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Laser Applications in Lung Parenchyma Surgery

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Summary

Although the bronchoscopical endoluminal laser coagulation and vaporisation of central bronchial carcinoma has been globally used as a standard procedure since the early eighties, laser application still remains the exception in thoracic surgery, even in medical centres. There are two main reasons for this unsatisfactory situation: a lack of basic research, and a false perception of the capabilities offered by the 1064 nm Nd:YAG laser. To date, our working group is the only one that has demonstrated the advantages of the Nd:YAG laser's 1318 nm wavelength for lung parenchyma resections.

Owing to its 80% water content, the lowest tissue density of all parenchymatous organs and its strong tendency to shrink as a result of its air content, the lung is the ideal organ for photothermal laser applications. Since the 1318 nm wavelength shows a ten times higher absorption in water than its 1064 nm counterpart, the desired combination effect – cutting capability plus coagulation plus fistula sealing – can be achieved only with this laser. This combination effect enables virtually any form of parenchyma resection, and centrally located tumours can be haemostatically exposed and resected. The technical advances can best be seen in lung metastatic surgery. The results obtained after laser resection of multiple metastases in 100 patients clearly show a parenchyma-sparing effect as evidenced by the reduction in the lobectomy rate from 25% to 5%. Despite a significant increase in the number of metastases (to an average 6.3 and a maximum of 124 metastases per patient), and including bilateral and synchronous metastases, the 5-year survival rates remained constant at 32.5% as described in the literature. The most important prognosis factor is complete resection, which could be performed as a precision resection in 95% of all cases despite the fact that 41% of these metastases were centrally located.

The future will show whether the introduction of the 1318 nm Nd:YAG laser into lung parenchyma surgery will produce a similar progress as could be achieved in liver parenchyma surgery some ten years ago through the introduction of the CUSA and water jet techniques.

Key words
Nd:YAG laser, 1318 nm wavelength, lung parenchyma resection, metastases resections

Introduction

Back in 1967, using one of the first pulsed 1064 nm Nd:YAG lasers, Minton already showed in experiments with rabbits that lung metastases can be resected and vaporised with laser light (16). Since no flexible fibres were available at that time for delivering the laser beam to the tissue, the only (though inconvenient) option was to move the operating table so the test animals could be positioned under the fixed laser beam as required for resection. Nonetheless, despite these unfavourable circumstances, Minton was the first to recognise an indication that remains of eminent importance in lung parenchyma surgery to this day, namely that laser technique proves most effective in cases where multiple metastases need to be removed from the lung parenchyma. This is explained by the fact the laser basically allows the simultaneous

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cutting and coagulating as well as fistula/leak sealing when working on easily bleeding and fistula-prone tissue such as lung tissue. However, it goes without saying that many technical difficulties still had to be overcome, notably the need for sufficient power densities and suitable applicators. Therefore, laser technique could not be used in open thoracic surgery until twenty years later, even though the 1064 nm Nd:YAG laser established itself in the early eighties as a globally used standard tool for endobronchial laser coagulation and vaporisation of tumours located in the central airways (9).

It was not until 1985 when LoCicero, working with a CO_2 laser, reopened the debate on the use of lasers in open thoracic surgery as well (13, 14). However, since the CO_2 laser is a pure absorption or cutting laser, it proved inadequate for lung surgery and thus could not establish itself in this medical discipline. As a result, a number of medical centres in the United States, Japan and Europe began experimenting with 1064 nm Nd:YAG lasers, using bare fibres and sapphire tips to perform superficial resections (4, 10, 11, 12, 13, 15). As Table 1 shows, however, all of these teams achieved only low patientloads and published no further results, mainly because the technical difficulties posed by the available 1064 nm lasers could not be overcome without further basic research. To date, our working group remains the only one that has systematically combined laser-technological basic research with animal-experimental research on lung tissue determinants, all aimed at developing a laser system specifically suitable for use on lung tissue (1, 2, 7, 22).

