THERMAL EFFECT ARISING DURING EXPOSURE OF BONE TISSUE TO A CO_2 LASER

L. V. Prokopova, N. G. Nikolaeva, and A. E. Skovorodnev

UDC 616.71-018.02:615.849.19]-07

KEY WORDS: thermal effect; CO_2 laser; bone.

It has now been established that the basic effect of exposure to a CO_2 laser is thermal, and that it correlates with focusing power, and duration of irradiation and also depends on the properties of the biological structures [1-5, 8]. Temperature gradients have been identified in the depth and on the surface of soft tissues during exposure to high-energy lasers, and this has provided a basis for the successful use of laser energy in the treatment of neoplasms of organs and soft tissues and of various septic and inflammatory conditions [4, 5, 7]. There have been many investigations into laser surgery, but few have been devoted to the action of a CO_2 laser on bone tissue, and their results have been contradictory [1, 5, 9], and there have been too few thermometric and thermographic studies; the aim of the present investigation was accordingly to study the thermal effect arising in compact and spongy bony structures during exposure to a CO_2 laser.

EXPERIMENTAL METHOD

Human tibias, thawed to an ambient temperature of 20°C, were used as the test object. A Soviet surgical laser system ("Skal'pel'-1," infrared band, power 25 W, continuous action) on carbon dioxide gas was used for the investigations. The focused radiation had an intensity of 2000 and 1500 W/cm^2. The temperature of the bony tissue during laser irradiation was determined by means of copper—constantan thermocouples and self-recording electrical measuring instruments of the KSP-4 type. Channels 1 mm in diameter were drilled in the spongy and compact bone to a depth of 1, 2, 3, 4, and 5 mm, their course parallel to the irradiated surface. Thermocouples were introduced into the channels and thermography carried out both during laser irradiation and after its end. Irradiation was carried out by scanning, and the area of the irradiated surface was 1 cm^2. There were 96 experiments (three series). In series I the thermal effect arising in spongy and compact structures during irradiation with an intensity of 2000 W/cm^2 and a scanning speed of 1 cm/sec, with energy density of 200 J/cm^2, was determined. In series II thermometry was carried out in the spongy and compact tissues with an intensity of irradiation of 2000 W/cm^2, a scanning speed of 0.5 cm/sec, and with energy density of 400 J/cm^2. In the experiments of series III the thermal effect also was determined in spongy and compact structures, using an intensity of irradiation of 1500 W/cm^2, a scanning speed of 0.2 cm/sec, and with energy density of 750 J/cm^2. The results of thermometry of the bone tissue were analyzed on a DVK-3 personal computer. To find approximate analytical solutions, spline approximation of the temperature profiles was carried out. The results of calculation of the coefficients of the spline functions are given in Table 1.

EXPERIMENTAL RESULTS

Analysis of the thermographic data showed the thermal effects in the different series and within each series differed, depending on energy density, the character of the structure irradiated, its thickness, and the time elapsing after the beginning of laser irradiation. An increase in energy density led to a rise of temperature in the bone tissue, but with

Department of Surgery and Orthopedics of Childhood and Department of Medical and Biological Physics, N. I. Pirogov Odessa Medical Institute. (Presented by Academician of the Academy of Medical Sciences of the USSR A. A. Korzh.) Translated from Byulleten' Éksperimental'noi Biologii i Meditsiny, Vol. 112, No. 9, pp. 301-303, September, 1991. Original article submitted December 25, 1990.

 0007-4888/91/0009-1322$12.50

TABLE 1. Spline Approximation of Temperature Profiles during CO_2 Laser Irradiation depending on Energy Density, Character of Structure, and Its Thickness

Energy density, J/cm^2	Bone structure	
	compact	spongy
200	$M_0=0$	$M_0=0$
	$M_1=25,714286$	$M_1=16,697143$
	$M_2=-0,85714288$	$M_2=-0,42857143$
	$M_3=7,7142857$	$M_3=9,1071429$
	$M_4=4,856734$	$M_4=16,8497488$
	$M_5=0$	$M_5=0$
400	$M_0=0$	$M_0=0$
	$M_1=310,23529$	$M_1=186,5096$
	$M_2=-30,705882$	$M_2=-67,529412$
	$M_3=4,5882353$	$M_3=29,607843$
	$M_4=12,352941$	$M_4=2,9019608$
	$M_5=0$	$M_5=0$
750	$M_0=0$	$M_0=0$
	$M_1=33,642857$	$M_1=-84,104734$
	$M_2=7,4286714$	$M_2=126,42857$
	$M_3=36,642868$	$M_3=-13,607143$
	$M_4=27,356243$	$M_4=37,862315$
	$M_5=0$	$M_5=0$

