Minimally Invasive Therapy 1992: 1: 251–259

Neodymium: YAG laser and its application in minimally invasive surgery: an experimental study and clinical trial

M.M. LIRICI MD*, M.O. SCHURR*, M. WEHRMANN MD†,
E. KANEHIRA MD* & G. BUESS MD, FRCS*
*Department of Surgery, †Institute of Pathology, Eberhard-Karls University, Tübingen, Germany

Summary. A three-step experimental and clinical study has been performed in order to evaluate the effectiveness and the modalities of application of Nd : YAG laser in different minimally invasive surgical procedures. The *in vitro* study allowed us to carry out a close histological evaluation of the laser effects on more than 200 specimens from different tissues. Varying degrees of limited thermal alterations but no uncontrolled deep penetration into the tissue were found at the morphometric evaluation. During the *in vivo* study the laser application in laparoscopic cholecystectomy and transanal endoscopic microsurgery has been evaluated. Different applicators have been developed and tested in order to achieve the safest use of laser energy. The effectiveness of Nd : YAG laser in achievement of coagulation of arterial bleeding has been found lower than that of monopolar HF energy. The healing process after transanal procedures was without complication, the scar showing only a small zone of granulation tissue. During the first two steps of the present study we set up the operative technique of laser TEM and the modality of application of Nd : YAG laser that we extended into the clinical trial.

Keywords: minimally invasive surgery (MIS), Nd: YAG laser, histological effects, laparoscopic laser cholecystectomy, transanal endoscopic laser microsurgery (laser TEM), laser applicators

Introduction

The increasing complexity of minimally invasive interventions requires a continuous improvement in technology. It is essential that the combination of cutting and coagulating properties in one device is optimal since in endoscopic surgery a bloodless field is mandatory and control of bleeding is not possible, as it is in open surgery. Due to its physical characteristics (deep penetration into biological tissue, low water and haemoglobin absorption), the Nd: YAG-laser could play an important role in achieving these requirements [1]. Since the benefits provided by lasers are as yet unproven [2–5] and no studies concerning the application of laser technology in MIS are reported in the literature apart from its use during laparoscopic cholecystectomy [6], we carried out a three-step experimental and clinical study in order to evaluate the effectiveness and the best modality of application of the Nd: YAG laser in this field. The first two steps consisted of an experimental *in vitro* and *in vivo* study during which a close histological examination of laser effects on different tissues and specimens was carried out. The histological results allowed us to define the best modality of application of the Nd: YAG laser during the *in vivo* study. The setting up of the laser operative procedures was also completed in this phase as well as the development of special applicators which enhance the effectiveness and the safety of the laser in laparoscopic and transanal surgery.

Correspondence: Dr G. Buess, Department of Surgery, Eberhard-Karls University, Klinikum Schnarrenberg, Hoppe-Seyler-Str. 3, 7400 Tübingen, Germany.

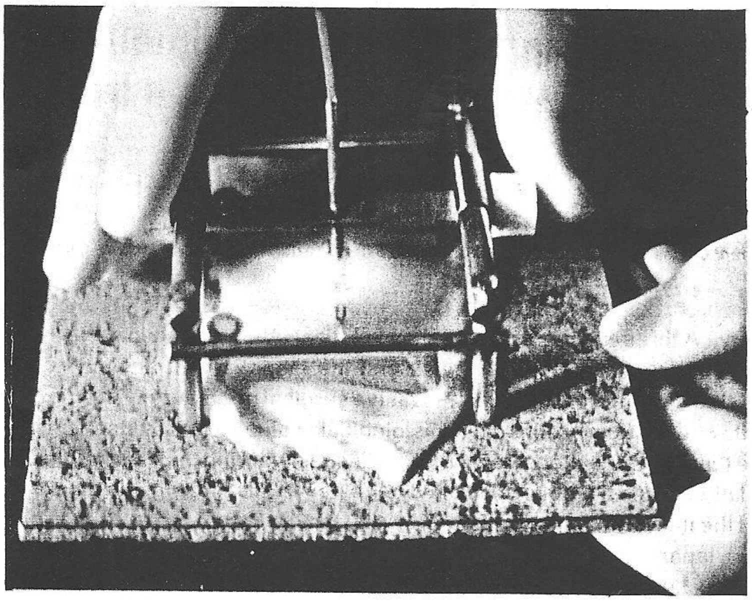


Figure 1. Holder for *in vitro* studies with mounted rectal specimen.