Material and Method

Due to its parenchymal tissue having a typical water content of 80% but a very low tissue density (just a fifth of the liver parenchyma), a very low heat capacity and a variable air content, the lung is the ideal organ for photothermal laser applications (see Table 2). Therefore, resecting lung parenchyma requires a laser with a powerful coagulation capability in addition to excellent cutting properties, given the high vessel density. After all, the surgeon must always expect fis-

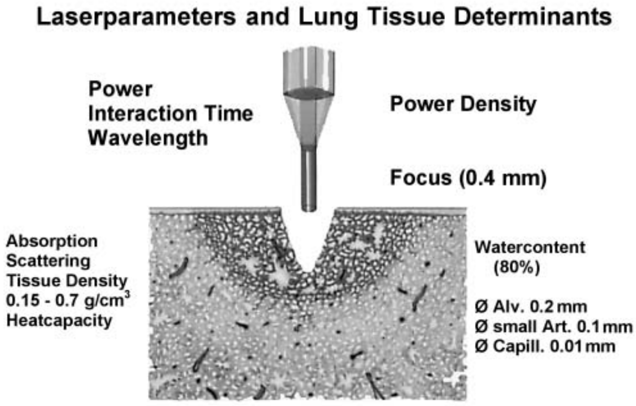
Table 1. Literature Survey: Nd:YAG Laser Resection in Pulmonary Surgery.

Author	Article	Laser	Wave Length	Subject
LoCicero	1985 Ann Thorac Surg (14)	$C0_2$		Hemostasis, Sealing of Air Leaks
Rolle	1988 Laser in Med and Surg (22)	Nd YAG	1064 nm/ 1318 nm	Experimental/clinical n = 47 Wegde and Segmental Resections
Moghissi	1989 J Thorac Cardiovasc Surg (18)	Nd YAG	1064 nm	Local Excision, “Coin Lesions”
LoCicero	1989 J Thorac Cardiovasc Surg (13)	Nd YAG	1064 nm	Laser assisted pulmonary resections
Kodama	1991 J Thorac Cardiovasc (11)	Nd YAG	1064 nm	Resection of Lung Metastases n = 25
Branscheid	1992 Euro J Cardio Thorac Surg (4)	Nd YAG	1064 nm	Resection of Lung Metastases n = 14 Laser only n = 51 comb. with Lobectomy
Kodama	1992 Kyobu Geka (10)	Nd YAG	1064 nm	Resection of Lung Metastases n = 25 Segmental Resection (NSCLC) n = 25
Mineo	1998 Chest (15)	Nd YAG	1064 nm	Resection of Lung Metastases n = 23
Rolle	2002 Ann Thorac Surg (23)	Nd YAG	1318 nm	Lobe-Sparing Resection of Multiple Pulmonary Metastases n =100 (6.3/Pat)

tulae and increasing bronchopulmonary leaks, particularly when dissecting lung parenchyma, the more so the deeper one works down in central direction. Comparing the absorption behaviour of different lasers in water, one gets an absorption curve rising steeply in several stages, beginning at 1000 nm in the near infrared range and ending at 105 times the base value for the Er:YAG laser (1, 3, 5). Such high absorption means that the applied energy is immediately transformed into tissue vaporisation (= cutting), with the result that no significant coagulation occurs (as evidenced by the CO_2 laser). Consequently, both the Er:YAG and CO_2 lasers are unsuitable for use on the lung parenchyma.

The same reasoning applies to the holmium laser, which becomes unsuitable at a wavelength of 2100 nm because once again absorption becomes so dominant at this point that sufficient coagulation of the lung parenchyma is no longer guaranteed. Thus, the Nd:YAG laser remains the only promising laser for further development with a view to using it on the lung parenchyma. So back in 1988, we started testing the second wavelength of the Nd:YAG laser (1318 nm) in animal experiments, based on the knowledge that the 1318-nm wavelength significantly differs from the standard (1064 nm) wavelength by its ten times higher absorption in water but still offers sufficient laser light scatter, due its proximity to the beginning infrared spectrum, to satisfy the vital coagulation requirement as well (see Table 3). Our hopes materialised soon. After just a few tests it became clear that the 1318 nm wavelength provided in fact the intended combination effect – cutting capability plus coagulation capability – so perfectly as could not be achieved with the 1064 nm wavelength (23, 26). As a welcome side-effect, we also found strong lung tissue shrinkage, which provides two additional advantages: mechanical reinforcement of the coagulation effect, and fistula sealing far into the central lobe region. In fact, the surfaces coagulated and sealed off

Table 2. The most important tissue determinants are: 80% water content, Iow tissue density of 0.15 g/cm^3, and a high shrinkage capacity due to the air content of the alveoli.



