Med. & biol. Engng. Vol. 8, pp. 541–548. Pergamon Press, 1970. Printed in Great Britain

A CO_2 LASER FOR SURGICAL RESEARCH*†

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Abstract—The characteristics of CO_2 lasers that render them interesting for surgical applications are reviewed. An instrument consisting of an integrated CO_2 laser and beam manipulator, designed specifically for surgical research work, is described. Operational characteristics of the instrument relevant to such work are reported. An accessory for endoscopic surgery is described and instrumentation for microsurgery is discussed. Surgical researches now in progress with this instrument are mentioned.

1. INTRODUCTION

A RENEWED interest in laser surgery has taken place since the introduction of the CO_2 laser to the medical field. The major characteristics of this laser that make it interesting for surgical applications are that it is a high power continuously operating laser and that its wavelength of operation is in the infra-red at $10 \cdot 6\ \mu m$, a wavelength that is almost completely absorbed by most biological tissues. This high degree of absorption in combination with the high power, the continuous mode of operation, and the fact that the laser beam can be focused to a very small spot size, permit the application of radiation to tissues in dosages sufficient to cause rapid burning and vaporization of a well localized volume of tissue. The purely thermal effect of this radiation overcomes the major difficulty encountered by surgeons with the earlier high power pulsed or *Q*-switched lasers such as the ruby and neodymium lasers. With these lasers, it was found that the disruptive effects of the radiation on tissues were not localized and that viable cells were transported from the region of impact of the radiation to other locations. Some authors attribute these effects to sonic waves created by the short pulses of high energy. In addition, the wavelengths of operation of these lasers generally require staining of tissues if a high rate of absorption is required.

Early research work in our laboratory to explore the potential applications of CO_2 lasers to surgery (YAHR and STRULLY, 1966) indicated that it was necessary to make available to surgeons a laser specifically designed for such work and conveniently operable in a surgical research laboratory setting. Such an instrument was developed and is described in this article.

2. BASIC DESIGN AND MECHANICAL EMBODIMENT

The laser was designed to have a multimode power output to the manipulator of about 75 W, and a useful output from the manipulator of 50 W in a multimode beam. A flowing gas system and an a.c. power supply are used for maximum reliability and simplicity. The schematic diagram of the entire instrument is shown in Fig. 1. The major components are (1) the gas discharge tube and the optical cavity approximately $1 \cdot 5$ m long; (2) the gas flow system consisting of three high-pressure tanks of CO_2, He and N_2, pressure reducing valves, solenoid valves, flow control needle valves, pressure measuring gauge, gas mixing chamber and exhaust pump; (3) the electrical system consisting of the high-voltage transformer and the control circuits; (4) timer, shutter, and heat sink; (5) the beam manipulator.

Figure 2 shows the over-all appearance of the

* *Received* 7 *October* 1970.

† Based on a paper presented at the Conference on Lasers in Medicine, Middlesex Hospital Medical School, London, 1969.

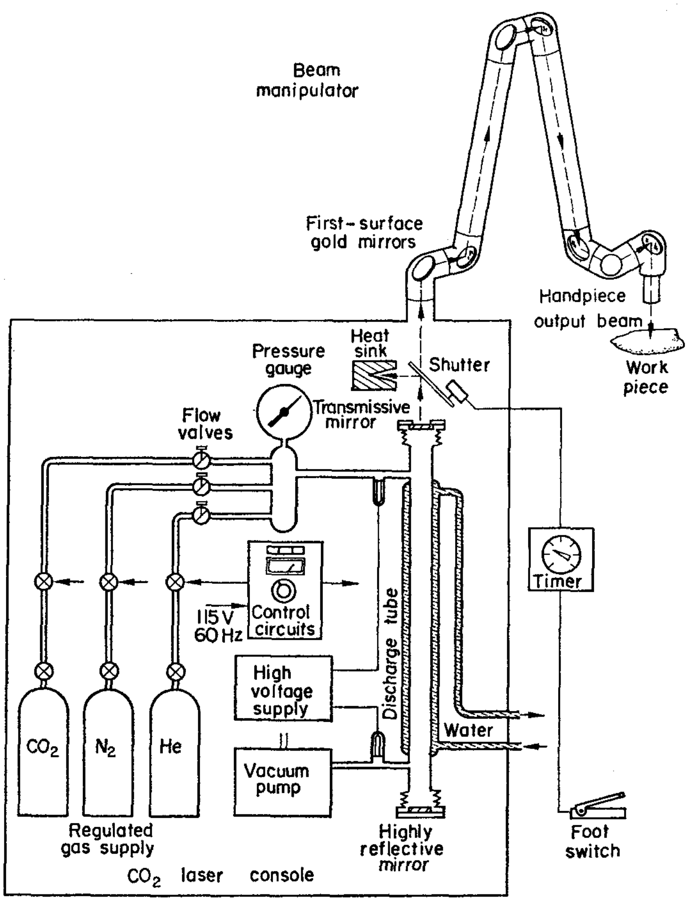

FIG. 1.

instrument. The entire system is contained in a sturdy, standard, 6 ft, electronic rack cabinet. The laser beam emerges from the top of the cabinet where it enters the beam manipulator. The controls on the front panel are (1) a main power switch, (2) the knob of an auto-transformer controlling the voltage applied to the primary of the high-voltage transformer; this control permits the output power of the laser to be varied smoothly from close to zero to its maximum value; (3) two pushbutton switches, one to activate the vacuum pump, the other the solenoid operated gas valves; (4) a key-operated safety switch that prevents unauthorized application of the high-voltage to the discharge tube; (5) two illuminated pushbutton switches, one green, the other red, to turn the laser voltage on and off respectively when an additional toggle switch is in its 'normal' position. When this toggle switch is in its 'remote' position, the high voltage can be turned on and off by a foot switch. The foot switch may also be used to control the timer and shutter, in which case the laser is energized in the 'normal' mode. In Fig. 3, a view of the console with the front cover removed, one sees the three invar bars rigidly spacing the mirrors that form the optical cavity of the laser. The mirrors are kinematically mounted and micrometers are used for adjusting their positions. One gold-plated, stainless steel mirror is fully reflective, the other partially transmitting, consists of a multi-layer dielectric

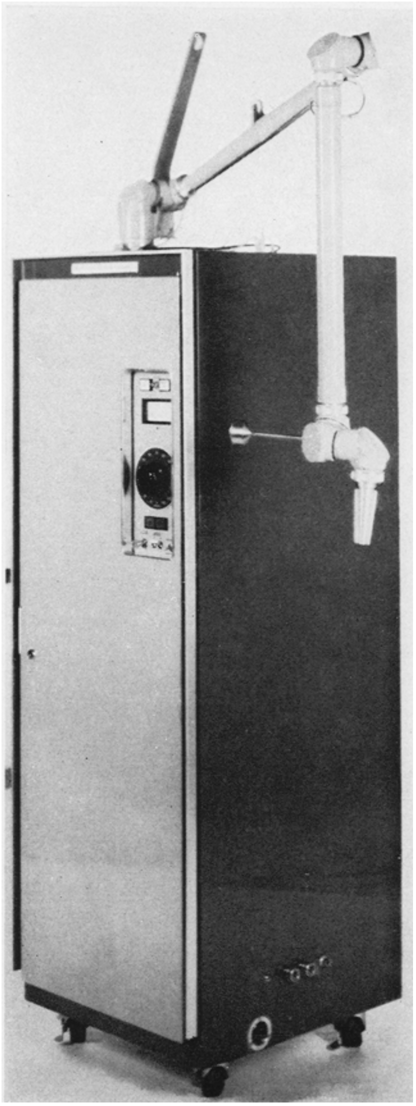

FIG. 2.

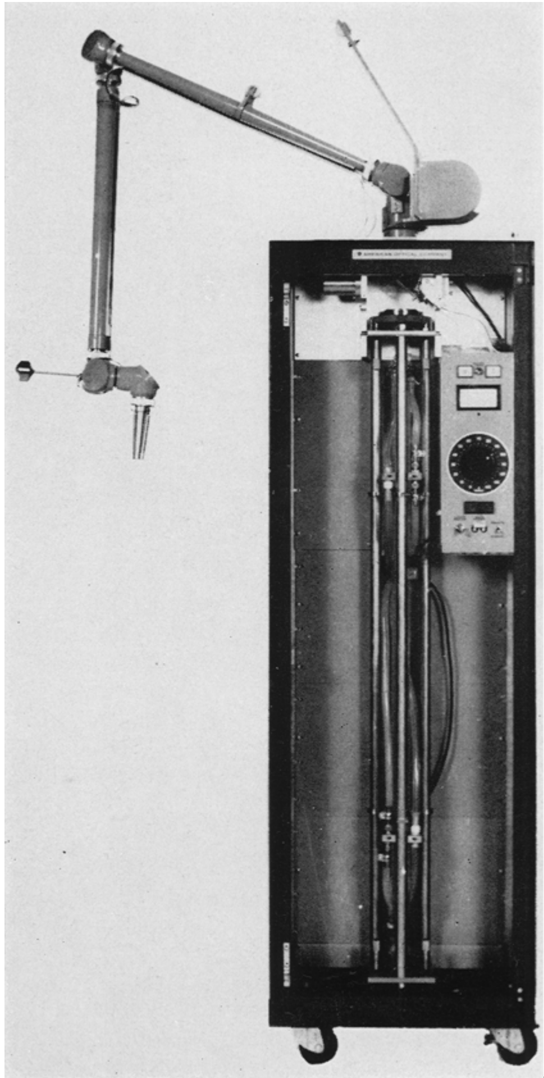

FIG. 3.