Materials and methods

First step: experimental in vitro *study*

We tested the Nd:YAG laser (Heraeus Lasersonics Co., Hanau, Germany) with a wavelength of 1060 nm in a series of 200 *in vitro* experiments. We used fresh bovine rectal and porcine liver tissue, mounted in a static applicator to keep the direction and the distance of the fibre tip constant (Figure 1). For light transmission we utilized bare fibres (600 μm in diameter), gas cooled fibres (1000 μm) with sapphire tip (conus shaped, clear and frosted) and sculptured fibres (conus shaped, 600 μm and 1000 μm). The bare fibre was used in contact mode for cutting and in non-contact mode for coagulation. The power density ranged from 10 W to 60 W in steps of 5 W. The sapphire tip and the sculptured fibre were used for cutting in the contact mode. The power density (PD) was between 10 W and 35 W in steps of 5 W. All the experiments were carried out in continuous wave (cw) and in pulsed mode. The pulse time ranged from 0.2 s to 0.8 s and the pauses from 0.2 s to 0.3 s. All the specimens were histologically examined. The tissue was fixed in 4% formalin, dehydrated and embedded in paraffin. From each specimen 3–5 μm thick serial sections were cut and stained with haematoxylin & eosin and elastica-van Gieson. The parameters investigated were: the form of the crater, debris formation in the lumen of the crater, extent and quality of the thermal alteration in the adjacent tissue at the edges and the bottom of the crater. The following parameters were examined morphometrically: maximal width and depth of the crater, maximal width of thermic alterations in the adjacent tissue at the edges and the bottom of the crater. A standard Zeiss lightmicroscope with tracing device and a modified digitizer (Summagraphics Co., Munich, Germany) with light point courser (MTS Co., Tübingen, Germany) connected to a desk top computer were used for the morphometric studies.

Second step: Experimental in vivo *study*

Laser TEM – operating procedure. We used the 40 mm TEM operating rectoscope according to Buess [7, 8]. The 12 animal experiments (sheep) were carried out under general anaesthesia. The bowel was cleaned by irrigation. The normal technique was modified to be suitable for Nd:YAG laser application. A new application device was developed (Figure 2). The 4 mm instrument is angled at the tip around 45° and the inserted fibre is brought into a good working position towards the tissue. A Luer-lock plug can be used for CO_2-gas cooling or for rinsing with saline solution. Laser TEM is a two-step procedure; first we performed a ring of coagulation on the rectal wall in non-contact mode at 40 W PD, with pulses of 0.5 s and pauses of 0.2–0.3 s. Then we cut in the coagulated trace (Figure 3) in contact mode at 35 W PD, with pulses of 0.2 s and pauses of 0.2–0.3 s. When cutting the tissue layer by layer we coagulated with free beam in between each layer. In each case we performed a full thickness excision

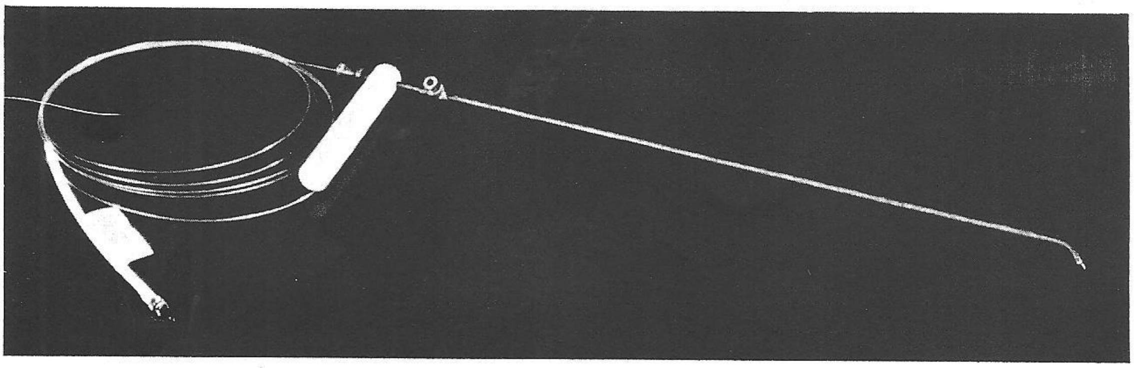


Figure 2. TEM laser applicator.

at different levels and sides of the rectal wall from the dentate line up to 15 cm from the anal verge. The defect in the rectal wall was closed with a continuous suture (PDS 3–0) secured with a silver clip. Antibiotics (ampicillin) were supplied post-operatively in one case.