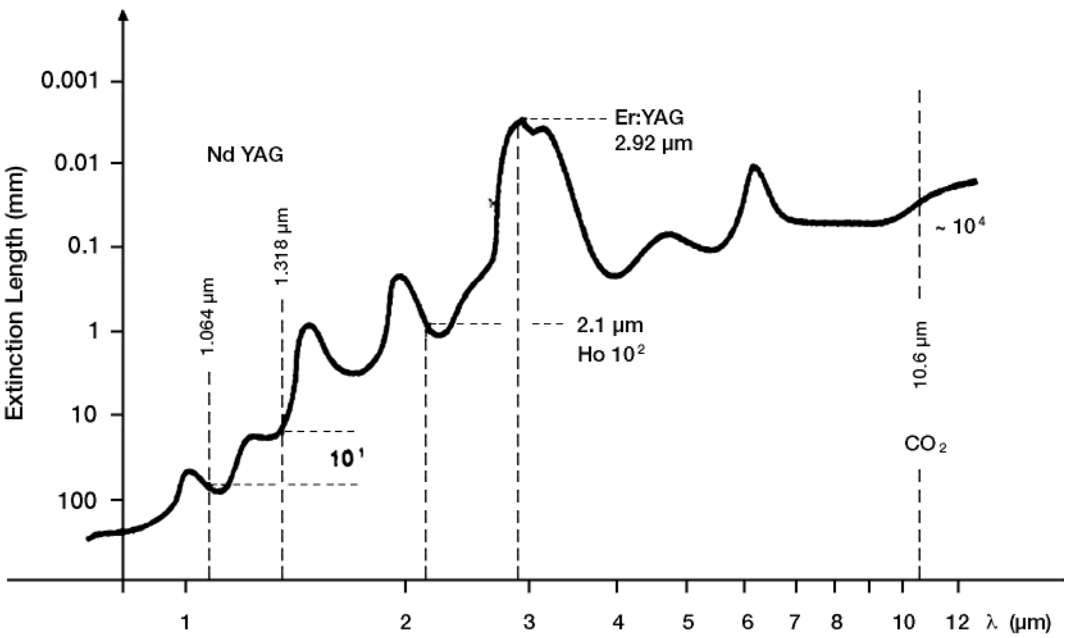
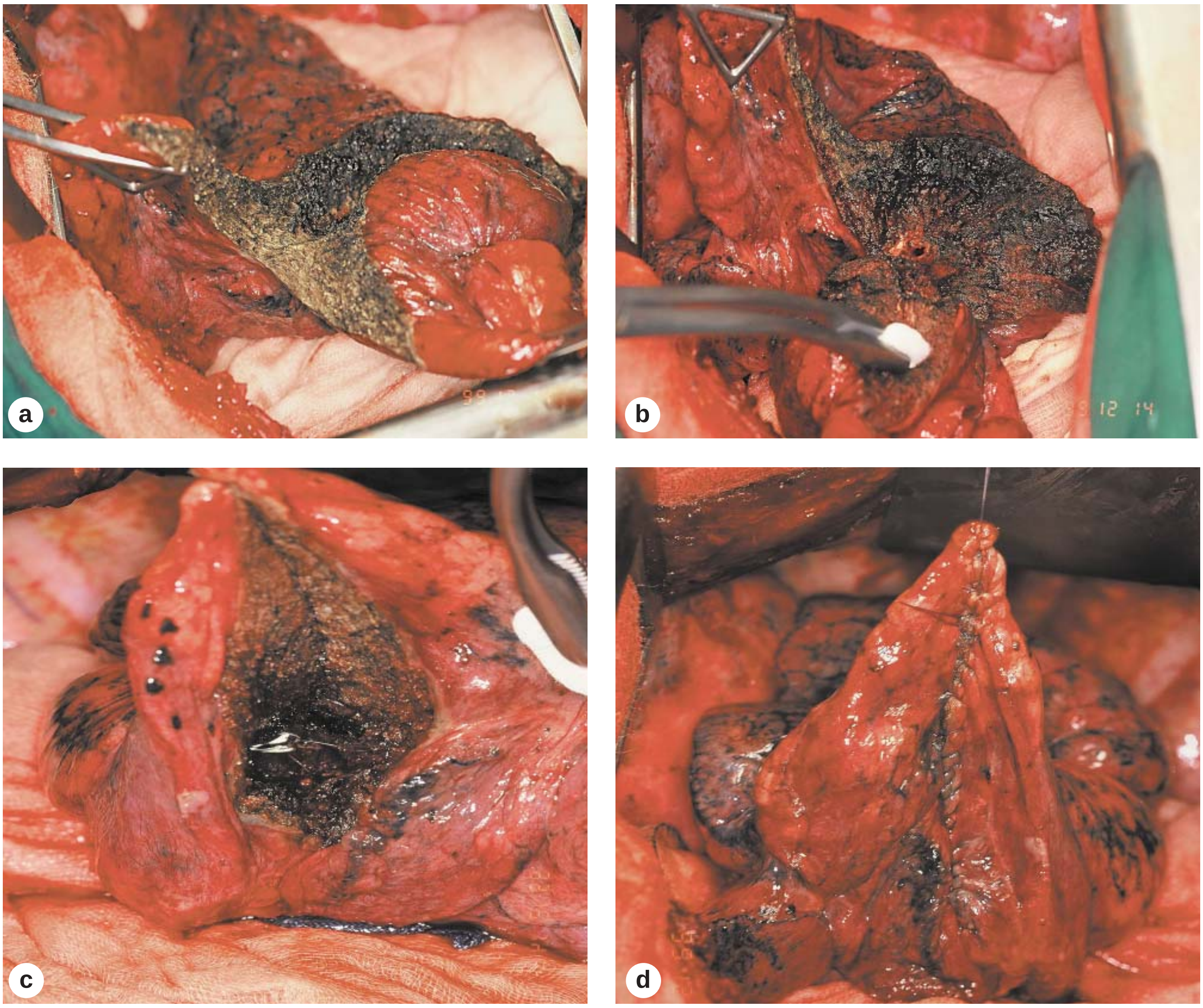


