LOS ALAMOS SCIENTIFIC LABORATORY
UNIVERSITY OF CALIFORNIA
LOS ALAMOS, NEW MEXICO 87544

712643

OFFICE MEMORANDUM

E. A. Knapp

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FROM : Arvid Lundy, Mike Minor and Sally Shlaer

SUBJECT : