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A CLINICAL SERVO SYSTEM FOR SHIFTING THE RANGE OF PION BEAMS*

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Summary

An energy absorbing instrument, designed for use with a linear accelerator producing a high intensity beam of negative pions is described. The system makes use of a variable column of energy absorbing fluid with depth controlled by a hydraulic servomechanism to conform to theoretically or experimentally derived sweep curves in the form of histograms or continuous functions. The dose versus depth curves which result from the vertical sweep of this instrument show excellent flattening over the stroke. The details of construction and control of a prototype "range-shifter" are described, as well as an innovative design for improving the form and function of the device. A unique method for command-function storage and interrupt control using programmable memories and microprocessor techniques is discussed which has proven satisfactory in applications involving human patients.

Introduction

At Los Alamos considerable effort is being directed toward the use of negative pi-mesons for cancer therapy.[1,2] Since nuclear capture and the resulting short-range radiation occurs at a rather specific depth of material for a given energy, the utility of the beam can be greatly enhanced by providing a device which can move this intense star region over a specified range in a controlled manner.[3] An energy absorbing fluid such as a water column can be used, or, for reasons of corrosion and lubrication, a light oil such as mineral oil or higher density hydrocarbons such as ethylene glycol. The insertion of a column of such a liquid into the beam will degrade the beam energy in proportion to its depth. To make a range-shifter of this type useful as an experimental tool it must first of all have fast dynamic response and good precision, and also be readily adjustable for positioning above experimental apparatus. To aid the experimenter, it should be easy to command and control and should be reproducible in its responses. Finally, as a therapy tool it should be quiet in its operation and possess a cleanly designed appearance. Above all it should be highly reliable and require little maintenance.

Range Shifter - Mechanical Design

The operational prototype range-shifter is shown in Fig. 1 as it was installed in the treatment room of the Biomedical Facility at Los Alamos. The pion beam is directed downward where it passes through the variable thickness column of fluid sandwiched between two acrylic windows, one fixed and one movable, before entering the treatment volume. The range-shifter is mounted on a cantilevered boom which swings freely and can be positioned by hand in the horizontal plane between detent-lock positions. In addition, the boom can be driven vertically over a 50 cm range by an air motor and ball screw.

The total weight of the boom and range-shifter is about 175 Kg. The beam aperture is centered 1.8 m from the hinge pin pivots and the aperture diameter is 24 cm. The depth of the cylindrical tank which contains the range shifting mechanism is 33 cm and the stroke of the fluid column is controllable over a range of 13.5 cm. At the bottom of the stroke the minimum thickness, including the two acrylic windows, is 3 cm. To judge what these dimensions mean in terms of 80 MeV pions, the range of these particles in mediums such as oil and light plastics is about 19 cm. A choice was made early in the prototype design in favor of hydraulic actuators because of the ease with which a long stroke could be achieved within the size limitations of the reservoir envelope. Three such actuators are used in parallel for redundancy and to amplify the force applied to the upper movable window. There are also three independent sensor drive assemblies to provide position feedback information from high precision one-turn potentiometers. One of the three assemblies also carries a d-c tachometer. In the prototype, the sensors and their running gear are partially immersed in light, clear transformer oil which the movable window displaces as it is driven vertically by the cable cylinders. The oil is prevented from entering the space above the upper window by a long-stroke stainless steel bellows, the convolutions of which provide near-viscous damping when operating under the oil surface.

The hydraulic manifolds which supply the actuators pass through the wall of the reservoir tank into the interior of the jib boom which houses the servovalve, pressure relief bypass valves, and the supply line filter. The servovalve forms the heart of the servo-control system. Electrical signals to the torque motor of the servovalve and transducer feedback signals are connected to the control computer room by a 30 m umbilical cord attached to the boom. All analog control functions and the microprocessor command system are located in the computer room.

Second Generation Range Shifter Design

The prototype unit was first used in the spring of 1976 to test dose distributions in water while developing codes by which to design command functions. Following extensive work of this sort as well as some tests involving living cells, the decision was made to use the range-shifter for the first time on human patients during November-December, 1976. The prototype design shortcomings became immediately apparent to the users among which were the need for a conical base on the tank to facilitate head and neck treatments and to allow greater ease of set-up; the need for the smallest possible minimum thickness, and the ultimate need for a stroke of 18 cm minimum, which provoked consideration of absorbing fluids with densities greater than hydrocarbon oil. Improvements were also required in the command and control system.