Table 3. Schematically simplified representation of the absorption spectrum of water (acc. to Bayly). The diagram exhibits the 1064 nm and the 1318 nm wavelengths of the Nd:YAG laser as well as the ten times higher absorption capacity of the latter wavelength.



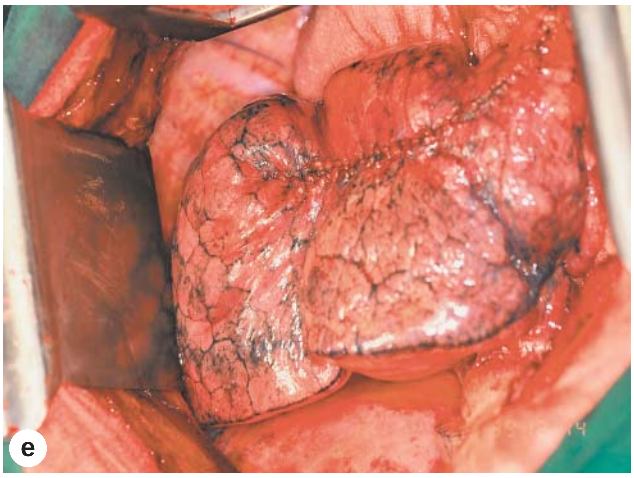


Fig. 1a. Laser resection of segment IX, left lower lobe, in an 80-year-old female patient with a peripheral NSCLC, ∅ 3.5 cm.

Fig. 1b. Hemostatic laser resection under excellent visual conditions down to the segmental bronchus level.

Fig. 1c. Segment IX completely resected, bronchus and artery treated with a transfixion suture, laser resection surface air-tight under water.

Fig. 1d. Reconfiguration of the lower lobe with continuous suture of the pleura visceralis.

Fig. 1e. Residual lower lobe completely spread, ventilated, no atelectasis.

through defocussed irradiation with the 1318 nm laser withstand artificial ventilation pressures of up to 25 cm H_2O. Obviously, this beats all known haemostyptics and tissue glues several times over.

Fig. 1 (a–d) shows a complete segment-9-resection from the left lower lobe, performed on an 80-year-old female patient with a 3.5 cm peripheral bronchial carcinoma, in which case no lobe resection was possible for functional reasons. The entire parenchyma resection was performed exclusively with a 1318 nm Nd:YAG laser, haemorrhage-free and under excellent visual conditions, down to the segmental arteries and the segmental bronchus level. Only the bronchus and the artery required a transfixion ligature. The essential point is that the laser coagulation surface reliably withstands ventilation pressure and the residual lobe completely inflates after adaptation of the visceral pleura with a continuous suture, thus resuming its function in this high-risk patient. Note that it is not possible to perform this segmental resection with stapler sutures, as the tissue diameter of the pyramidal lower lobe is too large for staples.