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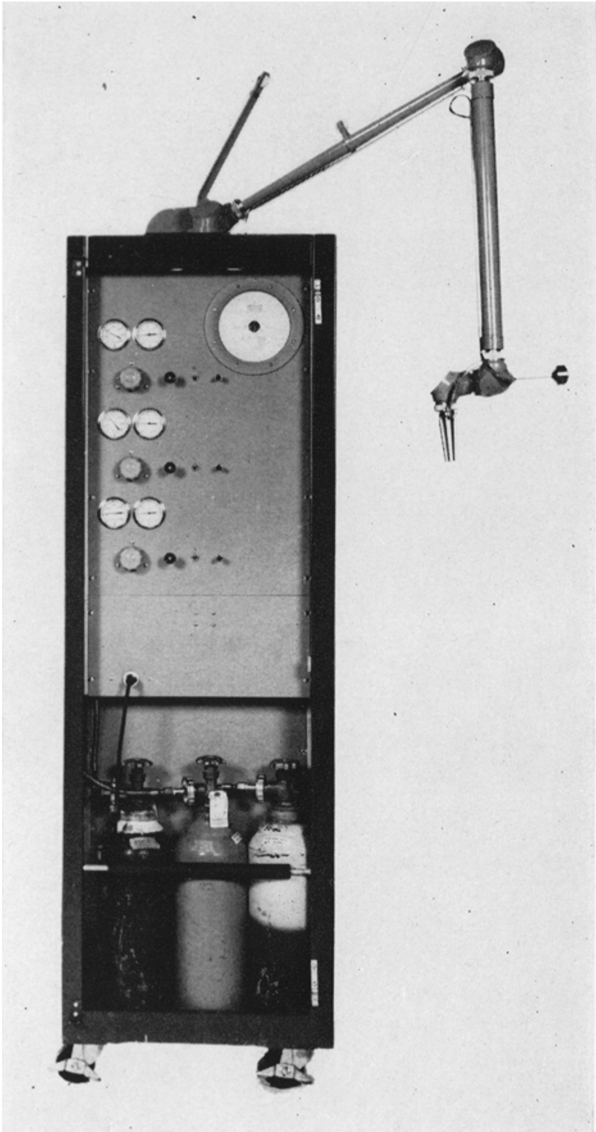

Fig. 4

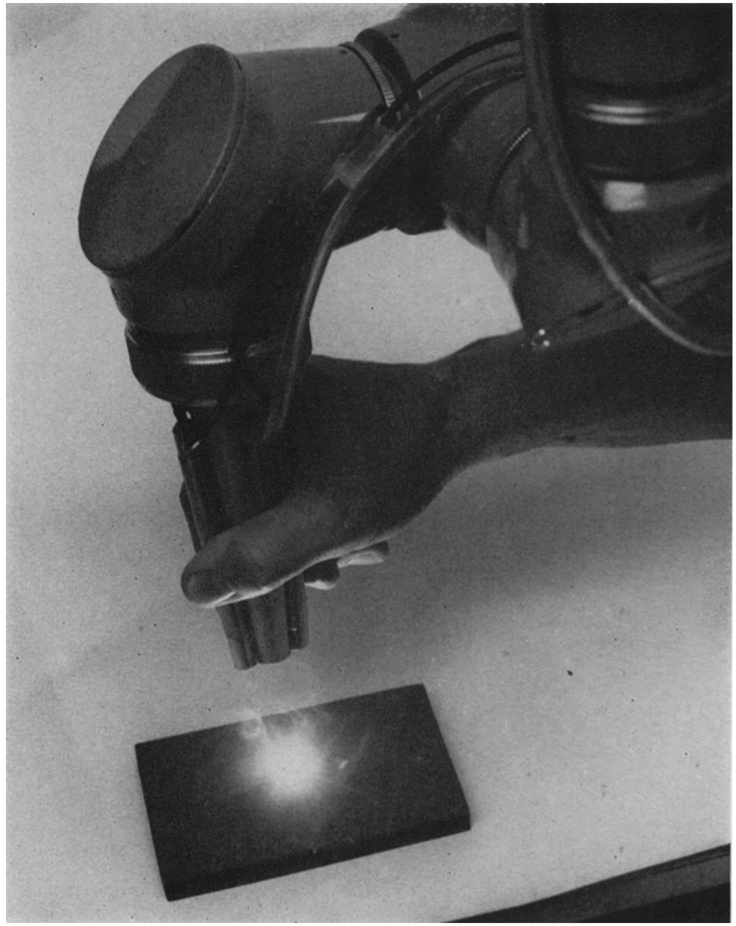

Fig. 7.

