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Effect of Nd-YAG, XeCl, and Nitrogen Laser Radiation on Human Aorta , and Some Arterial Tissues

Abbas J. H. Al-Wattar , Mayyada K.J.Moualla, and Khalil I. Hajim*
Physics Department, College of Science, University of Baghdad
**** Institute of Laser and Plasma for Post-Graduate Studies, University of Baghdad.***

Abstract

The effect of laser radiation on human aorta, coronary, and pulmonary arteries, and pulmonary veins has been investigated. Xenon-Chloride (eximer), Nitrogen, and Nd-YAG pulsed lasers of wavelengths 308, 337, and 1060 nm respectively were used. Their effects on fresh postmortem tissues, normal and diseased, was studied. The diameter and depth of ablation of the exposed tissues, in air, were measured as a function of many factors related to the type of laser and nature of the tissue. The effect of properties of the applied lasers, such as average power density and deposited energy density, on the exposed tissue surface were studied. The increase of these two parameters cause an increase in the depth and diameter of ablation. However the diameter increases until it reaches a saturation value defined by the laser spot cross section. The laser effects were studied as functions of the tissues' nature and thickness. Normal tissues were found to have higher values of ablations' diameters and depths in comparison in with atheromatous tissues. It has been found also that the laser ablation decreases as the tissue thickness increases. It has been found that optical properties of the tissues, such as absorption coefficient, play important role in laser – tissue interaction. When the absorption increases the effects of laser increase too. Light microscopy showed that clean cuts with histological normal edges were produced when UV lasers had been applied, with no thermal effects on the tissues. However, it was observed that the thermal side effect reached more than 200 µm on the area around the cuts when the near – infrared (Nd-YAG) laser was used.

تأثير أشعاع ليزر النديميوم–ياك وكلوريد الزينون و النايتروجين على الشريان الاورطي البشري وبعض الانسجة الوريدية

عباس جاسم حمادي، ميادة معلة و خليل ابراهيم حاجم

الخلاصة

لقد تمت دراسة تأثير اشعاع الليزر على الشرايين الاورطي والتـــاجي والرئـــوي والوريـــد الرئـــوي. واستخدمت ليزرات كلوريد الزينون والنايتروجين والنديميوم – ياك ، ذات الاطوال الموجية ٣٠٨ و ٣٣٧ و١٠٦٠ نانومتر على التوالي. و درست تأثيراتها على انسجة هذه الاوعية الدموية السليمة والمريضة الطازجة بعد الوفاة. ولقد قيس قطر الاستئصال وعمقه (الاعظم) للانسجة المعرضة (في الهواء) واعتمادها على عدة عوامل مرتبطة بنوع الليزر و طبيعة النسيج. و تمت دراسة تأثير خواص الليزرات المستخدمة مثل متوسط كثافة القدرة وكثافة الطاقة المترسبة على سطح الانسجة المعرضة. ان زيادة هذين العاملين يؤدي الى زيادة في قطر و عمق الاستئصال. غـــير ان قطـــر الاستئصال يزداد حتى يصل الى حد الاشباع الذي يتحدد بمقطع حزمة الليزر. وعند دراسة تأثير طبيعـــة وسمـــك

الأنسجة، فقد وجد بأن السليمة تمتلك قيما اعلى لقطر وعمق الاستئصال مقارنة بالانسجة المصابة بتصلب عصيدي. ووجد ايضا بأن الاستئصال يقل بزيادة سمك الانسجة المعرضة. كما وجد بأن الخواص البصرية للانسجة مثل معامل الامتصاص تلعب دورا مهما في تفاعل الليزر مع الانسجة. فبزيادة الامتصاص تزداد تأثيرات الليزر ايضا. وبينت الدراسة الحالية باستخدام المجهر الضوئي حدوث قطع واضح و محدد المعالم و ذو حافات اعتيادية و بدون تأثيرات جانبية حرارية على الانسجة عند استخدام ليزرات الاشعة فوق البنفسجبة. ولكن لوحظ بأن التأثيرات الجانبية الحرارية تبلغ اكثر من ٢٠٠ مايكرومتر على المساحة حول القطع عند استخدام ليزر الاشعة تحت الحمراء – القريبة (النديميوم – ياك).

Introduction

In the past three decades the most significant studies related to the field of laser-tissue interaction have been published [1-3]. In recent years lasers have already contributed to the treatment and diagnosis of a variety of medical specialties [4-6].

In fact today's clinical lasers and their applications may represent only the infancy f laser medicine [7]. The physics of interaction of particular lasers on certain issues represents an open area of research including physical parameters and techniques. In the present work the effect of laser radiation on human arterial (normal and diseased) tissues has been investigated. Three different pulsed laser sources were used: XeCl excimer laser (308nm), Nitrogen laser (337nm), and Nd-YAG laser (1060 nm). The effect of these, UV and IR, lasers on fresh postmortem tissues of aorta, pulmonary and coronary arteries and pulmonary veins have been studied. The dependence of the hole diameter and maximum depth of ablation of these tissues on many parameters related to types of lasers and nature of tissues was investigated
Materials and Methods

The pulsed lasers used in the present work have the following specifications: (i) XeCl excimer laser of Lumonic Co. The laser emission wavelength λ_e= 308nm, with pulse energy E_o=20mJ, average pulse duration τ=5.5ns, and pulse power (P.P.) (= E_o/τ) = 3.64 MW. The pulse repetition rate (R.R.) was between 1–10pps and some times 50pps and working voltage (WV) = 28 kV. (ii)Nitrogen (N_2) laser of Lumonic Co.. This laser has: λ_e=337nm, E_o=1.7mJ, τ=2ns, P.P.=0.85MW, R.R.=5–20pps, and WV=34kV. (iii) Nd-YAG laser of J.K. Laser Co.. This laser has: λ_e=1060nm, E_o=18.5J, τ=10ms, P.P. = 1.85kW, R.R.= 1–40 pulse per min., and WV = 1.6 kV.

An energy meter type ED – 2000 of pyroelectric crystal head was used to measure the pulse energy of XeCl and N_2 lasers in the UV range , and a calibration curve of pulse energy versus input voltage was used to determine the pulse energy in the IR range for Nd-YAG laser.

The area, a_o, of laser beam cross section (at the position where the tissue samples were placed) was measured using an optical microscope and a special paper (trace paper for UV and burn paper for IR regions). For XeCl and N_2 lasers a_o = 160 mm^2, and for Nd – YAG laser a_o=200 mm^2. To increase the power density of the laser beam, focusing lenses were used (a quartz lens of focal length f=15 cm for UV and a special glass lens of f=20cm for IR). In this case a_o was reduced to 0.28mm^2 (measured at the focal plane of the lens, where the samples were placed) with equivalent diameter (ED) = 0.6 mm, for XeCl and N_2 lasers. For Nd-YAG laser, the corresponding values are a_o=19.6mm^2 and ED=5mm.

Determination of confocal beam parameter Z_o

This parameter is defined as the distance through which the waist of the beam increases by √2, and it gives an indication about the region where the change of the beam cross section is negligible, so that the incident laser power density on the sample surface can be considered constant . The confocal parameter, Z_o, is given by the formula [8]:

$$Z_o = \pi\omega_o^2 n / \lambda \quad (1)$$

where ω_o is the waist of the laser beam, n is the refractive index of the medium, and λ is the laser wavelength.

Using Eq.(1), the values of Z_o were then calculated, with lens (Z_{o2}) and without lens (Z_{o1}) using the measured values of ω_o in each case. The values are: Z_{o1} = 520,475,and 189 m; Z_{o2} = 90, 83, and l850 cm for XeCl , N_2 , and Nd-YAG respectively. These values are large enough so that the laser power density of the beam was insensitive to the small variations of the samples positions if they might occur. This was checked experimentally.

Tissue samples preparation

A – Exposure process : Human tissues of aorta, coronary, and pulmonary arteries, and pulmonary veins (normal, atheromatous, and bleeding) have been used in the present work. The samples were fresh post-mortem segments taken within 30 hours after death. More than 100 samples were used. The samples were prepared and cut to dimensions: about 3 cm in length, 1- 3 cm width, and 1- 3 mm thickness (except for coronary arteries where the thickness was about 0.2 mm). The samples were then kept in liquid nitrogen (at 77 K) for about 3 – 5 hours . Before exposing to laser radiation, the samples were let to thaw for about 45 minutes to reach room temperature. The samples were heldon a quartz glass base to allow laser radiation to pass through in case of complete ablation of tissue results. When a focusing lens was used, the samples were placed at the focal plane of the lens. The exposure process was performed in air with the laser beam incident normally on the internal surface of the tissues (Intimae).

B – Measurements of diameter and depth of ablation: After the exposure process, the samples were immersed in liquid formaline, and then treated with ethanol,xylol, and paraffin . The samples then cut into thin slices of 10 μm thickness by a rotary micro-tome(Type 1512, Leitz Co.). And finally Canada balsam was used as paste for the tissue slices on microscope slides. The detail of this procedure is described elsewhere [9].

A calibrated light microscope (Type 5452581-Olympus) was used to measure the diameter and depth of ablation of the exposed tissue slices .

Experimental results

A- Effect of laser radiation without lens: XeCl and Nd-YAG lasers were used only in these experiments, with the following parameters:

XeCl laser: Average power, P_{ave},(= E_o x R.R.) between 0.02 – 0.2 W, average power density, P_D ,(= P_{ave} / a_o) between 125 – 1250 W / m^2 , total number of pulses , N , (= R.R. x time of irradiation) between 3000 – 18000 pulses, pulse power density , PPD , = 2.27 x 10^{10} W / m^2 , and a_o = 160 mm^2

Nd-YAG laser: P_{ave} = 12.3 W, P_D = 62 kW / m^2 , N between 1 – 10 pulses, PPD =9.3 MW / m^2 , and a_o = 200 mm^2 .

Table (1) shows the effect of XeCl laser on the tissues using 50 samples . For Nd-YAG laser 40 samples were irradiated of healthy (H) and atheromatous (T) aorta, and pulmonary(H) arteries of thickness between 1.5 – 2.5 mm , but no effect was found on these tissues .

B- Effect of laser radiation using focusing lens: A quartz lens (f =15 cm) of transmittance 91 % was used to focus the UV radiation of XeCl and N_2, and a special glass lens (f = 20 cm) of transmittance about 100% was used to focus the IR radiation of Nd- YAG laser . Due to the reduction of laser spot cross section by the lens, ablation of tissues was produced . Two parameters are involved in this respect , the first is the diameter , D , of the hole , and the second is the maximum depth Z_m .

Measurements of the hole diameter of ablation (D)

The diameter D has been measured for tissues of different thickness, applying different exposure conditions of the lasers. Between 30-50 slices, of thickness 10 μm, were used of each tissue sample to get its largest hole diameter. These experiments were performed as follows:

1- Using XeCl laser: This laser was used under the following conditions: PPD = 1.3 x 10^{13} W / m^2 , P_D = 70 – 1400 kW / m^2 , a_o = 0.28 mm^2 (with effective diameter D_{eff} = 600 μm), exposure time t_{ex} = 1 – 100 s (some times 14 min.), and R.R. = 1 – 20 pps . The dependence of D on total number of pulses , N , and P_{ave} has been investigated . 165 samples of healthy, atheromatous , and bleeding (B) aorta arteries were used . The results are tabulated in Table (2).

For the sake of more accurate comparison between the effect of XeCl and N_2 lasers, the pulse energy of the former was made equal to that of the later (i.e. 1.7 mJ) using an attenuation cell. The results are given in Table (3).

2 – Using nitrogen laser: This laser was used under the following conditions: E_o = 1.7 mJ, PPD = 3 x 10^{12} W / m^2 , P_D = 30 – 60 kW / m^2 ,and t_{ex} = 40 – 180 s. The measured values of D with other related parameters are given in Tables (4) and (5).

3 – Using Nd-YAG laser :This laser was used under the following conditions:PPD = 9.4 x 10^7 W / m^2 , P_D = 6.3 x 10^5 W/m^2 , a_o = 19.6 mm^2 (D_{eff} = 5 mm = 5000 μm), R.R. = 1 – 20 pulse per min. , N = 5 – 20 pulses . About 50 samples were used of aorta (H and B), and pulmonary (H) arteries. Fig.(1) is a photograph of a hole diameter D. The results are given in Table (6).

It can be seen from Tables (2) – (6) that D increase as N increase. Typical example is shown in Fig.(2) for XeCl laser.

Measurements of the maximum depth of ablation (Z_m)

After exposure to laser radiation , the samples were cut into slices of 10 μm thickness until the maximum depth of ablation , Z_m , was reached . Two lasers only were used in these experiments , namely, XeCl and Nd - YAG lasers. The N_2 laser was not employed due to its relatively low energy pulses. For instance, when pulmonary (H) artery was exposed to 1800 pulses of N_2 laser (P_{ave} = 17 mW) , the resulting Z_m was only 80 μm. The experiments with the other two lasers were done as follows:

1- Using XeCl laser: In these experiments the condtions were similar to those used for hole diameter measurements.Fig.(3) is a photograph of depth of ablation Z_m . The values of Z_m are tabulated inTable (7) for pulmonary(H), and aorta (H and T) arteries.
2- Using Nd-YAG laser: Here aorta (H) arteries only were exposed to the IR radiation of this laser. The values of Z_m are listed in Table (8). One can see from Tables (7) and (8) that Z_m increases with the increase of N. Typical example is shown in Fig.(4) for XeCl laser (P_{ave} = 0.02

and 0.2 W), of aorta(H) and pulmonary (H) arteries.

Discussion

In the present work , the diameter ,D, and maximum depth ,Z_m , of ablation have been studied as functions of the following factors: Average power density ,P_D , energy density (fluence) ,E_D , and and the wavelength , λ , of the laser used , and also their dependent on the nature of the tissues that exposed to laser radiation.

Effect of E_D and P_D: These quantities are considered important factors that determine the laser – tissue interaction . They are defined as follows:

$$P_D = P_{ave} /a_o = E_o f/a_o \quad (2)$$

where f = R.R.

$$E_D = P_D t_{ex} = E_o N/a_o \quad (3)$$

The effects of P_D and E_D were studied with, and without focusing lense:

(i) Without focusing lens: No noticeable effect was observed on the tissues when Nd-YAG laser was used, of E_D = 9.2x10^4 – 92.3x10^4 J/m^2, and P_D = 6.2x10^4 W/m^2 . Similar result was obtained when XeCl laser was used , of E_D = 38xl0^4- 75xl0^4 J/m^2 , and P_D = 125 W/m^2 . But a change in colour was observed when E_D increased to ll3x10^4 J/m^2 , and P_D to 1250 W/m^2 (see Table (1)).

(ii) With focusing lens: In this case ablation has occurred in nearly all cases with the three types of lasers due to increase of P_D about 570 times for XeCl and N_2 lasers, and 10 times for Nd-YAG laser. Using focusing lens,therefore, enhances the effect of laser beam on the tissues due to the decrease of the beam cross section and a corresponding increase of E_D and P_D. For instance, in case of XeCl laser when a tissue was exposed for 1800 seconds without lenses (E_D = 22.5 MJ/m^2), just a change in color occurred. While ablation occurred after 20 seconds of exposure time when focusing lens was used , with the same P_{ave} in both cases { see Tables (1) & (2) }. This is ,of course, due to the increase of energy deposited per unit area per unit time P_D.

Effect of variation of E_D for fixed P_D

When P_D is kept fixed , then E_D increase as the time t_{ex} or N (= f t_{ex}) increase(Eq.(3)) . We see ,therefore, that D and Z_m , in general, increase as N increases { see Tables (2) & (7), and Figs. (2) & (5) }. As can be seen from these figures both D and Z_m equal to zero for N ≤ 20 pulse (E_D ≤ 1.4 1.4 MJ/m^2) , and then both increase as N increases further due to increase of deposited laser energy. However D reaches a saturation value for N ≥ 100 pulse (E_D ≥ 7 MJ/m^2) when it approaches the diameter of the laser spot on the tissue (= 600 μm for UV lasers) as a limit.

Effect of variation of P_D for fixed E_D

Referring to Tables (4) and (7) and ther related tables for, XeCl and N_2 lasers that are concerned with the dependence of D and Z_m on P_{ave} and P_D for fixed values of E_D (fixed N), and using tissues of similar properties, one can conclude the following:

1- Z_m increases as P_{ave} (and P_D) increases, as expected. This is in agreement with the results obtained by other workers [10 - 13].

2 – With regard to the diameter of ablation D , it was found that D in general increases as P_{ave} increases, except in some few cases where it remains approximately constant or decreases slightly due to experimental errors. These errors were as a result of the combined effects of the inclined orientation of the tissue with respect to the cutting knife of the micro tome, and the uncertainty in the

measurement of D by the optical microscope.