Laser cholecystectomy operating procedure. In three animals (pigs) we performed laparoscopic laser cholecystectomy under general anaesthesia (Figure 4). Three applicators were tested; a straight applicator with an inserted conus-shaped 600 μm fibre (Laserblade, Lasersonic Co.) at 15 W PD in cw mode; a deflectable device (modified Albaran's instrument) which angles the inserted fibre up to 90° and thus enhances the instrumental degrees of freedom and makes laser application easier in different laparoscopic procedures (Figure 5a); a hook-shaped applicator (Figure 5b) with a central channel to insert the fibre. The tissue is elevated with the hook and either dissected bluntly or with laser pulses. The hook tip works as a back stop in the beam pathway, in order to avoid deep penetration into the liver bed and the gall bladder wall. The handling is similar to conventional high frequency hooks and allows performance of the usual cholecystectomy procedure. Both devices, the curvable and the hook, are 5 mm in diameter and can be cooled with CO_2-gas or rinsed with saline solution via a Luer-lock plug. Both were used with bare fibres (600 μm) at 35 W PD in pulsed mode (pulses of 0.2 s and pauses of 0.2–0.3 s) and contact application.

All the gall bladders and rectal excised tissue as well as the scar regions in the bowel and the liver bed,

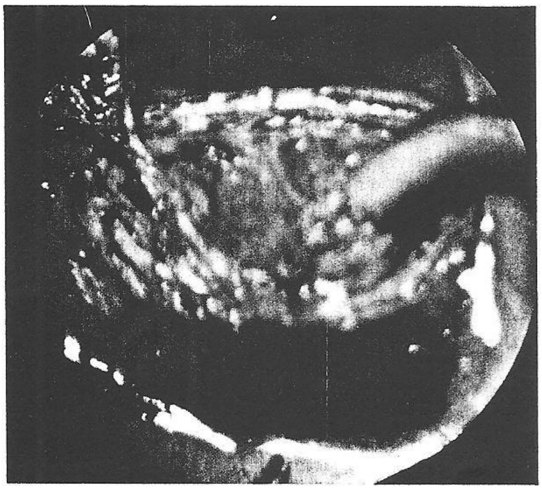


Figure 3. Laser TEM: final laser dissection of the rectal wall.

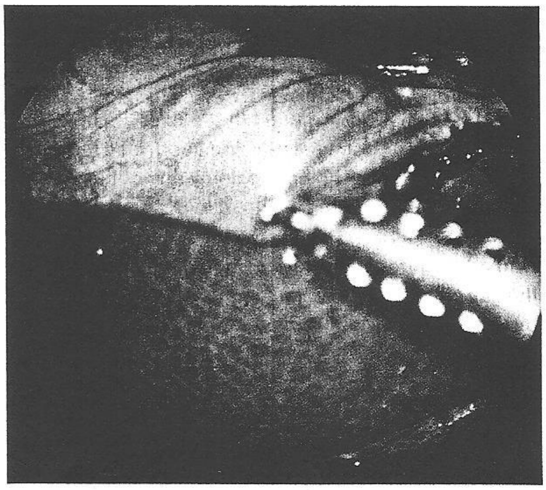


Figure 4. Laparoscopic laser cholecystectomy: the hook-shaped applicator allows safe laser dissection of the gall bladder using the conventional technique.

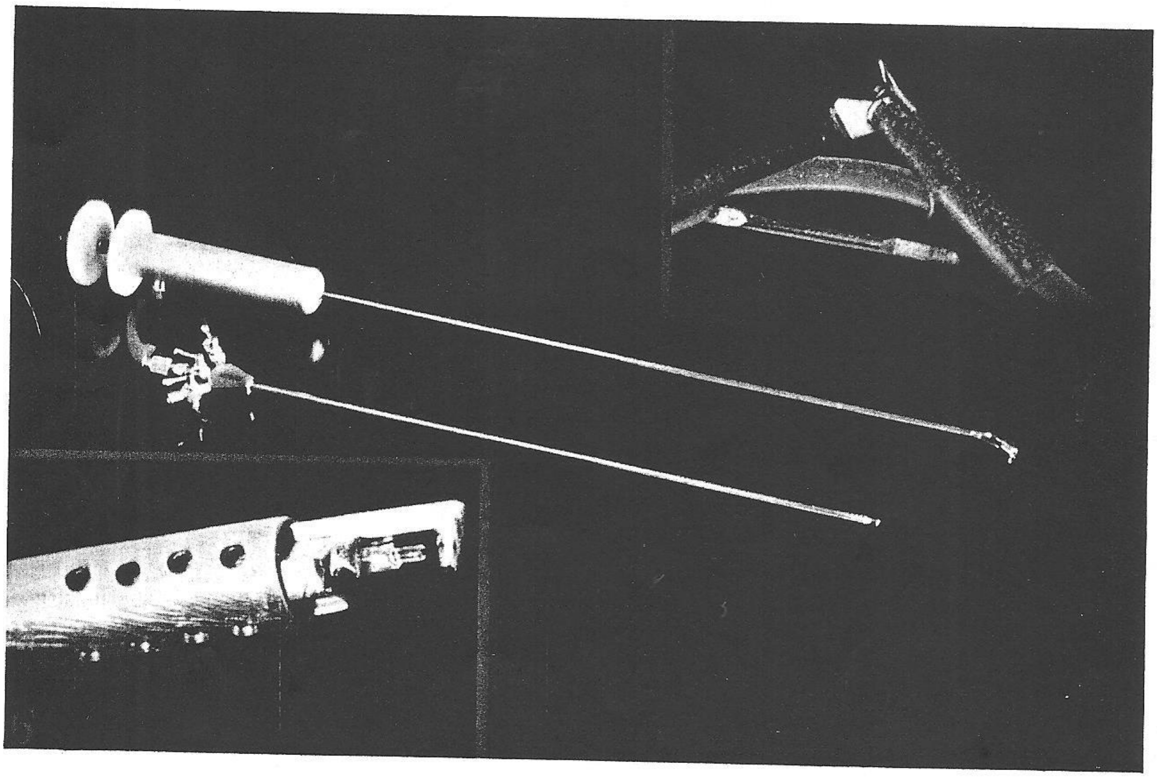


Figure 5. (a) Steerable laser applicator for laparoscopic procedures. (b) Hook-shaped laser applicator for laparoscopic cholecystectomy.

obtained 3 weeks after the experiments, were histologically and morphometrically examined as described for the *in vitro* study.

Third step: clinical trial

Using the experience gained in the experimental study we began the first clinical trial. We performed laser TEM, laparoscopic laser cholecystectomy and adhesiolysis in the first eight patients using the methods described above.

In addition to the routine pathological examination of the gall bladders and rectal excisions, the lesions caused by the laser were also explored.

Results

First step: experimental in vivo *study*

Histological examination. The histological specimens showed variable degrees of limited thermal alterations in all samples. The character of the lesions was nearly identical in each case:

1 In all specimens a small zone of carbonization could be observed.

2 The adjacent necrosis zone was in the form of coagulated and homogenized tissue.

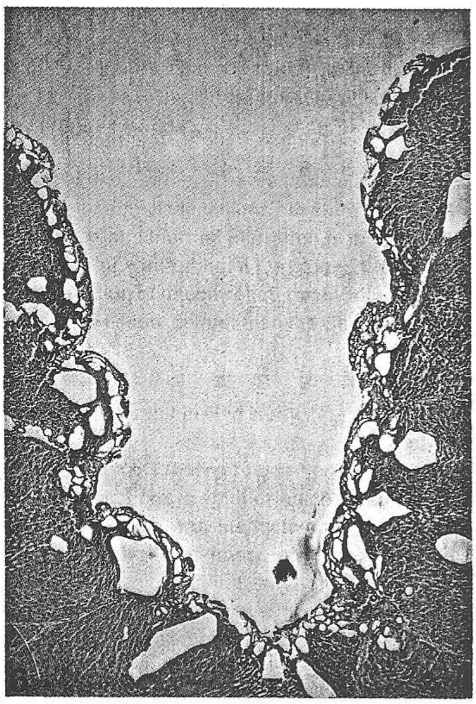
3 Vacuolization of the tissue with rounded lacunae, differing in size.