A new range shifter head has been designed and will be installed in the summer of 1977. To achieve the conical base along with an increased stroke, longer cable cylinders were required which had to be mounted horizontally as shown. A single sensor package is used, containing two redundant position potentiometers, the tachometer and a shaft encoder, all belt driven for minimum backlash and inertia. The size and volume of the reservoir has been considerably reduced despite the increased bellows stroke of 18 cm.

The minimum thickness has been reduced to 2 cm with the option of going to 1.5 cm pending completion of dynamic tests. This has been achieved by the use of thin windows, especially fabricated out of polycarbonate, an extremely tough plastic, as well as the use of smooth command functions rather than step-wise histograms which should alleviate the cavitation problem in the thin oil layer at the bottom of the stroke.

Servo Design and Command Logic

The control system for the range-shifter is hybrid in nature, utilizing analog feedback loops for fast, smooth, readily compensatable performance, as well as a digital memory for the storage of numerous command functions and for programmable interrupt control of these command functions. The block diagram shown in

Fig. 2 includes the transfer functions significant for the speed at which the range-shifter operates. The simplest form of the control equation reduces to a second order where, in the absence of nonlinearities, the addition of active rate feedback merely increases the time constant of the damping pole.

Once the closed loop control system became operational so that simple analog commands could be used to control the prototype range shifter, it became necessary to devise a command function generator which could deliver functions appropriate to the physics requirements of pion therapy. An M6800 Microprocessor (MPU) system was developed which was aptly suited to either step-wise functions or quasi-continuous functions. Most of this system is still being used despite improvements subsequently made to suit the needs of the users.

Upon turning on the range shifter servo, the operator adjusts the bias to bring the range shifter to its zero reference position, normally the minimum thickness. When the MPU takes command, the 0-10 volt D/A output causes the movable window to be driven positively upward, increasing the depth of absorbing fluid and causing the star region to move upward proportionately. The shape of the sweep curve command signal is quite arbitrary, provided it lies within the 0-10 volt limits and that its time scale is appropriate to the speed limitations of the servo-mechanism and the displacement limitations of the absorbing fluid at the bottom of the stroke.

The microprocessor based command function generator is mounted in the same rack as the patch panel for the analog controller. The front panel control switches and readouts are all connected to the MPU via a peripheral interface card. The D/A card converts a twelve bit digital word into a voltage which drives the setpoints of the range shifter. There is a facility for loading new dose tables into random access memory via a teletype link. It is clear that rather exotic functions are well within the capability of this system.

A remote control panel has been connected in parallel with the original one for convenience of operation of the range shifter from the main computer console. This remote terminal has the status LED's and an abbreviated set of control pushbuttons for starting and aborting the system along with a separate 4-digit hexadecimal switch for selecting the starting address of the dose table.

Tests of the Servo System

Tests of the range-shifter servo show the time constant of the forward loop damping pole, with the rate loop open and the servovalve supply pressure at 1400 KPa to be 0.02 seconds. This sets the break frequency at 8 Hz which is adequate for experiments conducted so far. However, the flow gain $K_Q(P)$ of the servovalve is a strong function of supply pressure and to check its response speed the servo has been tested at as high a flow gain as the cable cylinders can bear without seal rupture. An analog sweep curve was generated with a diode function generator to command a very rapid reversal as shown in Fig. 3a. The analog rate and position signals were monitored during this reversal and the results show the acceleration achieved to be greater than 1.5 g's.

The tracking precision of the system to near-analog commands is shown in Fig. 3b. In this case a 63-point cusp sweep command signal is delivered by the CFG on a 10-second time scale. The servo responds well to the granularity of the command which includes time steps as short as 40 ms. This quasi-continuous form of the sweep function will eventually supersede the histogram form. A typical histogram command signal calculated to produce a uniform dose over a 5 cm sweep is shown along with its analog response in Fig. 3c. The integrated tracking error for this function is less than 3%, which appears to have negligible effect on the dosimetry measurements.