From the results obtained, in the present work, it has been found that both E_D and P_D effected D and Z_m . However, there is a discrepancy in the literature about which is more important E_D or P_D. Some of the researchers assume that P_D is more important [11- 14], while others consider E_D is the more important [15]. To clarify this point, let us consider the results that have been obtained with the lasers used {see Tables (1),(2), and (4)}:

(i) For XeCl laser: When P_D = 1.25 kW/m^2 and E_D = 2.25 MJ/m^2, no ablation has occurred but only a change of color of the exposed tissues resulted. But when P_D increased to 71 kW/m^2 with E_D = 1.42 MJ/m^2, ablation has occurred.

(ii) For N_2 laser: When P_D = 30.4 kW/m^2 and E_D = 1.21 MJ/m^2 , no ablation and no change in color have occurred. But when P_D increases to 60.8 kW/m^2 with the same value of E_D , ablation has occurred.

(iii) For Nd-YAG laser: When P_D = 62 kW/m^2 and E_D = 0.93 MJ/m^2, no ablation or change in color have occurred. But when P_D increased to 630 kW/m^2, with the same value of E_D {Table (8), N = 1}, ablation has occurred.

It can be seen from these results that although E_D was kept fixed in the cases of N_2 and Nd-YAG lasers or even decreased in the case of XeCl laser, but ablation of tissues has occurred when P_D increased (above a threshol value P_{Dth}). One can, therefore, conclude that when $P_D < P_{Dth}$ no ablation occurs whatever the value of E_D . But when P_D becomes greater than P_{Dth}, ablation occurs when $E_D \geq E_{Dthreshold}$.
See for instance Figs. (2) and (5) , where D and Z_m are both zero (no ablation) when
$E_D \leq$ 1.42 MJ/m^2 for XeCl laser. From the previous discussion one can conclude that the average power density, P_D , plays more important role in tissue ablation than the energy density E_D . However it is practically easier to control the value of E_D by merely controlling the exposure time t_{ex} for a given P_D.

Effect of laser wavelength

The effect of laser wavelength , λ , on the tissue ablation was studied by changing λ and keeping other factors fixed (e.g. beam cross section = 0.28 mm^2, pulse energy = 1.7 mJ , etc.) . The nitrogen (λ = 337 nm), and XeCl (λ =308 nm) lasers wrer used in this study { Tables (3) & (5) }. Fig. (6) shows the dependence of D on N of pulmonary artery (H) for both lasers. It can be seen from this figure that D is greater for XeCl laser because the photon energy of this laser is greater by about 9 % than that of N_2 laser , and also because the absorption coefficient , A , of the tissue for XeCl laser light is greater than that of the nitrogen laser. For example, we have measured **A** for aorta artery(H) and found that it was greater for XeCl laser by about 18 % than that of nitrogen laser [8] (this will be published else where).

Effect of tissue thickness*:*

The effect of the tissue thickness, **d** , on Z_m and D was studied by keeping other factors fixed (e.g. nature of tissue, λ , P_{ave} ,P_D , E_D , and N). Tables (9) and (10) show the dependence of Z_m and D on **d** . One can see from these results that both Z_m and D decrease as **d** icrease. This is because the change of the artery thickness , **d** , is caused by structural changes of the tissue wall layers. Since as **d** increases, the layers become less elastic due to the increase of muscular fibers, especially in the middle layer (e.g. for elderly persons). This makes it more difficult for the laser beam to penetrate the tissue.

Similar results were obtained by other workers [11, 12, 16].