Figure 6. *In vitro* study: histological findings of the liver tissue cut by the shaped fibre. Note the sharply demarked margins with a dark zone of carbonization followed by coagulated tissue and vacuoles. H & E. × 250.

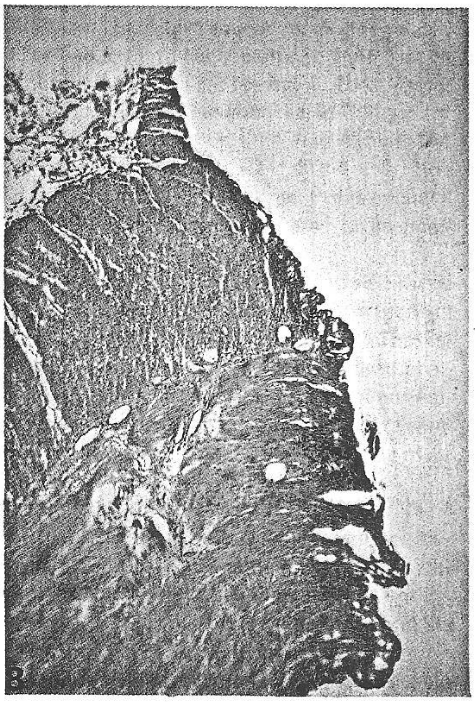
Figure 7. *In vitro* study: histological findings of the rectal tissue cut by the bare fibre. Note the blunt shaped lesion with small zone of thermal alteration. H & E. × 250.

Figure 8. Laser TEM *in vivo* study: histological findings of the muscularis propria of the rectum and its adjacent connective tissue. Note the margins of the excidate. H & E. × 200.

Figure 9. Laser TEM *in vivo* study: histological pattern of the healing process of the rectal wound at the third post-operative week. Complication free healing process with just a small zone of granulation tissue. H & E. × 160.


6


7


8


9

Table 1.

Specimen	Kind of lesion	Margins of lesion	Contents of lesion	Carbonization	Coagulation	Vacuolization	Intermediary zone	Maximal depth of lesion (μm)	Maximal width of lesion (μm)	Zone of thermal alteration (side of lesion) (μm)	Zone of thermal alteration (bottom of lesion) (μm)	Shape of lesion
r, c, sf (1000), 35W	2	0	0	Yes	Yes	Yes	Yes	970	500	200	190	Sharp
r, c, sf (600, 35W	2	0	0	Yes	Yes	Yes	Yes	940	800	190	160	Sharp
r, c, sf (600), 20W	2	0	0	Yes	Yes	Yes	Yes	860	650	110	110	Sharp
l, c, sf (600), 35W	2	0	0	Yes	Yes	Yes	Yes	2100	1250	170	110	Sharp
l, c, sf (1000), 20W	2	0	0	Yes	Yes	Yes	Yes	810	620	260	240	Sharp
r, c, bf (600), 40W	2	1	0	Yes	Yes	Yes	Yes	1340	1040	180	100	Blunt
l, c, bf (600), 40W	2	0	0	Yes	Yes	Yes	Yes	1480	620	220	170	Blunt
r, nc, bf (600), 45W	2	1	1	Yes	Yes	Yes	Yes	1030	950	220	190	Blunt
l, nc, bf (600), 35W	1	1	1	Yes	Yes	Yes	Yes	370	1950	180	180	Blunt
r, c, sf (600), 35W, pulse	2	0	0	Yes	Yes	Yes	Yes	850	790	180	150	Sharp
r, c, bf (600), 40W, pulse	2	0	0	Yes	Yes	Yes	Yes	1210	1000	170	100	Blunt
l, c, sf (600), 35W, pulse	2	0	0	Yes	Yes	Yes	Yes	1980	1030	160	110	Sharp
l, c, bf (600), 40W, pulse	2	0	0	Yes	Yes	Yes	Yes	1320	610	220	160	Blunt
l, nc, bf (600) 35W, pulse	1	0	0	Yes	Yes	Yes	Yes	360	1870	170	170	Blunt
r, nc, bf (600), 40W, pulse	2	1	1	Yes	Yes	Yes	Yes	890	810	200	180	Blunt

l, liver. r, rectum. c, contact. nc, non-contact. bf, bare fibre. sf, cone-shaped fibre. xw, used PD. Kind of lesion (0, no; 1, excavation; 2, crater). Margins of lesion (0, smooth; 1, irregular; 2, fissures). Contents of lesion (0, no contents; 1, little debris; 2, much debris).