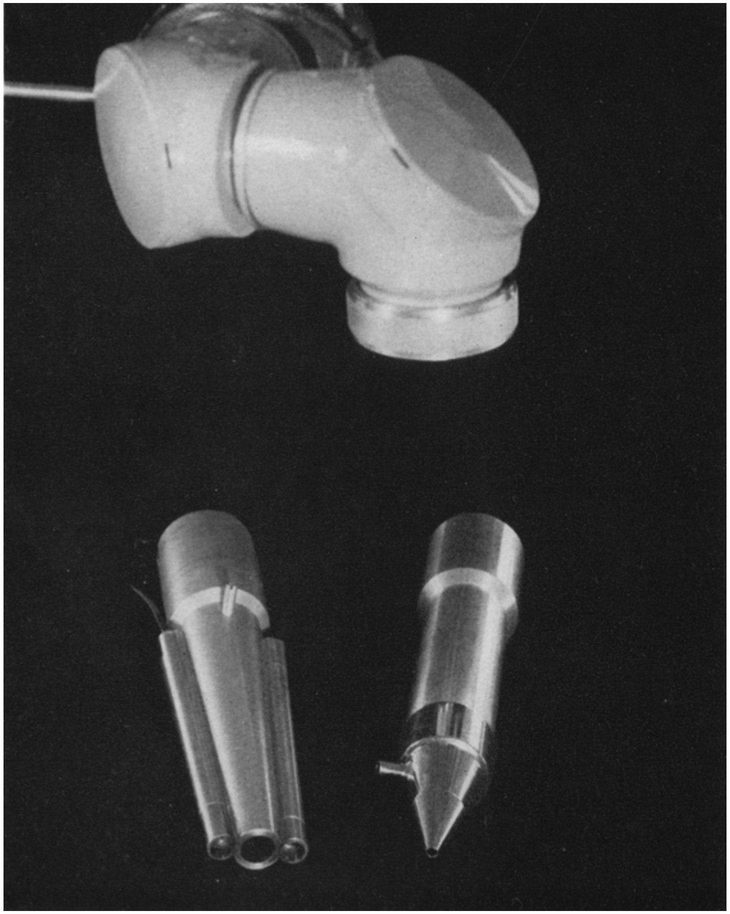

Fig. 8.

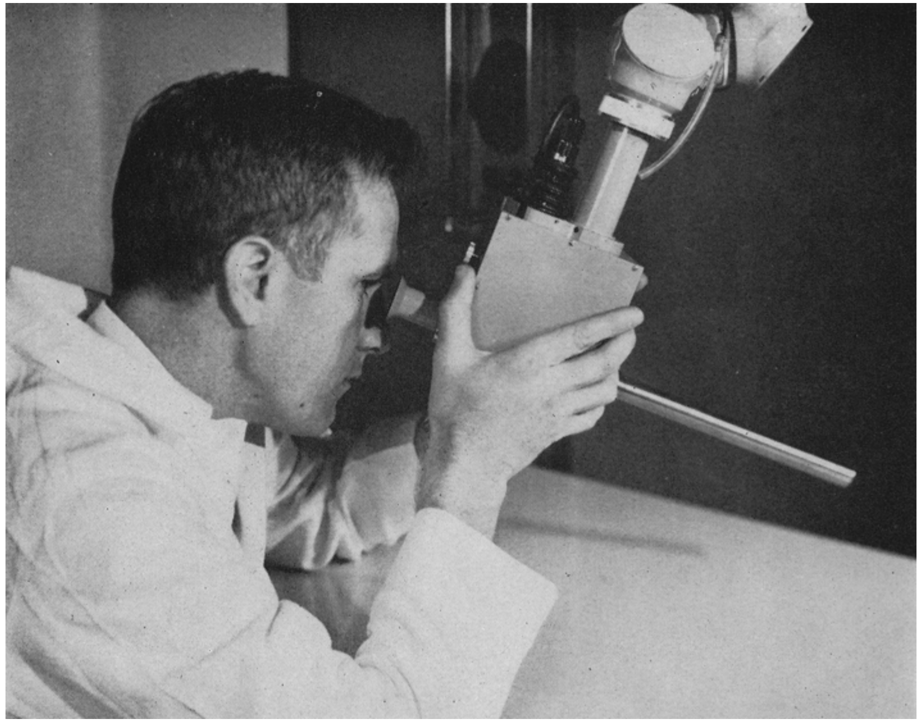

Fig. 10.

coating on a zinc sulphide substrate (trade name Irtran-2). To the left of the output mirror the heat sink is visible; this is a hollow carbon cylinder in an aluminum housing. Immediately above the output mirror is the solenoid operated shutter vane that deflects the laser beam into the heat sink. Figure 4, a view of the console with the back door removed, shows the three gas tanks in position with their main gas cut-off valves and the flexible pressure hose leading to three sets of pressure control valves and gauges. Each gas is controlled by the main valve in the tank and three additional valves. The first admits gas to the pressure reduction device and controls its output pressure; the second is used as an on–off valve preceding the solenoid operated valve and final needle valve. Switches to operate each solenoid valve independently are provided in the back to permit an initial setting of the individual gas pressures.

