination technology would have great potential for future paediatric MAS systems.

While it is not within the scope of this project to resolve all the ergonomic problems that paediatric surgeons encounter during MAS, small improvements to the practice of paediatric MAS are not difficult to achieve, such as the use of appropriate paediatric MAS instruments, and the awareness of the limitations of current illumination systems and the relationship between illumination and human visual perception in MAS. The advancement of surgical technologies such as MAS and the

application of ergonomics on such technologies require people to be re-educated, as demonstrated by the illumination studies which suggest there is a need to re-teach the surgeon how to correctly interpret endoscopic images. The author is optimistic that with a greater awareness of and more focus on improving the ergonomics, the practice of paediatric MAS will become safer and better, both for the surgeon and for the patient.

5.2 Further perspectives

The clinical application of paediatric MAS continued to expand during the period of this research project, including the wide adoption of the minimal access approach in neonatal surgery. More research in the ergonomic issues highlighted in this thesis and further development of the prototypes created would advance our understanding and improve the practice of paediatric MAS.

5.2.1 Intra-abdominal anthropometric measurements

In addition to the external abdominal anthropometric data as obtained in the current project, intra-abdominal anthropometric data (from cross-sectional imaging techniques and/or intra-operative measurements) combining with tissue compliance mapping data (Fakhry et al., 2007) can be used to develop high fidelity simulators or virtual reality systems. Development of such simulator systems would be useful for future paediatric ergonomic studies with specific surgical tasks, e.g. task performance in suturing a fundoplication wrap or bowel anastomosis, and also for paediatric MAS training.

5.2.2 Power supply and heat dissipation of the LED endo-illuminator

Future improvements in the battery supply would avoid the need for the light cable altogether and enhance the ergonomics of the external workspace. However, development of the heat sink is required to allow the LEDs to function more efficiently within the abdomen or thorax for longer operative periods, preferably replacing the steel rod with electrical wire and allow direct delivery of the LED device into the operative space.

Brighter and small LED devices are expected from the SSL industry. Future design should also withstand the autoclave process so that the device can be reused repeatedly.

5.2.3 The role of shadows in endoscopic tasks

With separate LED illumination, sharp shadows were produced. The ergonomic benefit of using sharp shadows in task performance such as endoscopic suturing is not known and warrant investigation.

With the advent of new MAS techniques, e.g. NOTES, using separate illumination sources would become more widespread. The role of endoscopic shadows in depth perception warrants further investigations, e.g. the difference between dynamic and static endoscopic field, would help to define and design futher ergonomic research. This could also help to highlight the different ergonomic needs in the operative environment when endoscopic shadows are used.

5.2.4 Laser illumination in MAS

The laser illumination system would be a further alternative light source and the very small laser fibres would allow multiple insertions to light up the whole abdomen or thorax uniformly. Further development of the laser illumination is underway at Imperial College London to investigate the characteristics and potential clinical application of this novel illumination system.

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