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Nd-YAG Laser Photocoagulation of Canine Myocardium with the Transparent Contact Probe

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Abstract. Laser photocoagulation of myocardium is an alternative to surgical resection in the treatment of drug resistant ventricular tachycardia. In certain areas of the heart, however, bare fibre delivery of laser energy involves a risk of unintentional damage to nearby structures. The purpose of the study was to determine whether Nd-YAG laser irradiation, delivered with the transparent contact probe, would produce adequate laser photocoagulation of the canine myocardium in comparison to bare fibre delivery of the laser energy. In nine mongrel dogs, continuous wave Nd-YAG laser irradiation with and without a transparent contact probe was directed at the epicardium. Pulse power was 10, 15 and 20 W, pulse duration 5, 7 and 10 s, and spot size was 1 mm. A total of 178 lesions were analyzed microscopically. After a 200 J pulse energy delivered by the contact probe, the lesion depth was 4.9 ± 0.5 mm (mean ± s.d.), which is usually adequate to ablate arrhythmia sites. Bare fibre delivery of laser energy did not produce deeper lesions. There was no difference between the bare fibre and the transparent probe in the occurrence of major arrhythmias (4/86 bare fibre, 3/92 transparent probe). We conclude that the transparent contact probe allows safe and effective laser irradiation of sites of origin of ventricular arrhythmias.

INTRODUCTION

Endocardial resection, guided by electrophysiologic studies, is currently the accepted surgical therapy for intractable ventricular tachycardia (VT), but the optimal surgical therapy still remains to be established (1). The postoperative mortality of 8–23% before hospital discharge is mainly due to congestive heart failure. In survivors, the surgical cure rate is 60–90%, depending on patient selection and the technique used (2, 3).

To ablate arrhythmogenic sites, photocoagulation of myocardium by laser irradiation is an alternative to surgical resection (4–8). Clinical application of laser photocoagulation with the Nd-YAG laser was started in 1985 by Svenson et al (9), and the initial results have been promising. However, in the dog it has been shown that bare fibre laser irradiation using a fibre tip–tissue distance of 2 cm may in some areas, for instance, in the vicinity of the mitral valve and the valvular apparatus, result in unintended damage to these structures by direct exposure or by backscatter of laser light (10).

To avoid the risk of unintentional damage, the fibre tip–tissue distance may be reduced, allowing more precise laser energy delivery. Mechanical trauma by the sharp fibre optic may be avoided by shielding the fibre tip with a flat transparent contact probe which allows direct, atraumatic contact with the surface to be irradiated (11). Mechanical stimulation of the heart by the contact probe, however, may induce arrhythmias. The purpose of this study was to determine whether Nd-YAG laser irradiation, delivered by transparent contact probe, produces adequate photocoagulation of canine myocardium without augmenting acute

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arrhythmogenicity in comparison to bare fibre delivery of the laser energy.

MATERIALS AND METHODS

In nine mongrel dogs (weight 18–30 kg) anaesthesia was induced with Etomidate 20 mg i.v. (Hypnomidate, Janssen Pharmaceutica BV, Tilburg, The Netherlands). After endotracheal intubation, artificial ventilation was started (Siemens-Elema 600 A Servo ventilator) and anaesthesia was maintained with Halothane (Halothan, Hoechst Pharma, Amsterdam, The Netherlands) 0.7–1.0% added to a 1:1 gas mixture of O_2 and N_2O. During the procedure, EKG, intra-arterial blood pressure, central venous pressure, rectal and esophageal temperature and end-tidal CO_2 concentration of the expiratory air were continuously monitored.

A left thoracotomy was performed in the fourth or fifth intercostal space after establishing analgesia (Sufentanilcitrate, 0.25 mg i.e.; Sufenta Forte, Janssen Pharmaceutica BV) and muscle relaxation (Vecuroniumbromide, 0.1 mg kg^{-1} i.v.; Norcuron, Organon Teknika BV, Boxtel, The Netherlands). The heart was suspended in a pericardial cradle. Myocardial temperature was measured before and after the laser procedure with a needle thermistor. The sites for laser irradiation were chosen at random, but epicardial vessels were avoided. During the laser procedure, the myocardial surface was flushed by saline (1 ml s^{-1}, 24 °C).

A 100 W continuous wave (cw) Nd-YAG laser (MediLas-2, MBB, Munich, Germany) with a wavelength of 1064 nm was coupled to a 0.6 mm core diameter gas cooled (CO_2, 1 l min^{-1}) silica fibre. On this fibre, a flat transparent contact laser probe with a diameter of 2.2 mm (MT 1.5, Surgical Laser Technologies, Malvern, PA, USA) could be mounted. The bare fibre was fixed on the epicardial surface with a hand-held device, which established the same 1 mm spot size on the epicardium during contact of the transparent probe. With an external power meter (model 5104, Laser Instrumentations, UK) the output of the bare fibre and the flat contact probe were each set at three levels: 10, 15 and 20 W. The pulse duration was 5, 7 or 10 s. For the transparent probe, the maximum pulse power of 20 W was chosen according to the manufacturer's recommendation. Irradiation was discontinued if subsurface vaporization (indicated by a popping sound and crater formation) or a major arrhythmia occurred. The latter was defined as idioventricular fibrillation/flutter or ventricular tachycardia (ventricular rhythm of ≥3 consecutive complexes with a rate >100 bpm).

Table 1. Resulting lesions produced by bare fibre and transparent probe

Lasing parameters		Number of lesions	
Watts (W)	Seconds (s)	Bare fibre	Transparent probe
10	5	10	11
10	7	11	10
10	10	10	12
15	5	11	11
15	7	10	11
15	10	10	11
20	5	9	9
20	7	10	11
20	10	5	6

After the laser procedure, the animal was sacrificed by exsanguination and the heart removed and fixed in 4% buffered formalin. Laser lesions were excised and embedded in paraffin, sectioned and stained with Haematoxylin and Eosin and with Masson–Trichrome. Subsequently, lesions were studied using polarizing filters to determine birefringence changes of the lesions.

In total, 178 lesions were analyzed microscopically (86 with the bare fibre, 92 with the transparent probe). Table 1 gives the lasing parameters used with the resulting numbers of lesions produced with the bare fibre and transparent probe. The border of the lesion was defined by the outer border of a rim of contraction bands. Using a calibrated ocular, surface width (SW), maximum width (MW) and depth (D) were determined accurate to 0.1 mm.

RESULTS

The following measurements are presented as mean ± standard deviation (s.d.), unless otherwise stated. Statistical analysis of the results was performed using SPSS/PC+ statistical software using a multivariate analysis of variance and covariance, paired and unpaired Student's t test, and Fisher's exact test whenever appropriate. P values <0.05 were considered to be of statistical significance.

Heart muscle temperature was 36.2 °C

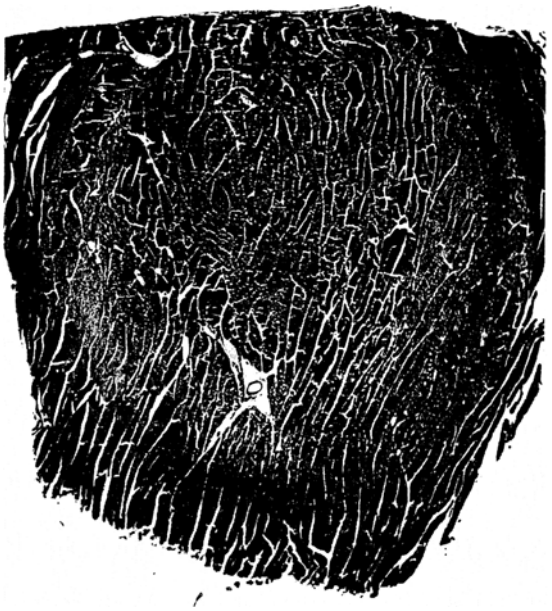

Fig. 1. Photocoagulation lesion made by Nd-YAG laser irradiation with a transparent contact probe (15 W, 10 s). Note the rim of contraction bands at the edge of the lesion. Staining Haematoxylin/Eosin, original magnification ×23.9.

(range 35.1–37.0 °C) before and 35.3 °C (range 33.9–36.1 °C) after the procedure.

Macroscopy showed a central white zone of coagulation in the lesion. If subsurface vaporization had occurred, a central crater was visible. Microscopically, a 'full blown' lesion (150–200 J) had the following characteristics (Fig. 1). There was a central zone of photocoagulation, characterized by loss of cellular structure and with a hyaline appearance. Neither cellular boundaries nor striations could be discerned in these areas. Nuclei were absent or pycnotic. The cytoplasm was hypereosinophilic. Carbonization was noted infrequently. The zone of coagulation was surrounded by a thin zone of thermal damage that could not easily be appreciated macroscopically. In this border zone, there was a gradual transition to normal-looking myocardium. The outer border of this zone was demarcated by a zone of transverse eosinophilic contraction bands (Fig. 2). With a polarizing microscope, loss of birefringence was noted throughout the lesion. It extended to the outer boundary of the zone of contraction bands (Fig. 3). In the border zone, nuclei varied from pycnotic to normal-looking, while the cellular structures and striations were discernible. In the central zone of photocoagulation, interstitial haemorrhage due to ruptured venules was sometimes present. Most arteries and veins, however, remained intact, although their walls showed vacuolization and pycnotic nuclei as signs of thermal damage. Centrally in the lesion, the smaller vessels were occluded by fibrinogen clots (Fig. 4). When the transparent probe was used, a slight impression was frequently noted on the epicardial surface, but for the remainder there was no morphologic

Fig. 2. Zone of contraction bands. At the left is the normal myocardium, at the right the irradiated myocardium. Masson-Trichrome stain, original magnification ×594.