Effect of nature of tissue

The effect of nature of tissue on the ablation by laser radiation has been studied, in the present work, keeping other factors fixed (e.g.tissue thickness, average power, etc.). Fig.(7) demonstrate the dependence of Z_m on **N** for aorta artery (H) and (T), using XeCl laser . It can bee seen that Z_m for healthy aorta artery is greater, by about 30 % , than that of atheromatous aorta artery. This attributed to the higher absorption coefficient , A , of aorta(H) (by about 40 %) than that of aorta (T) arteries [9]. The increase of the absorption means an increase of the absorbed or deposited laser energy, and enhancing its effect on the tissue. One can also use similar reasoning to explain why D for bleeding aorta is greater than that of the healthy one by about 10 %, since **A** of the bleeding aorta is greater by about 10 % than that of the healthy one. When D approaches the saturation value (which is determined by the laser spot cross section). It becomes insensitive to the optical properties of the tissue (i.e. absorption). Similarly, the diameter D for aorta(H) is slightly higher (by about 5 %) than that of bleeding aorta { Table (6) }, because **A** of aorta (H) is the higher. Finally , when healthy aorta and pulmonary arteries and veins, of about similar thickness, were exposed to XeCl laser radiation under similar conditions, it was found that the differences between the values D were negligibly small for these tissues . This is because they have similar structure {see Table (11)}. It is interesting to mention that light microscopy showed that clean cuts with histological normal edges were produced when UV lasers had been applied with no thermal effects on the tissues. While the thermal side effect may reach more than 200 μm on the area around the cuts when near – infrared, Nd – YAG, laser was used.

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Table (1):Effect of XeCl laser on healthy (H) , and atheromatous (T) arterial tissues , without using lens. PPD = 2.3x10^{10} W/m^2, P_{ave} = 0.2 W, & P_D = 1250 W/ m^2

Tissue thick – ess d (mm)	Tissues	No. of ulses N	Effect
2	Aorta(H)	3000 – 6000 9000 - 2000	NonCol or change
1 - 2	Pulmonary(T)	3000 – 9000 9000 -12000	NonCol or hange (C.C.)
2 - 3	Aorta (T)	3000 – 2000 15000	Non C.C.
0.2	Coronary (H)	3000 – 6000 9000 - 8000	Non C.C.

Table [2]:The dependence of hole diameter D on no. of pulses N of aorta arteries:
A – Healthy using 15 samples in each case ; B – Atheromatous ; C – Bleeding (red color) . Using XeCl laser (PPD = 1.3x10^{13} W/m^2, P_D = 70 – 1400 kW/m^2)

(A)

Tissue thickness d (mm)	P_{ave} (W)	N	D (μm)
1.8	0.02	10 20 25 40 60 73	--- 266 290 327 529 409
1.8 - 2	0.1	25	491
1.5	0.2	20 25 50 60 100 120 200	--- 415 407 516 589 626 680
1.6	0.4	100 200	559 506

(B)

d (mm)	P_{ave} (W)	N	D (μm)	No. of Samples
1.5	0.1	25 200	267 658	10
2.0	0.1	50	297	20
2.3	0.1 0.2	100 100	461 512	40
2.4	0.1	5 25 75 100 250	--- 213 381 463 558	20

Table (2) - **(C)**

d (mm)	P_{ave} (W)	N	D (μm)	No. of Samples
1.5	0.1	100	662	10
1.5	0.2	20 50 100 120 200	--- 485 629 636 665	35

Table (3):The dependence of hole diameter D on no. of pulses N, of healthy aorta and pulmonary arteries (about 20 samples in each case). Using XeCl laser of pulse energy = 1.7 mJ , and PPD = $3x10^{12}$ W/m^2 .

d (mm)	Tissue	P_{ave} (mW)	N	D (μm)
1	Aorta	8.5	600 1200 1800	60 68 80
1.2	Aorta	8.5	600 1200 1800	51 62 74
1.6	Aorta	17	300 600 1200 1800	--- 23 40 56
1	Pulmonary	17	300 600 1200 1800	40 58 72 84

Table [4]:The dependence of D on N for aorta (H) arteries. Using N_2 laser of PPD = $3x10^{12}$ W/m^2 .

d (mm)	P_{ave} (mW)	N	D (μm)	No. of Samples
1.2	8.5	200 300 600	--- 28 32	15
	17	200 300 600	30 51 71	
2	17	600 1200	25 37	20

Table[5]:The dependence of D on N for pulmonary (H) arteries. Using N_2 laser of PPD = $3x10^{12}$ W/m^2 .

d (mm)	P_{ave} (mW)	N	D (μm)	No. of Samples
1	17	300 600 1200 1800	25 38 56 73	35
1.3	8.5	25 900	--- 92	10

Table[6]: The dependence of D on N , for healthy(H) and bleeding (B) aorta, and pulmonary(H) arteries. Using Nd-YAG laser of PPD = $9.4x10^7$ W/m^2, and P_D = $6.3x10^5$ W/m^2. No. of samples = 50.