A precise aneroid pressure gauge (Wallace and Tiernan) permits reading of the initial vacuum and setting of the valves. The high-voltage transformer, circuit connections, pressure and vacuum lines and vacuum pump are all contained in the space between the sets of panels visible in the front and back views of Figs. 3 and 4. All parts of the instruments are easily accessible through removal of panels. The laser resonator can easily be removed from its hinged suspension in the cabinet and operated externally from the control console.

3. BEAM MANIPULATOR

The beam manipulator uses reflecting mirrors throughout; it is based on the simple optical principle illustrated in Fig. 5. A mirror is fixed rigidly to an axis of rotation and forms a 45° angle with it. If a light beam is co-linear with this axis, the reflected beam is located in a perpendicular plane and can assume any direction in this plane. By addition of a second 45° mirror and a second axis of rotation, the emerging beam can assume any direction in space.

Figure 6 shows schematically the entire manipulator system. There are essentially four pairs of mirrors: since two pairs have one mirror in common, there are a total of seven reflecting mirrors. There are 6 axes around which the laser beam can be rotated; the one co-linear with the

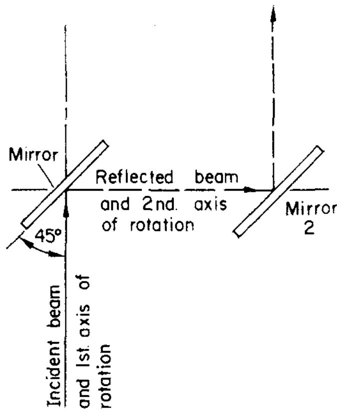

FIG. 5.

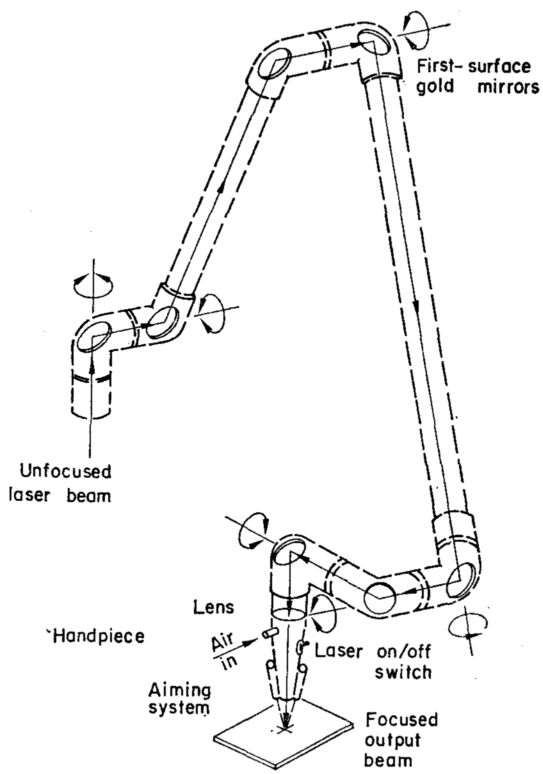

FIG. 6.

optic axes of the resonator is the only one fixed in space. Rotation of the mirrors is obtained through precision, ball bearing, rotary joints. Co-linearity of the beam with all the axes of rotation is made possible through close machining tolerances and alignment provisions at each mirror. Adjustments are also provided to make the first fixed axis of rotation co-linear with the laser beam. Adjustments of the seven mirrors are carried out by a systematic trial and error method utilizing the visible beam of a He–Ne laser and inserting the reflecting mirrors one after the other in sequence, starting at the input mirror. The manipulator arm is 2 m long and requires high precision mechanical tolerances, accurate alignment and a very rigid construction to minimize errors in output beam direction over this distance. After reflection from the last mirror, the beam is focused by means of a conventional lens. Lenses are located in detachable hand pieces which are interchangeable and can be sterilized. For long focal length objectives, an optical system is provided to project visible cross hairs at the location where the invisible $10 \cdot 6\ \mu m$ beam will be focused when the laser is activated. For short focal length objectives, the beam can be located by estimating visually the projected tip of the truncated cone that terminates the hand piece and that contains most of the focused beam. An overall view of the manipulator is shown in Figs. 2 and 3. The three rotary joints immediately preceding the focusing lens are mainly responsible for the ease with which one can direct the laser beam; these can be seen in Fig. 7, a view of the end of the manipulator in use. The detachable hand pieces are shown in Fig. 8.