(a) (b)

Fig. 3. Photocoagulation lesion made by Nd-YAG laser irradiation with the bare fibre (15 W, 5 s). (a) Staining Haematoxylin/Eosin. The zone of contraction bands at the border of the lesion can be appreciated at the left. (b) the same lesion using polarizing light microscopy. The normal myocardium at the left shows birefringence. In the lesion, including the zone of contraction bands, the birefringence is lost. Original magnification ×57.75.

difference between lesions made with the bare fibre and with the contact probe.

The microscopic measurements of the surface width, maximum width and depth of the lesions are summarized in Fig. 5. Some small differences were found, but in general, the results obtained by bare fibre and contact probe delivery of laser irradiation were comparable.

Subsurface vaporization was identified as a central crater in the lesion. It occurred more frequently with the bare fibre (18/86) than with the transparent tip (6/92, $p < 0.03$, Fisher's exact test). It was not associated with major arrhythmias.

Major arrhythmias never occurred as a result of mechanical manipulation with the hand-held device or the transparent tip. In 4 dogs, 7 episodes of major arrhythmias occurred—6 episodes of ventricular fibrillation, which had to be converted with DC shock, and one episode of ventricular flutter which terminated spontaneously. Three of these episodes started during laser irradiation. Four started within 1 s after the end of laser irradiation. The arrhythmia started usually after 7 s of irradiation (5 times) and twice after 10 s of

Fig. 4. Central zone of photocoagulation. The wall of the bigger artery shows extensive vacuolization. The lumen contains no thrombus. The smaller artery, in contrast, is occluded by a thrombus. Staining Haematoxylin/Eosin, original magnification ×239.25.

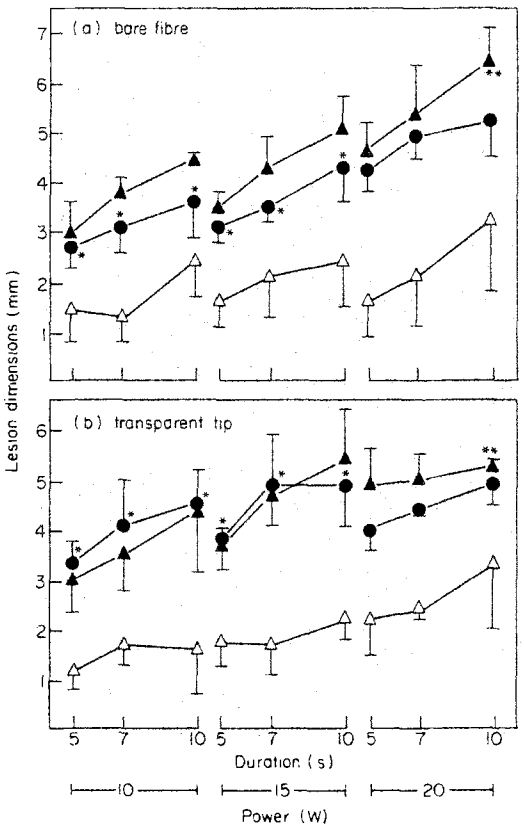

Fig. 5. Surface width (△), depth (●) and maximum width (▲) of photocoagulation zone in relation to pulse power (W) and pulse duration (s). (a) bare fibre; (b) transparent tip. *: Depth was greater for the transparent probe compared to the bare fibre ($p < 0.05$). **: Width was smaller for the transparent probe than for the bare fibre ($p < 0.05$).

irradiation. There was no difference between the bare fibre and the contact tip in the incidence of ventricular flutter/fibrillation (4/86 bare fibre, 3/92 transparent tip).

DISCUSSION

The 'site of origin' of post-infarction VT is commonly a re-entrant circuit at the endocardial side of the ventricular wall at the border between normal and infarcted myocardium (12, 13). The re-entrant circuit may be also intramural or epicardial (14, 15). To ablate arrhythmogenic myocardium, cw Nd-YAG laser at wavelength 1064 μm is to be preferred to the argon (16) or CO_2 laser (17) because of deeper photocoagulation and reduced risk of perforation. The 4.9 mm deep photocoagulation in the present experiment is sufficient to ablate endocardial or epicardial sites of origin. The use of the contact probe did not reduce the coagulation depth.