In our first pilot study, conducted in 1988 and comprising no less than 47 patients, we could already demonstrate that the 1318 nm Nd:YAG laser can be safely used for the low-complication resection of all sorts of benign and malignant tumours, including excisions of nodules, open lung biopsies, wedge resections, and typical and atypical segmental resections (21, 22, 24). However, a number of problems remained, which we simply could not solve without the medical industry's support. For example, we only had a prototype laser with insufficient individual components. Another problem was the low energy efficiency of the 1318 nm laser wavelength, which is only 34% of the corresponding value of the 1064 nm wavelength, thus leaving the surgeon with insufficient power densities when simply filtering out the second wavelength. Consequently, we were forced to develop a completely new laser system suitable for serial production in order to enable wide-spread application of this laser technology. It was not until it became reasonably clear that the 1064 nm Nd:YAG laser had no future in thoracic surgery that we could obtain the support of the Trumpf company (formerly Hüttinger) and Martin for this development challenge. So in 1995 and 1996, our joint efforts led to the following improvements:

To achieve higher laser power outputs for the 1318 nm wavelength, it was necessary to almost double the Nd:YAG laser's average energy efficiency from 3% to 5%. The beam quality, too, was improved to such an extent that the laser light could be easily coupled into fibres having a diameter of less than 0.6 mm without any heat build-up or energy losses. Moreover, the flexible fibre cables had to be adapted to the (wavelength-specific) high absorption characteristics by choosing a very low water content. Finally, we developed a special focussing handpiece featuring a four-lens system allowing a near one-to-one projection of the fibre diameter relative to the working focus (beam spot), thus enabling power densities of up to 24 kW/cm^2.

Fig. 2 shows the complete laser equipment, including a description of the major individual components. Among them is a high-performance smog evacuator, which is needed in large-scale parenchyma resections because they produce a great deal of smog (so-called "plume") that must be removed at once.

Results

Instead of dealing individually with the various different types of lung parenchyma resection, from circular excisions of nodules to wedge resection to atypical and typical segmental resections, we are going to present here the results of multiple and bilateral lung metastases resections. We take this approach because the removal of such metastases includes all of the above resection types and combinations, due to their different sizes, quantities, and localisation (including central location). Moreover, this clearly represents the most important indication for parenchyma-sparing lung resections.

Pulmonary metastatic surgery has been an established discipline for more than 20 years. It is performed on a large group of patients, as 30% of all patients with malignancies develop lung metastases in the course of their diseases (19, 20, 23, 27, 28). Even today, it is still widely held belief that the occurrence of lung metastases marks the final stage of the disease so that only short survival times are to be expected and chemotherapy represents the only feasible treatment option, if any. However, this view has become obsolete. We recommend consulting an experienced

Components of Nd:YAG Laser System

- 1318 nm wavelength
- Doubled energy efficiency of 5%
- High beam quality for coupling in thin fibres
- Flexible quartz fibres 0.4 mm diameter, low water content
- Four lens focussing handpiece
- High performance smoke evacuation system

Fig. 2. Components of modern laser equipment for the application on lung tissue.

thoracic surgeon in any such case in order to determine whether or not a potentially curative approach is possible by completely resecting all lung metastases. Of course, such an approach presupposes the absence of additional extrathoracic metastases and the functional operability of the patient – two conditions that can be expected in no less than 20% of all cases.

Most European and international thoracic centres show a preference for resecting solitary metastases developing a long time after the primary tumour, since these conditions offer the best prospects. A maximum of three to five metastases is frequently considered the limit, while bilateral resections are usually declined on the assumption that such a condition represents a generalisation of the disease (19). It is exactly here where our therapeutic approach comes in. We intend to demonstrate that the 1318 nm Nd:YAG laser enables the low-strain resection of significantly more as well as bilateral metastases with comparable results. This obviously translates into an essential extension of the indication, because patients so far considered inoperable can now benefit from surgical treatment as well.

In an initial observation study with 150 consecutive patients we were able to show that – owing to the 1318 nm laser technique – the resection could be performed as a parenchyma-sparing “precision resection” in 95% of all cases, so that a lobectomy was necessary only in the remaining 5% of the cases (against an international lobectomy rate of 20–30%, as evidenced in the literature), even though 6,3 metastases on average and a maximum of 124 metastases were removed per patient. Thanks to a careful and comprehensive palpation of the collapsed lung, 25% more foci could be resected than were indicated in the spiral CT scan. This parenchyma-sparing technique enables the surgeon to rigorously remove almost any finding considered suspicious upon palpation of the organ, thus enhancing the chances of achieving the main objective: a resection as complete as possible (23, 24).