Depth-Dose Experimental Results[4]

When the negative pion beam is driven into the water phantom with the range-shifter removed, the star region shows up clearly as seen in Fig. 4a. The peak is normalized to a scale of 100 and the plot represents in this case the total dose delivered as a function of depth. The star peak at half-maximum is about 2.5 cm wide. In this case, the range-shifter was inserted with a reference thickness of 3.5 cm and the star region was shifted leftwards by about this much as shown in Fig. 4b. Then the 5 cm isodose histogram command was applied and the servo produced a sweep which resulted in only a 3% variation in dose over the shifted range. The plateau dose is also active during the sweep and can be seen to increase proportionately. A similar measurement made with a 10 cm histogram is plotted in Fig. 4c. For this sweep, the dose distribution drops off with depth which can be made to compensate for the fact that RBE increases with depth thus hopefully giving a uniform biological effect with depth.

The first treatments with human patients point out the need for knowledge of the effects of range-shifted pion beams on composite tissues as in head and neck therapy. As the work develops so will the range-shifter functions. Should the profiles require greater speed in the future, system parameters such as gain and pressure can be adjusted accordingly.

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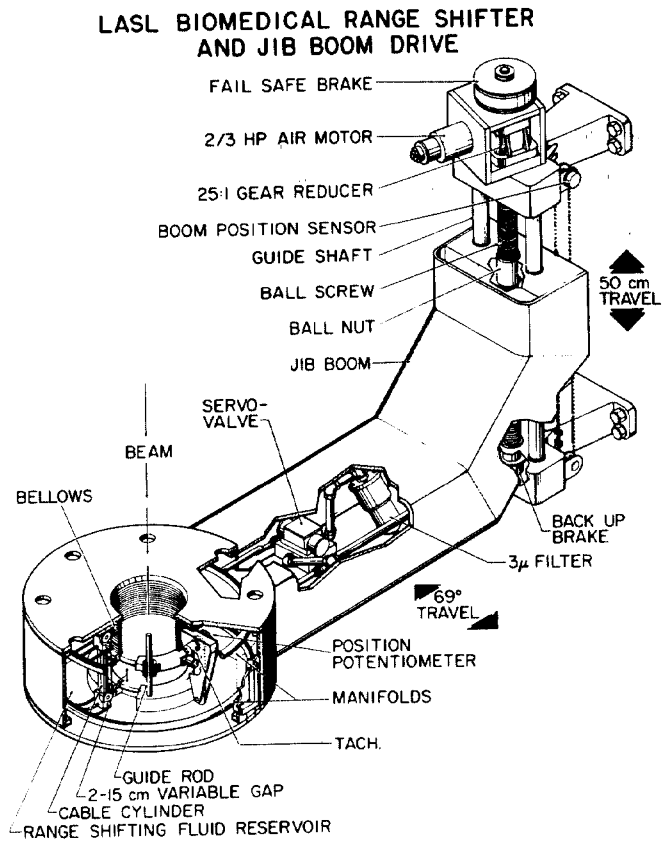