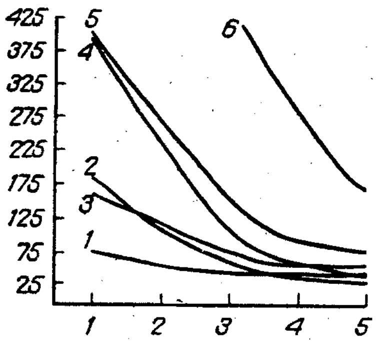

Fig. 1

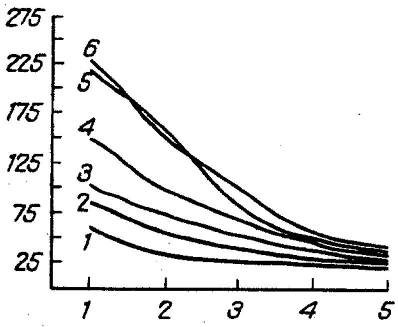

Fig. 2

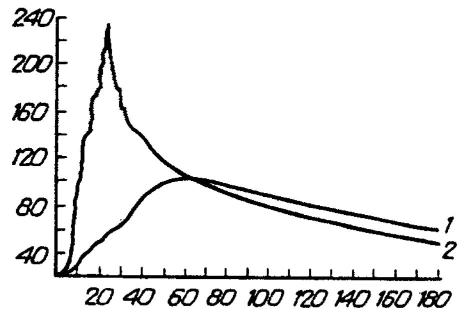

Fig. 3

Fig. 1. Dependence of thermal effect (maximal temperatures) arising in bone tissue during CO_2 laser irradiation on character of bone structure, its thickness, and energy density (computer model). Abscissa, thickness of bone (in mm); ordinate, temperature (in °C); 1, 3, 5) thermal effect in compact bone at 200, 400, and 750 J/cm^2, respectively; 2, 4, 6) in spongy bone at 200, 400, and 750 J/cm^2, respectively.

Fig. 2. Dependence of thermal effect observed in bone tissue 60 sec after CO_2 laser irradiation on character of bone structure, its thickness, and energy density (computer model). Abscissa, thickness of bone (in mm); ordinate, temperature (in °C); 1, 3, 5) thermal effect in spongy bone at 200, 400, and 750 J/cm^2, respectively; 2, 4, 6) in compact bone at 200, 400, and 750 J/cm^2, respectively.

Fig. 3. Typical thermographic curves of CO_2 laser irradiation of bone tissue (at 400 J/cm^2). Abscissa, time (in sec); ordinate, temperature (in °C). 1) Compact bone; 2) spongy bone.

increasing distance away from the irradiated surface, there was an exponential fall of temperatures in all three series of experiments (Figs. 1 and 2). During irradiation of bone tissue there was a complex process of nonstationary heat exchange by local heat conduction. Besides absorption of radiation on the surface of the bone tissue and heat conduction within its substance, the intensive heat exchange by convection had an appreciable influence on the thermal effect in spongy bone, due to boiling and evaporation of the liquid phase in the surface and adjacent layers. This and also the relatively low specific heat may explain the much higher temperatures in the layer of spongy bone next to the surface compared with the compact structure. This was shown on the thermographic curves as a higher peak of temperatures in the initial stage of heating, for example: 220 ± 51.9°C at a depth of 2 mm with an intensity of 400 J/cm^2, compared with 114 ± 29°C in compact bone. After the end of exposure to the laser and a corresponding fall of temperature, heat transmission by convection decreased: heat exchange took place by conduction. The temperature curves for the spongy bone in the initial stage of heating were characteristically "steeper," but with the course of time (with identical parameters of irradiation and at the same depth) the temperatures in the spongy and compact bone were briefly equal, after which they fell slowly and parallel to each other, but the temperature was maintained at a higher level in the compact tissue than in spongy bone, due to the greater thermal conductivity of spongy tissue. For example, with an energy density of 400 J/cm^2 at a depth of 2 mm (Fig. 3), when irradiation ended a higher but less prolonged thermal effect was observed in the spongy structure than in compact bone (238 and 106°C, respectively); a temperature of not less than 200°C was maintained in the spongy bone for 5 sec, and not less than 180°C for 10 sec; at the 60th-70th second the temperatures in these two structures were equalized (105-107°C), after which the thermal effect remained steady, but after 2-3 min the temperature in the spongy tissue was 9-10% lower than in compact bone, where it was not until the end of the 4th minute that it reached 54-56°C. Considering that the temperature range 55-57°C is the "lower oncostatic boundary" and that at this temperature irreversible changes take place in cells [4], it becomes evident that CO_2 laser radiation can induce ablastic and sterilizing effects not only at the surface, but also in the depth of bony tissue. On the basis of these results it is possible to select differentially the optimal conditions for irradiation depending on the aim of the procedure, which is to achieve a concrete thermal effect, and also depending on the character and thickness of the bony structure. Taking all these facts into consideration, the use of a CO_2 laser in bone oncology and in the surgery of bone sepsis can be regarded as advantageous and promising.

LITERATURE CITED

1. M. Sh. Azamatov and R. Sh. Azamatov, The Use of Lasers in Surgery and Medicine [in Russian], Part 1, Moscow (1989), pp. 114-115.
2. L. D. Arazashvili, Abstracts of Proceedings of the 8th All-Union Congress of Stomatologists [in Russian], Vol. 2, Moscow (1987), pp. 3-4.
3. V. N. Galankin and K. V. Botsmanov, Arkh. Patol., **46**, No. 9, 48 (1984).
4. S. D. Pletnev, N. D. Devyatkov, V. P. Belyaev, and M. Sh. Abdurazakov, Gas Lasers in Experimental and Clinical Oncology [in Russian], Moscow (1978).
5. G. W. Allen, Milit. Med., **146**, 120 (1981).
6. V. W. Ansanelli, Laser Surg. Med., **6**, No. 5, 470 (1986).
7. F. Heppner, P. W. Ascher, P. Holser, and M. Mökry, Laser Surg. Med., **7**, No. 2, 280 (1987).
8. G. Laufer, Appl. Opt., **22**, 676-681 (1983).
9. G. Morein, S. Gassner, and I. Kaplan, Acta Orthop. Scand. **49**, 244 (1978).