The more or less copious fumes liberated by biological tissues exposed to the $10 \cdot 6\ \mu m$ laser radiation are prevented from reaching the lens, and from obscuring the operating site, by a small jet of air derived from a compressor located in the console and introduced in the hand piece just past the lens. In actual practice, and depending upon the application, more vigorous clearing of the operating area may be desirable through additional fans or air jets.

4. ACCESSORIES

(a) *Timed shutter mechanism*

The reflective vane which directs the laser energy from the manipulator arm into a heat sink can be controlled by a timing mechanism which opens the shutter for a preselected period of time from $0 \cdot 1$ s to 6 s. Employing a shutter in this way, eliminates dosage inaccuracies that are generally caused by the transients associated with gas discharges when the high voltage is turned on. The separate unit containing the timer can be located close to the operating site. This unit is provided with a four-position function switch. In the first position, the shutter is closed and cannot be activated by the foot switch. In position two, the shutter is open as long as the foot switch is depressed. In the third position, the shutter is opened by the foot switch and closes automatically after a preset period of time, and in the fourth position, the shutter is held open.

(b) *Laser endoscope*

This accessory is typical of a family of devices which may be needed to deliver the laser beam to remote locations accessible through body openings. While the specific nature of such devices may vary from one application to another, the principal problems are common. These are positional control, dosage of the laser beam, and visualization of the operating site. The endoscope described here represents a typical solution to these problems. It will be recalled that the laser is powered by 60 Hz high voltage. As a consequence, the power output is in the form of pulses having a repetition rate of 120 Hz. This makes it possible to realize a time sharing device, without loss of power, in which short periods of illuminating and viewing are timed to occur between the pulses of laser energy and, because of the 120 Hz repetition rate, all visual phenomena appear continuous and simultaneous to the eye. Time sharing in this way makes it possible for the line of sight, illuminating light and the laser beam to be directed along a common path, down a single tube, to a target site.

A schematic diagram of the endoscope system

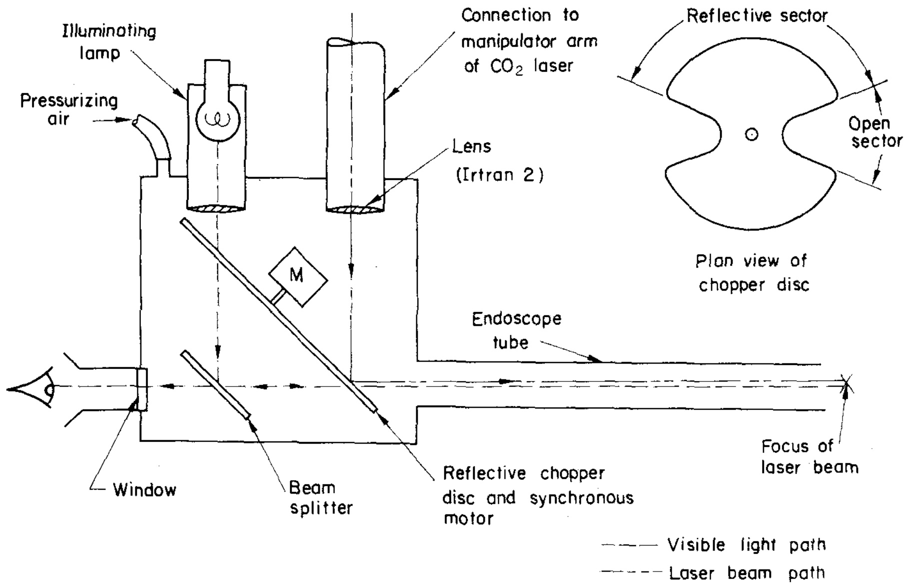

FIG. 9.

is shown in Fig. 9. Each pulse of laser energy is intercepted by the reflective portion of a synchronously rotating chopper disc and directed down a tube with essentially no loss of energy. Those losses which do occur as a result of chopping and beam splitting are in the visible light path only, and are easily compensated for by using an intense light source. A lens in the laser beam is arranged to focus the energy near the distal end of the endoscope tube. An external air supply pressurizes the device and produces a slight flow of air down the tube to purge the worksite of smoke.

The endoscope is attached to the manipulator arm of the CO_2 laser just as are the hand pieces described earlier. This allows the endoscope tube to be placed in any desired position. The endoscope can be hand held as shown in Fig. 10. In actual practice, however, it may be inserted as needed and held in place by an appropriate support. Localization of the spot where the laser beam will impinge is obtained prior to insertion of the endoscope by checking that the focused spot of the laser is aimed at the centre of the luminous disc provided by the viewing lamp. Three thumb screws position the reflective chopper disc to obtain this adjustment.

5. OPERATIONAL DATA

(a) *Overall operation of the instrument*

The laser instrument here described has been used actively in experimental surgery on animals in several hospital laboratories. The experience obtained so far indicates that the major design objectives have been met. These include trouble-free operation for prolonged periods of time, relative ease of manipulation of the laser beam, and overall simplicity of operation. Once the instrument is installed and initial adjustments have been made, the system is ready to operate from an atmospheric pressure start in less than 5 min. The vacuum pump can be left operating indefinitely and, in this case, the instrument is ready to operate within a minute after the solenoid actuated valves have been opened. If the instrument is in daily use, the only valves that need to be closed are the solenoid operated gas valves and any valve supplying cooling water. One set of the small size tanks contained in the instrument is sufficient for 50 h of continuous operation, at which time replacement of the Helium tank is necessary. Adjustments of the cavity mirrors are necessary only rarely, and can be accomplished with ease. The beam manipulator arm has proved that it will maintain its alignment when not subjected to undue stress. When changing from one focal length objective to another, it is sometimes necessary to adjust the last mirror in the manipulator so that the focused beam is brought in coincidence with the illuminated cross-hairs or, for the short focal length objective, exits properly from the truncated cone enclosing the convergent beam.

(b) *Power output*

The power output of most lasers is generally a function of the volume of the active medium. The power output of the CO_2 laser is roughly proportional to the length and diameter of the discharge tube; other parameters which influence the power output and are of interest for the considerations to follow are the radii of curvature and the spacing of the mirrors that form the optical cavity of the laser. These latter quantities, in conjunction with the geometry of the discharge tube, determine the power distribution within the laser beam in planes perpendicular to the direction of propagation. It is the nature of this power distribution that determines the smallest spot size to which the laser beam can be focused by means of an optical system. If this power distribution is represented by a Gaussian function, i.e., the laser operates in its lowest order spatial mode, it is possible in principle to focus the laser radiation to a spot size having the dimensions of the wave length. For other types of distributions, this is not true. The lowest order mode can be obtained only at the sacrifice of power.

The optical cavity of the laser here described is formed by two mirrors having radii of curvature of 8 m and 3 m, spaced by 1·5 m. The output is taken from the 3 m mirror and consists of several higher order modes. The beam can be focused to a minimum diameter of approx. 1 mm with a 6 in. (15 cm) focal length lens. Smaller spot sizes can be obtained with the shorter focal length lenses. Under these conditions, the output power of the laser measured at the worksite is consistently between 40 and 50 W, and decreases only very slowly with time. When this happens, the mirrors may need readjustment.

To obtain spot sizes which are closer to the theoretical limit, one must operate the laser in its lowest order mode. This can be done either by reducing the beam width with apertures inside the optical cavity or by changing the 1 in. (2·5 cm) dia. discharge tube to one having a diameter of about 9 mm. With the aperture, the useful power output from the manipulator arm is reduced to approximately 5 W. With the smaller diameter discharge tube, approx. 25 W of useful output can be obtained.

6. FURTHER INSTRUMENTAL DEVELOPMENTS

(a) *Dosage measurements*

In the present version of the instrument, the power setting is obtained from a graph of laser power output vs. tube current. This requires fairly frequent calibration and an external power meter. It would be desirable, for more accurate dosage data, to have available a continuous power indication while the instrument is operating. Such an accessory has been developed and tested. It consists of a narrow reflective rotating blade which diverts approximately 2 per cent of the power output of the laser onto a sensitive thermopile. After suitable calibration, the power output of the laser is displayed directly on a panel meter. This accessory is mechanically compatible with the existing instrument and will be available in the near future.

(b) *Microsurgery*

It has become apparent through our contact with several surgical laboratories that many investigations may require a much smaller spot size than is presently available.

A spot size of the order of 20 μm to 100 μm can be obtained through the use of an aperture or of a different discharge tube as was mentioned earlier in section 4 (b). The choice between these methods will depend upon the power that is required. It is apparent, however, that in most cases the small spot size by itself is not sufficient; it is necessary to make the focused laser beam conveniently available in the working space provided by a surgical microscope and, in addition, it is essential to locate the position where the laser beam will impinge with a precision of the order of the spot size.

One possible solution to these requirements is shown in Fig. 11. It is based on the fact that by depositing a thin layer of gold on a quartz substrate, one can obtain a beam splitter which will deflect about 50 per cent of the laser beam energy and transmit about 20 per cent of the visible energy from the work area to the microscope. A visible He–Ne laser beam is made to

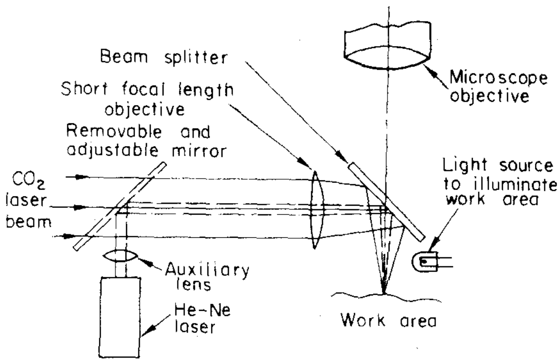

FIG. 11.

traverse the short focal length objective which focuses the CO_2 laser to a small spot size. By adjusting an auxiliary lens and a removable mirror system, the focused spots of the He–Ne and of the CO_2 lasers are made to coincide on an auxiliary target. After these adjustments are made, the CO_2 laser beam can be used after removal of the auxiliary mirror. The entire system is rigidly connected to the optical cavity of the CO_2 laser. This system is now in an exploratory stage.