Fig. 1 The Range Shifter and its Jib Boom Support

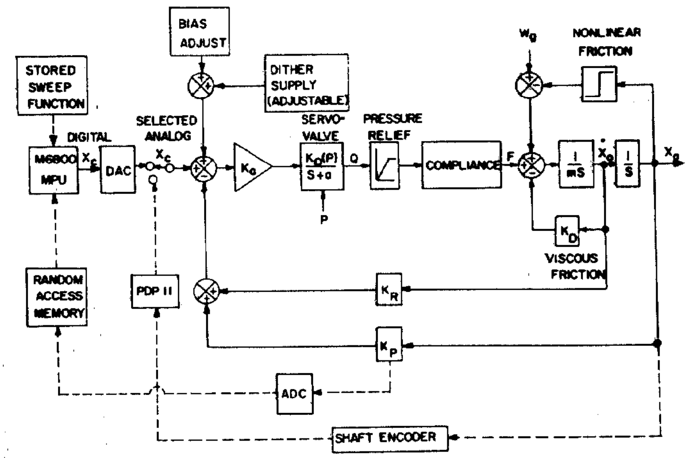

Fig. 2 Command and Control System

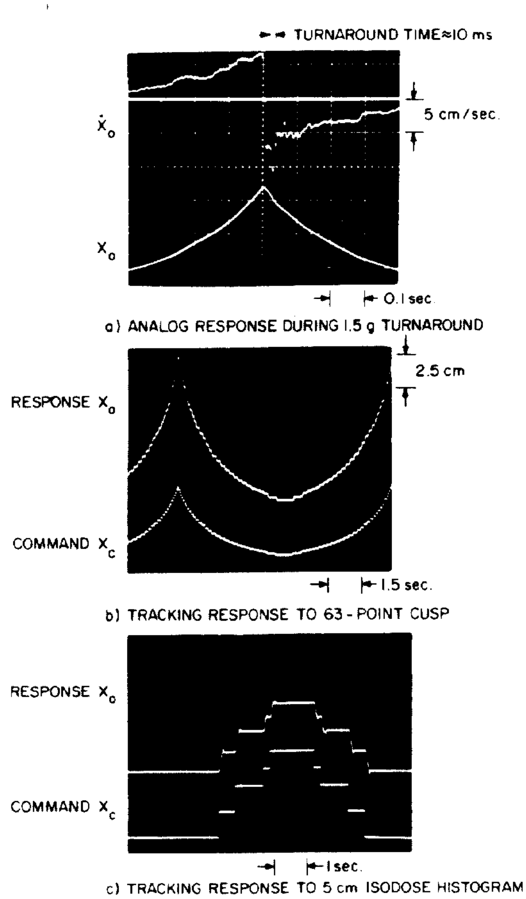

Fig. 3 Analog Servo Responses

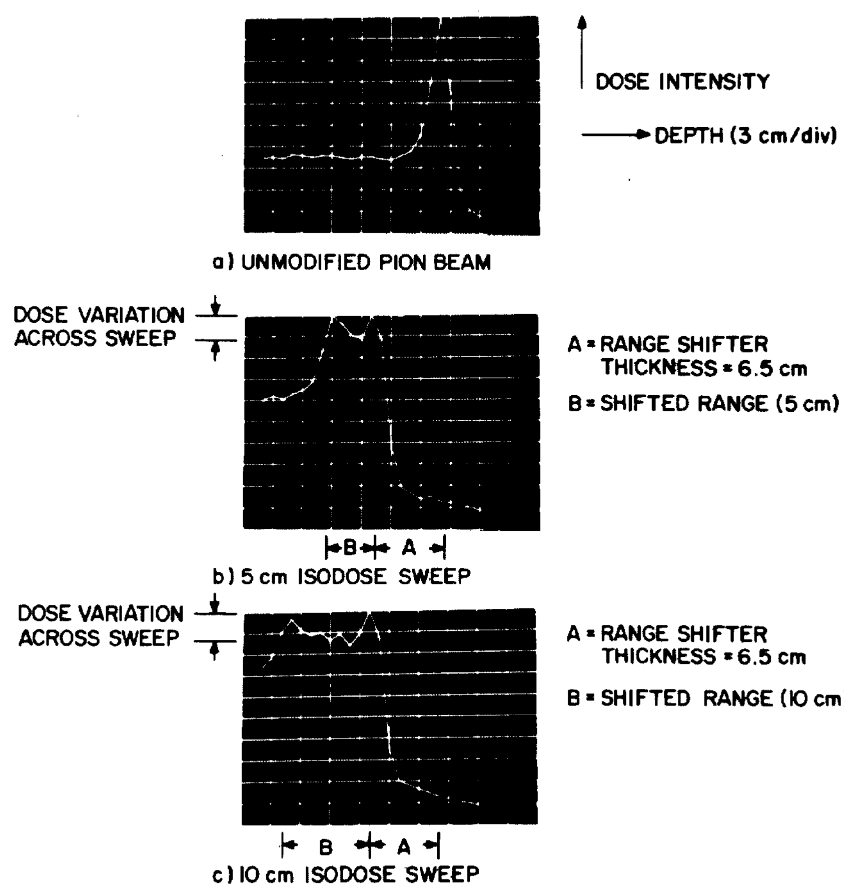

Fig. 4 Controlled Dose Distributions using Computed Sweep Functions