d (mm)	Tissue	P_{ave} (W)	N	D (μm)
1	Pulmonary (H)	12.3	5 10	659 798
1.2	Aorta (H)	12.3	5 10	1109 1335
1.4	Aorta (H)	12.3	5 10 15	944 1184 1315
1.4	Aorta (B)	12.3	5 10 15 20	1015 1104 1289 1366

Table (7) : The dependence of max. depth of ablation Z_m on N, for pulmonary (H), aorta (H), and aorta {atheromatous, T,} arteries. Using XeCl laser of pulse energy = 20 mJ, PPD = $1.3x10^{13}$ W/m^2, and P_D = 70 – 1400 kW/m^2 .

d (m)	Tissue	No. of Samples	P_{ave} (W)	N	Z_m(μm)
1	Pulmonary (H)	15	0.02	60 100 120 190	160 444 638 1076
1.2	Aorta (H)	30	0.2	20 60 100 120 190 250 500	--- 279 612 778 1200 1064 1516
1.7	Aorta (H)	20	0.2	20 60 100 300	--- 505 559 1410
1.5	Aorta (H)	10	0.1	100 200	559 958

Table (7) Cont.

d (mm)	Tissue	No. of Samples	P_{ave} (W)	N	Z_m (μm)
2	Aorta (H)	20	0.1	25 35 50	181 213 260
1.6	Aorta (T)	30	0.2	20 100 300	--- 426 971
2.4	Aorta (T)	20	0.2	50 100 500 1000	158 306 1490 1862
3.2	Aorta (T)	12	0.2	250 500	771 1170

Table [8]: Dependence of Z_m on no. of pulses N, for aorta(H) arteries. Using Nd-YAG laser, of pulse energy 18.5 J, PPD = $9.4x10^7$ W/m^2, and $P_D = 6.3x10^5$ W/m^2.

d (mm)	No. of Samples	P_{ave} (W)	N	Z_m (µm)
1.1	15	12.3	1 5 10 20	213 559 771 1283
1.5	10	12.3	1 10 20	80 718 1490

Table [9] : Dependence of Z_m on tissue thickness d, for aorta (H) and (T) arteries, using XeCl laser.

Tissue	P_{ave} (mW)	N	d (mm)	Z_m (µm)
Aorta (H)	200	100	1.2 1.7 2.0	612 559 399
Aorta (H)	100	50	1.5 2.0	359 260
Aorta (T)	200	500	1.6 2.4	1516 1490

Table [10] : Dependence of D on d, for aorta (H) & (T), and pulmonary (H) arteries. Using XeCl and N_2 lasers.

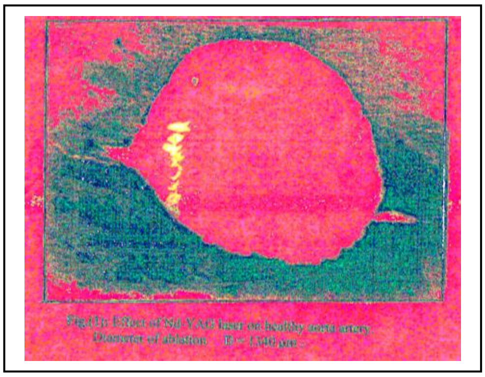
Laser	Tissue	P_{ave} (mW)	N	d (mm)	D (µm)
XeCl	(T)	100	25	1.5 2.4	267 213
			200	1.5 2.4	658 507
	(H)	17	600	1 1.6	58 23

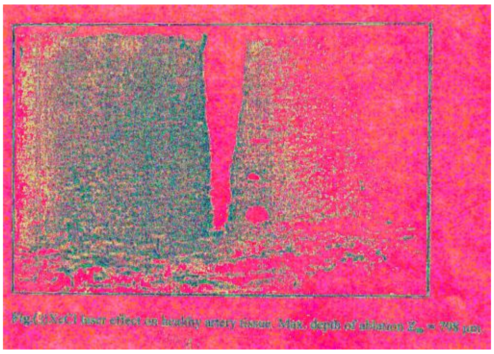
Table[10] Cont.

Laser	Tissue	P_{ave} (mW)	N	d (mm)	D (µm)
XeCl	(H)	17	1200	1 1.6	73 40
			1800	1 1.6	84 56
N_2	(H)	17	600	1.2 2	71 25
			1200	1 2	56 37

Table [11]: Dependence of the hole diameter D on nature of the tissue, for healthy aorta, and pulmonary arteries and veins. Using XeCl laser.