The zone of thermal alteration was not sharply demarcated from the adjacent tissue. In each case we found a small area of discoloured tissue, the 'intermediary zone', in which the structures were still identifiable with the light microscope (Figures 6 and 7).

Morphometry of the lesion. The results of the morphometrical evaluation of the lesions are shown in Table 1. The zone of maximal thermal alteration at the base of the lesion was never wider than at the side of the lesion and there was no sign of uncontrolled penetration of the laser beam into the tissue, deeper than the visible base of the lesion.

Second step: experimental in vivo *study*

Laser TEM. The Nd:YAG laser provided precise cutting and haemostatic functions in smaller mucosal and muscular haemorrhages but was ineffective in controlling severe bleeding. The effectiveness of the coagulation was improved by rinsing saline solution through the working channel of the TEM laser applicator during lasing, in order to wash away the blood and to allow the laser beam to reach the tissue. Laser coagulation was not as effective as the monopolar high frequency suction probe. The handling of the applicator was easy and similar to the usual TEM high frequency knife. The angled tip of the fibre had to be re-cut because of 'burn-out' on one or two occasions during the operation. The survival time of the fibre tip was increased by using CO_2 gas for cooling. The average operation time was 93 min. The peritoneum was opened in one case, when the level of the resection was 12 cm from the anal verge. In this animal a 48 h i.m. administration of ampicillin was given post-operatively.

The histological examination of the excised tissues showed sharply limited margins with just a small zone of thermal alteration as described above (Figure 8). The histology of the scar regions, harvested at the third post-operative week, showed an uncompromised wound healing process with just a small zone of granulation tissue (Figure 9).

Laser cholecystectomy. We did not have any problems during the laser dissection of the gall bladder in the animal experiments. The handling of the straight applicator resulted in possibly dangerous manoeuvres due to the straight pathway of the laser. Both the curvable and the hook shaped applicators did not show such a problem. No dangers related to the heating of the back-stop tip of the hook shaped applicator occurred. The average operation time was 21 min.

On histological examination only very superficial thermal lesions were found at the gall bladder wall. The submucosa was not penetrated. Examination of the liver bed, resected 3 weeks after the operation, did not show any sign of a severe lesion or a necrotic process.

The post-operative follow-up of all animals was without complication.

Discussion

The limits of endoscopic surgery in most fields of application are the lack of a tri-dimensional view and little tactile sense. The control of bleeding is another difficulty, when compared with open surgery. Technological developments are needed in order to overcome the disadvantages of endoscopic surgery and to enhance the benefits that such new procedures provide. The purpose of bringing laser technology into minimally invasive surgery is to use a tool which allows precise cutting and, at the same time, coagulates the margins of the lesion, as well as the bleeding sources. Since freedom of movement is an important aspect in minimally invasive surgery, the way the laser energy is transported from generator to tissue is relevant. Laser systems provided with flexible fibreoptics are easier to use in MIS. Another advantage is the ability to deliver a great amount of energy through a very small diameter of fibre. The Nd:YAG laser fits most of the requirements for laser application in MIS as described above, although there are some authors who report contradictory results and are critical of the use of the Nd:YAG laser [3, 4, 9, 10].

In the *in vitro* study we found the lesion resulting from the Nd:YAG laser slight and well demarcated from the adjacent tissue with good coagulation of the capillaries and small vessels adjacent to the cut as a result of the laser's scatter inside the tissue. The zone of thermal damage at the margins of the lesion, as evaluated morphometrically, was not related to the type of fibre nor the power density used. At the same PD the cone-shaped fibres produce a deeper and more narrow lesion than the bare fibres. In our experience the tissue effects of bare fibres, used in contact mode for cutting, when considering the area of lateral thermal alteration, are similar to those of shaped fibres. The necrotic zone at the visible base of the cutting line was not wider, with no sign of deeper necrosis. A wider area of tissue damage was found when the bare fibre was applied in the non-contact mode and although measurable was not significant.

There was no difference in size and depth of lesions caused by cone-shaped fibres and sapphire tips of the same diameter. The shaped fibre is as effective as the sapphire tip for cutting tissue but does not have its disadvantages which are related to the heating of the fibre-sapphire interface and the fragility of the hot tip. In addition, the length of the now-flexible sapphire makes the application through angled working channels difficult or impossible. Notwithstanding the precision of the cut provided by the sculptured fibres, a relevant disadvantage was that free beam coagulation was not possible as it is with bare fibres. Also important is that they can be used only once, since they rapidly loose their shape, due to the exhaustion of the quartz material.