The deeper photocoagulation with the contact probe at low pulse power may be due to reduced reflection of laser light from the epicardial surface with the transparent probe due to better matching of the refractive indices of the transparent tip (assuming silica, $n = 1.45$) with myocardial tissue ($n = 1.33$) than with air ($n = 1$) (18). In the presence of scar tissue, however, the coagulation depth may be affected by altered optical properties (18, 19).

Localization of the VT origin in the inferior wall, especially near or at the posterior papillary muscle, has been associated with a low primary success rate of endocardial resection. It is difficult to perform a subendocardial resection under the chordae and mitral leaflets or around the base of the papillary muscle (20) of if a deeper or epicardial site of origin is present (15). In the dog, Bakker et al (10) experienced that Nd-YAG laser irradiation with the bare fibre of the posterior papillary muscle in dogs may occasionally cause inadvertent damage to chordae tendineae and the mitral leaflets, eventually resulting in mitral regurgitation. With the transparent contact probe such damage can be avoided. In catheters for transluminal ablation of arrhythmogenic foci, the contact probe protects the fibre optic against thermal damage and the tissue against mechanical trauma from the fibre (21–24).

The presence of the transparent probe limits the maximum applicable power. If laser irradiation is delivered in an area less prone to inadvertent irradiation damage (epicardium, left ventricular free wall), achieved lesion depth may even be transmural using a bare fibre and high pulse power (25).

Subsurface vaporization is the combined result of the low absorption and high scattering coefficients of Nd-YAG laser light in myocardial tissue and changes in the tissue structure during heating of the tissue, resulting in a maximum temperature rise below the surface of the tissue (26, 27). The reduced incidence when using the transparent probe may be the result of mechanical compression of the tissue by the contact probe (28). Clinically, irradiation of normal myocardium is usually avoided, but subsurface vaporization may also occur when irradiating scar tissue, usually without clinical sequelae (9).

Damage to the intramural blood vessels was confined to the central zone of photocoagulation. Disruption of small venules caused interstitial haemorrhage. Smaller arteries and veins showed partial or total occlusion due to fibrinogen clots. Since no discernible red blood cells were present in these clots, red blood cells must have disrupted, probably by preferential absorption of laser energy by the haemoglobin. In chronic experiments, these blood vessels may recanalize, since in chronic experiments no occluding clots were seen (7). Bigger arteries and veins in the necrotic zone remained intact and patent. Blood flow in these vessels probably acted as a heat sink which prevented overheating of the blood and vessel wall (29).

A rim of contraction bands defined the border of the lesion remarkably well histologically. It is unlikely that ischaemia has played a role in the genesis of the contraction band necrosis, since the local blood vessels were still patent. Between the central zone of photocoagulation and the zone of contraction bands was a zone of apparently normal-looking myocardium. The loss of contraction bands is due to disruption of the myofibrils which occurs prior to coagulation of the proteins as observed in the centre of the lesion. However, this zone as well as the contraction band zone showed loss of birefringence under a polarizing microscope (Fig. 3). According to a recent preliminary report by Thomsen et al (30), loss of birefringence may be induced by tissue temperatures between 40–60 °C. It is associated with thermal necrosis. So, the zone of contraction bands indicates the outer border of the thermal damage caused by the laser irradiation.

Contraction bands indicate irreversible myocardial damage caused by intracellular Ca^{2+} overload. Ultrastructural study of the contraction band zone and the coagulation necrosis zone showed striking similarities between the changes induced by laser irradiation and those induced by intracellular calcium overload (8).

Lee et al (21) reported ventricular fibrillation during laser irradiation. In the present study, major arrhythmias as a direct result of the laser irradiation on the myocardium, occurred in 7/178 (4%) of cases. The onset of the arrythmia was limited to the acute phase of the laser irradiation (≤1 s after the laser pulse), and may be caused by a change in membrane potential resulting in electrical inhomogeneity in the border zone of the lesion (31). Mechanical triggering of these arrhythmias by the transparent tip itself did not occur. Laser photocoagulation does not appear to be arrhythmogenic in the long term. The sharply delineated lesion heals with a homogeneous scar and probably provides no morphologic substrate for re-entry ventricular tachycardia (32).

In conclusion, from these canine experiments it is inferred that the transparent tip, firstly, allows ablation of myocardium to a depth of 4.9 mm, sufficient to ablate a subendocardial VT site, and secondly, may allow safe and effective laser irradiation of VT sites close to the papillary muscles or other delicate anatomic structures.

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