Table 4 shows the survival rates of 100 metastatic patients according to Kaplan-Meier, based on an average observation time of 26.5 months, a complete follow-up, and with an average of 6.3 metastases removed per patient. The table also includes the clinical courses of patients who could not be completely resected because – in contrast to the CT findings – a miliary spread or a pleural carcinosis was detected intraoperatively (= incomplete resection), as well as those where a local recurrence of the primary tumour occurred after complete resection of the lung metastases (= complete palliative). The results show that a complete resection correlates with a highly significant increase ($p = 0.001$) in the survival rates, with 5-year survival rates at 32%, all tumours included (e.g. metastases in the case of malignant melanoma). We can also conclude that the traditional upper limit of five metastases can be significantly exceeded (given an average of 6.3 metastases per patient in our case) without worsening the results as long as all of the metastases are completely resected using advanced laser technology. However, if the resection remains incomplete, or if a local recurrence of the primary tumour occurs, the prospects deteriorate significantly, resulting in a 2-year survival rate of only 25% despite chemotherapy and irradiation. This again documents that curative resection of the primary tumour plus complete resection of all lung metastases offers a chance for long-term survival (24).

As evidenced in Table 5, our results clearly confirm the internationally disputed inclusion criterion of bilateral metastases. Provided the surgeon achieves a complete resection of all metastases, there is no evidence that patients with bilateral metastases will have significantly worse prospects. In such cases, our surgical tactics are to begin with the “more difficult” side (i.e. the one with the higher number of metastases, or with central metastases) performing an anterolateral, muscle-sparing thoracotomy. Following successful treatment of this side (i.e. complete resection), the other side is then treated in the same manner – and by the same access – some four weeks later on average. This two-stage interventional approach ensures that

Table 4. Survival according to resection status.

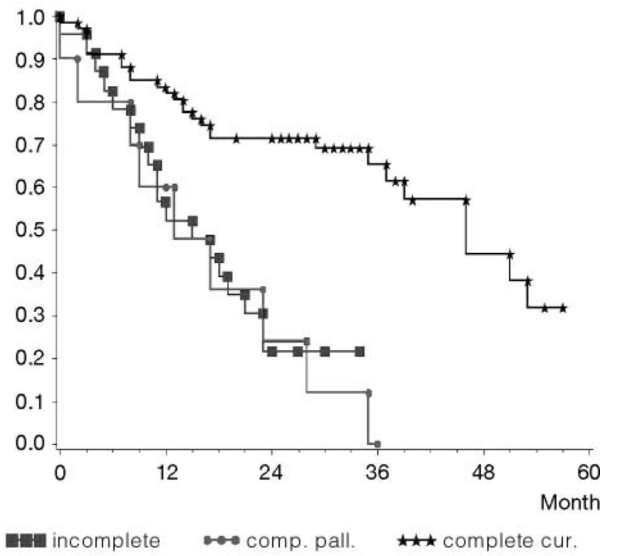
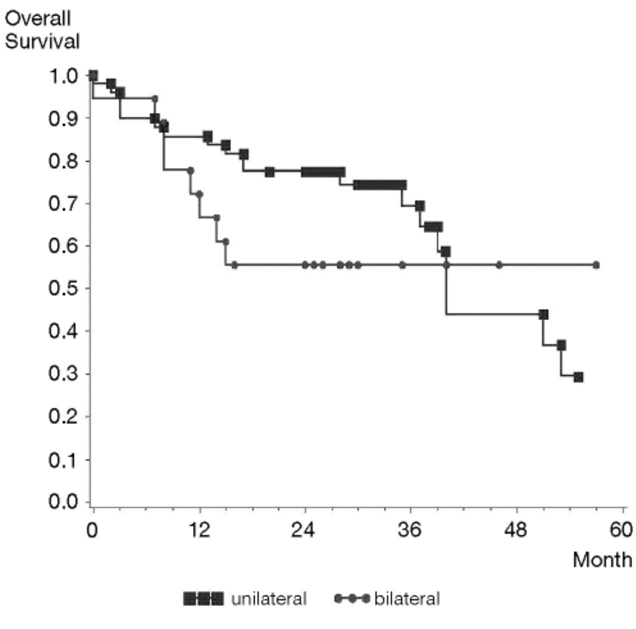


Table 5. Influence of unilateral versus bilateral laser resections.



during the intervening period, the lung treated first is allowed to heal under pulmonary physiotherapy so that it can reliably take over the function of the other lung while it is collapsed during the second operation. This procedure significantly reduces the overall complication rate. Another important finding is that there is no evidence for any (theoretically possible) oncologic disadvantages of our two-stage procedure.