7. MEDICAL APPLICATIONS OF CO_2 LASERS

With a laser beam focused to a small spot of about 1 mm dia. or less, most tissues, with the exception of hard bones, are cleanly cut by burning and vaporizing. Preliminary histological investigations (STELLAR, 1969) indicate that damage to tissues can be kept very small outside the impact zone if the appropriate dosage is used. Haemostatic control is good, since capillaries, small veins and arteries are readily coagulated by the laser beam. Loss of blood is small even when operating on highly vascular tissues. As an example, comparative studies on partial hepatectomies on dogs and monkeys with CO_2 lasers, electrocautery and scalpel indicate that the loss of blood is much less with the CO_2 laser technique (MULLINS *et al.*, 1968; GONZALEZ *et al.*, 1970).

Another research area for CO_2 surgery is the removal of cancerous tissues by vaporization and rapid burning. Such removal can be adequately controlled through the development of operative techniques and applied in locations where other techniques are either inapplicable or too traumatic. It was noted in this connection that CO_2 laser surgical procedures may be applicable to ulcerated and infected areas which are difficult to approach with other surgical techniques (STELLAR, private communication).

The broad unfocused beam of a CO_2 laser can be used in certain instances to destroy a thin layer of tissue without appreciably affecting the underlying layers. For example, research is under way to destroy the parietal cells of the stomach mucosa in an investigation related to the non-surgical treatment of peptic ulcers. It has been shown that it is possible to destroy the mucosa with only minor effects on the submucosa and without damage to the muscularis mucosae (EDLICH *et al.*, private communication).

In a related study (GOODALE *et al.*, 1970) it has been shown that it is possible to control the bleeding of gastric erosions (e.g., stress ulcers) by endoscopic means. Here, in comparative tests with conventional electrocautery, the unfocused CO_2 laser was instrumental in greatly reducing both the time required for the procedure and the concomitant blood loss.

A large potential area of application is the removal of controlled volumes of tissue by vaporization in areas to which access with more conventional surgical tools is difficult and traumatic, e.g., the removal of growths from vocal cords can be carried out with relative ease by focusing the laser radiation on the desired spot through an endoscope (JAKO, private communication). Blood vessel anastomosis is another potential area of application. Some preliminary experiments indicated that the CO_2 laser, focused to a very small spot size, can be used to cut circular holes of a few millimetres diameter in blood vessels and that the holes subsequently remain patent (YAHR and STRULLY, 1966). A CO_2 laser has been used in canine experimental cardiosurgery to produce selected myocardial lesions, intended to model several types of *A–V* blocks (NAPRSTEK *et al.*, 1970). Minimal reproducible lesions can be produced in the brain and spinal cords of cats. The potential use of such techniques in both functional neurosurgery and research have been pointed out by STELLAR (1969).

Most of the surgical researches mentioned so far are in their initial stages. Studies on wound healing in a variety of tissues are also in progress.

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UN LASER AU GAZ CARBONIQUE POUR LA RECHERCHE CHIRURGICALE

Sommaire—Les auteurs énumèrent les caractéristiques qui rendent les lasers au CO_2 intéressants pour des applications chirurgicales et décrivent un instrument consistant en un laser au CO_2 combiné avec un manipulateur de faisceau, spécialement conçu pour les travaux de recherche chirurgicale. Ils précisent les caractéristiques d'emploi qui rendent l'instrument approprié pour ces travaux. Ils décrivent un accessoire de chirurgie endoscopique, s'étendent sur les adaptations en vue de la microchirurgie et signalent les recherches actuellement en cours avec cet instrument.

EIN KOHLENSÄURELASER FÜR CHIRURGISCHE FORSCHUNG

Zusammenfassung—Die Charakteristiken eines CO_2-Lasers, die ihm Interesse für chirurgische Anwendungen verleihen, werden besprochen. Ein Instrument, bestehend aus einem integrierten CO_2- Laser und Strahlferngreifer, konstruiert speziell für chirurgische Forschungsarbeit, wird beschrieben. Arbeitscharakteristiken des Instrumentes von Bedeutung für solche Arbeit werden mitgeteilt. Ein Hilfsmittel für endoskopische Chirurgie wird beschrieben und Instrumentierung für Mikrochirurgie besprochen.