For the safe use of the laser in transanal endoscopic and laparoscopic surgery the set up of dedicated procedures, suitable parameters of application and specially developed applicators is required.

The comparison of the *in vitro* tissue effects of the Nd:YAG laser, when the constant wave and the pulsed mode are used with all the other parameters matched, shows that the deepest and widest lesions are always created by the constant wave mode. We therefore prefer the pulsed mode for both laser cholecystectomy and laser TEM. The control of the laser effects is easier due to the lower amount of energy applied to the tissue. Fast cooling of the fibre tip, which is directly related to the length of the pause, permits this. The right balance between the length of pulses and pauses allows the laser application to still be effective and the life of fibre tip to be extended. The best adapted pulse time for cutting in contact mode was 0.2 s; a longer pulse time is needed for free beam coagulation (0.5 s). The pauses ranged from 0.2 s to 0.3 s in both cases.

The clinical application of the Nd:YAG laser is well known in the field of flexible endoscopy [2, 11, 12]. In laparoscopic surgery some authors reported the use of the Nd:YAG laser for the dissection of the gall-bladder during cholecystectomy [6, 13, 14]. The rationale for bringing laser technology into transanal endoscopic microsurgery was the need of a deep and complete haemostasis before the division of highly perfused tissue [1, 15]. In conventional monopolar high-frequency coagulation this is only achieveable with high wattages, causing severe post-operative oedema [15].

The development of new applicators dedicated to different minimally invasive procedures is required so that laser light can be delivered to remote tissues.

A general requirement for laser applicators in MIS is simple handling of the endoscopic device and secure guiding of the fibre in the working channel. The applicator has to bring the fibre tip into a suitable working position towards the target tissue. The handling of the whole tool, represented by the applicator and the inserted fibre, should be similar to related high frequency devices wherever possible. This was the basis of the design and construction of the hook-shaped instrument for laparoscopic laser cholecystectomy. The feasibility of mechanical blunt dissection was, especially in the preparation of Calot's triangle, an important enhancement of the laser facilities. The back-stop effect of the hook minimized the risk of undesired background tissue injury by the laser beam. A disadvantage of this arrangement is the heating of the metal hook and the tip of the shaft by the beam's energy which can cause thermal damage to adjacent structures. This problem was solved by isolating the shaft with a Teflon tube and constant CO_2 gas cooling. The flow of the CO_2 insufflation for the pneumoperitoneum has to be reduced proportionately in order to avoid high intra-abdominal pressure. The same developmental principles were followed in the case of the TEM laser applicator. Straight devices available on the market were not usable because of the tangential axis of the shaft of the instrument in the operating rectoscope towards the rectal wall. Therefore, the tip of the new applicator was angled at around 45° to make fibre application possible. Its hand-grip was constructed according to ergonomical requirements. The design of endoscopic laser applicators could be further improved if the flexibility of fibreoptics was used to increase the instrumental degrees of freedom. The steerable applicator allows one to angle the tip of the fibre from 0° to 90° and makes possible laser application in different working positions towards remote anatomic structures. This device can also be controlled with one hand only.

There are some doubts as to the cost-effectiveness of lasers in laparoscopic cholecystectomy [5, 16, 17]. The wavelengths mostly used for this purpose are those of the KTP and Nd:YAG lasers [6, 13, 14]. No real advantage over electrosurgery has been proven [16, 17]. The risk of common bile duct injury seems to be higher when laser dissection is performed. In our experience the use of the special applicators should reduce such risks. The costs of lasers are very high [5] and therefore the application of such a technology should be reserved to centres where a multidisciplinary use of this appliance is planned.

In TEM the Nd:YAG laser provides a clean and highly defined line of incision. In order to avoid bleeding from the mucosal and submucosal layers a previous circular free beam coagulation is effective. In our experience the Nd:YAG laser was not sufficient to control severe bleeding from the deep layers of the rectal wall. In fact spilt blood absorbs the beam's energy before it can reach the tissue [18]. Since haemostasis is not easily achievable because of the missing mechanical compression by the application device, vessels larger than 0.5 mm in diameter have to be coagulated in advance. The effectiveness of coagulation was improved by rinsing the spilled blood away from the surface of the tissue during the lasing intervals by means of saline solution.