Table 6 again deals with the "number of metastases" prognosis factor, providing an evaluation based on the IRM (International Registry of Lung Metastases) (19). The categorisation used – "1 MET", "2 MET", "3 MET" and "4+ MET" – reflects the conservative international indication approach using an upper limit of only five metastases. In contrast to the IRM, we could find no deterioration in the prospects for the group with the highest number of metastases. Having resected 6.3 metastases on average per patient, we conclude that patients with a considerably higher number of metastases should also be operated on – provided that a complete resection is technically very probable.

Table 7 deals with the disease-free interval, meaning the time interval up to the first occurrence of lung metastases following removal of the primary tumour, which is considered a further independent prognosis factor in the literature. If metastases develop no earlier than three years (or more) after removal of the primary tumour, it is generally concluded that this indicates an oncologically retarded disease process with longer-term survival prospects. However, we would like to draw the reader's attention to the so-called "synchronous" metastases, which either develop within the first 12 months or are even diagnosed together with the primary tumour and which are stressed with an unfavourable prognosis. Interestingly, though, our results do not show any significant differences for this sub-group in terms of long-term survival, given a complete resection of all metastases. Because a complete resection is the single most important prognosis factor, we would suggest that patients with synchronous metastases should not be excluded from resection.

Comments

Using 1318 nm laser technology in lung parenchyma surgery could trigger a leap similar to that achieved in liver parenchyma surgery some ten years ago by the development of the CUSA technique and the water jet dissector.

At that time, blunt dissection with the suction device and the finger fracture technique were standard procedures in liver parenchyma surgery but have been rendered obsolete today. Thanks to the improved

Table 6. Influence of the number of metastases of survival in complete.

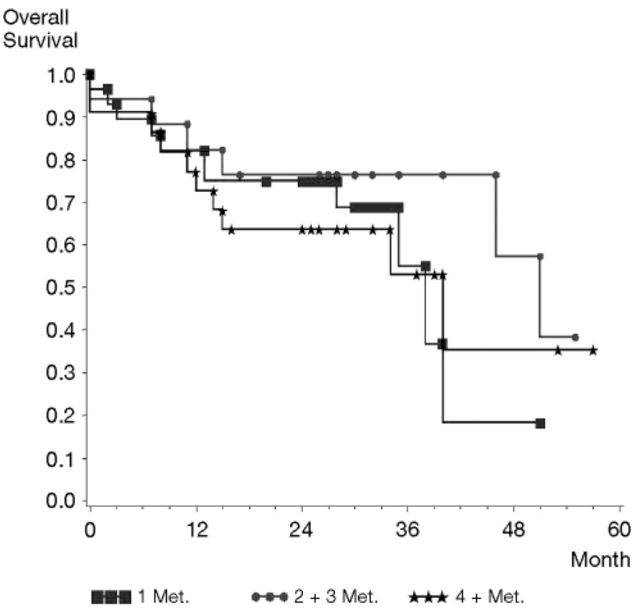
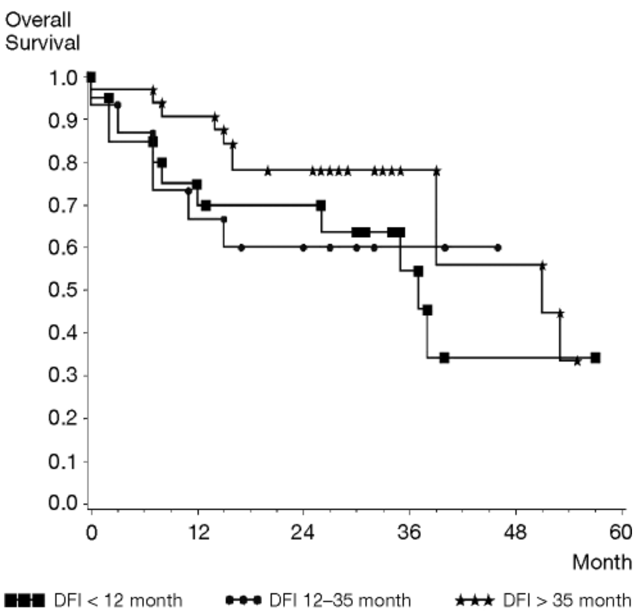


Table 7. Influence of disease-free interval to survival in complete.



preparation technique, together with blood loss minimisation and an almost complete avoidance of bile duct fistulae, it was possible to reduce the complication rate significantly and simultaneously increase the number of completely resected liver metastases. In the meantime, the advances achieved by new technology have been clearly evaluated, with a great variety of studies documenting the extended indication and the improvements in long-term results.