N (pulses)	P_{ave} (mW)	d (mm)	Tissue	D (µm)
100	200	1	Pulmonary vein	589
		1.1	Aorta artery	612
600	17	1	Pulmonary vein	51
		1	Pulmonary artery	58





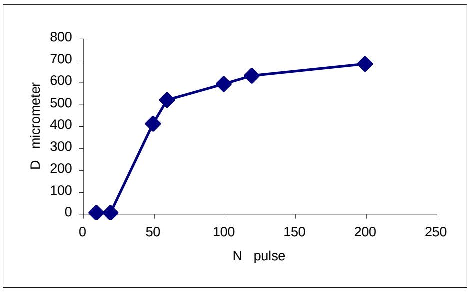


Fig.[3] Hole diameter D (µm) vs. no. of pulses N, for aorta Artery (H), d = 1.5 mm, using XeCl laser (P_{ave} = 0.2 W, P_D = 0.7 MW/m^2).

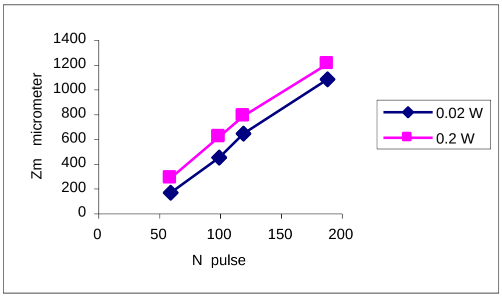


Fig. (4): Max. depth of ablation Z_m vs. no. of pulses N, of aorta artery (H)(P_{ave} = 0.2 W, upper curve), and pulmonary artery(H)(P_{ave} = 0.02 W. lower curve). Both tissues have d =1.1 mm, using XeCl laser of P_{ave} = 0.2 & 0.02 W.

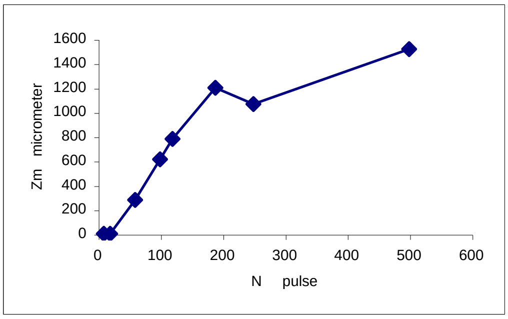


Fig.(5):Max. depth of ablation Z_m (μm) vs. no. of pulses N, of aorta artery (H), using XeCl laser (P_{ave} = 0.2 W, P_D = 0.7 MW/m^2)

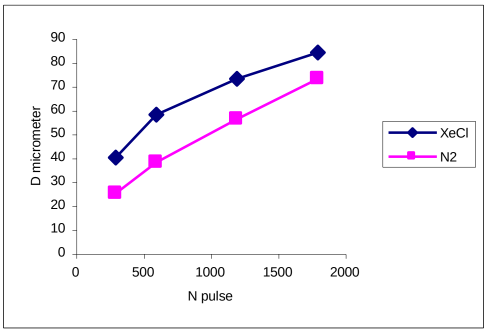


Fig.(6) : Hole diameter D vs. no. of pulses N , of pulmonary artery (H), using XeCl (λ = 308 nm), and N_2 (λ = 337 nm) lasers of same average power P_D = 17 mW. Tissue thickness d = 1 mm .

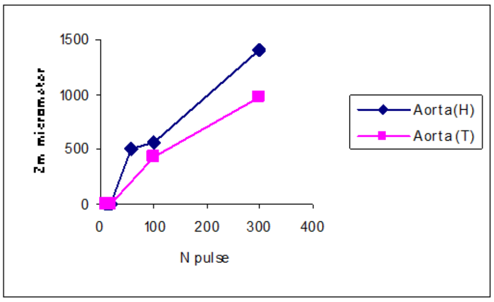


Fig.(7): Max. depth of ablation Z_m vs. no. of pulses N , of aorta artery { (H), d= 1.7 mm, upper curve }, and { (T), d = 1.6 mm, lower curve}, using XeCl laser (P_{ave} = 0.2 W) .

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