At the present time the Nd:YAG laser does not provide significant advantages in MIS, although its characteristics make it a suitable tool for future application. The flexibility of the fibreoptics and the high amount of energy transmissable especially, make the application of different lasers possible in combination with highly flexible and steerable laparoscopic instruments.

Acknowledgement

The Alexander von Humboldt Foundation that supported the author Marco M. Lirici with a research fellowship is acknowledged with gratitude. The BMFT, Ministry of Research and Technology of the Federal Republic of Germany, is also acknowledged with gratitude for its support.

References

1 Haina D, Landthaler M. Fundamentals of laser light interaction with human tissue, especially in the cardiovascular system. *Thorac Cardiovasc Surgeon* 1988; **36**: 118–25

2 Groisser VW. Nd:YAG laser therapy of gastrointestinal neoplasms and bleeding: current status and pitfalls. *Laser Med Surg News Adv* 1989 (April): 33–37

3 Schröder T, Brackett K, Joffe SN. An experimental study of the effects of electrocautery and various lasers on gastrointestinal tissue. *Surgery* 1987; **101**: 692–7

4 Schröder T, Hukki J, Castren M, Puolakkainen P, Lipasti J. Comparison of surgical lasers and conventional methods in skin incisions. *Scand J Plast Reconstr Surg* 1989; **23**: 187–90

5 Voyles CR, Meena AL, Petro AB, Haick AJ, Koury AM. Electrocautery is superior to laser for laparoscopic cholecystectomy. *Am J Surg* 1990; **160**: 457

6 Reddick EJ. Laparoscopic laser cholecystectomy: technique and results. *Dig Surg* 1991; **8**: 79–83

7 Buess G, Kipfmüller K, Hack D, Grüssner R, Heintz A, Junginger T. Technique of transanal endoscopic microsurgery. *Surg Endosc* 1988; **2**: 71–5

8 Cuschieri A, Buess G, Perissat J, eds. *Operation manual of endoscopic surgery*. Berlin: Springer Verlag, in press

9 Schwarz CD, Klepetko W, Miholic J, Salem G, Glöckler M, Moeschl P. Die Auswirkung der endoskopisch angewandten Hydrothermo- und Lasercoagulation auf die humane Magenwand in vivo. *Langenbecks Arch Chir* 1987; **371**: 201–6

10 Treat MR, Trokel SL, Reynolds RD, DeFilippi VJ, Andrew J, Liu JY *et al*. Preliminary evaluation of a pulsed 2.15 μm laser system for fiberoptic endoscopic surgery. *Lasers Surg Med* 1988; **8**: 322–6

11 Loizou LA, Grigg D, Boulos PB, Bown SG. Endoscopic Nd:YAG laser treatment of rectosigmoid cancer. *Gut* 1990; **31**: 812–16

12 Mathus-Vliegen EMH, Tytgat GNJ. Analysis of failures and complications of Neodymium: YAG laser photocoagulation in gastrointestinal tract tumors. A retrospective survey of 8 years' experience. *Endoscopy* 1990; **22**: 17–23

13 Spaw AT, Reddick EJ, Olsen DO. Laparoscopic laser cholecystectomy: analysis of 500 procedures. *Surg Laparosc Endosc* 1991; **1**: 2–7

14 Reddick EJ, Olsen DO. Outpatient laparoscopic laser cholecystectomy. *Am J Surg* 1990; **160**: 485–9

15 Reidenbach HD. Grundlagen der Präpartions- und Bluttstillungstechnik. In: Buess G, ed. *Endoskopie. Von der Diagnostik bis zur neuen Chirurgie*. Köln: Deutscher Ärzte-Verlag, 1990: 231–43

16 Corbitt JD. Laparoscopic cholecystectomy: laser versus electrosurgery. *Surg Laparosc Endosc* 1991; **1**: 85–8

17 Hunter JG. Laser or electrocautery for laparoscopic cholecystectomy? *Am J Surg* 1991; **161**: 345–9

18 Hertzmann P. Thermal instrumentation for laparoscopic general surgical procedures. In: Zucker KA, ed. *Surgical laparoscopy*. St Louis: Quality Medical Publishing, 1991: 57–75