In lung parenchyma surgery, the finger fracture technique is still the standard procedure for segmental resections, while wedge resections and atypical pulmonary resections are seldom performed with the clamping technique, staplers being the preferred option in these cases. This means, however, that an oncologically controlled, fistula-free and haemostatic resection is possible only on the so-called pulmonary cortex (i.e. on the periphery of the variously configured lobes) when using conventional methods. Dissection in central direction, not to mention a controlled resection of a focus or tumour from the centre of a lobe, is not possible with these techniques, which explains the high lobe resection rate of 20–30% mentioned above (19, 20, 27).

In contrast, the 1318 nm laser enables the surgeon to cut through the parenchyma of an entire lobe, either within anatomical or extraanatomical limits, on a haemorrhage-free basis and thus under excellent visual conditions. As in liver surgery, this dramatically extends the technical options as well as the indication for parenchyma resection. For example, any tumour located in the center of a lobe can be safely exposed and histologically checked, with the result that in the past five years no lobectomy has been necessary in our department for the histological clarification and subsequent removal of benign tumours. The results of the pulmonary metastasectomies performed with the 1318 nm laser demonstrate the technical improvements achieved in lung parenchyma resection. Despite their central localisation in 41% of all cases, 95% of all metastases could be removed by parenchyma-sparing precision resection, thereby reducing the lobectomy rate from 25% to just 5%. The extension of the indication concerns the number of metastases as well as the inclusion of patients with multiple bilateral and synchronous metastases. Thanks to the parenchyma-sparing and lobe-saving effect, it is also possible to perform repeated operations on patients with recurring metastases. And last but not least, surgical treatment also becomes an option for patients who have previously undergone successful resection of extrapulmonary metastases (liver, brain).

Based on the promising results that have been obtained to date, a large multi-centre study has been initiated with the purpose of investigating and assessing both the technical improvements and the indication extensions with regard to the various primary tumours involved.

Laseranwendungen in der Lungenparenchymchirurgie

Obwohl sich die bronchoskopische endoluminale Laserkoagulation und Vaporisation zentraler Bronchialkarzinome bereits Anfang der 80er Jahre weltweit etabliert hat, ist die Laseranwendung in der Thoraxchirurgie heute selbst in Zentren noch die Ausnahme.

Mit 80% Wassergehalt, der niedrigsten Gewebedichte aller parenchymatöser Organe und starker Schrumpfungstendenz durch ihren Luftgehalt ist die Lunge das ideale Organ für fotothermische Laseranwendungen. Berücksichtigt man die lungenspezifischen Gewebedeterminanten, kommt nur ein Nd:YAG Laser infrage, wobei zwei Wellenlängen zur Verfügung stehen. Da die 1318 nm Wellenlänge eine 10-fach höhere Absorption als die 1064 nm Wellenlänge in Wasser aufweist, kommt nur hier der gewünschte Kombinationseffekt aus Schneidefähigkeit, Koagulation und Versiegelung von Fisteln zustande. Dadurch wird jede Form der Parenchymresektion möglich und zentral gelegene Tumoren können bluttrocken freigelegt und reseziert werden. Der technische Fortschritt lässt sich am besten anhand der Lungenmetastasenchirurgie belegen. Durch den parenchymsparenden Effekt konnte die Lobektomierate von 25% auf 5% gesenkt werden, die Anzahl der entfernten Metastasen auf durchschnittlich 6,3/Patient erhöht und die Indikation auf bilaterale und synchrone Metastasen erweitert werden.

Die Einführung des 1318 nm Nd:YAG Lasers in die Lungenparenchymchirurgie ist analog zur technischen Verbesserung und klinischen Weiterentwicklung der Leberparenchymchirurgie durch die Einführung der CUSA- und Wasserstrahltechnik zu sehen.

Schlüsselwörter
Nd:YAG Laser, 1318 nm Wellenlänge, Lungenparenchymchirurgie, Metastasenresektionen

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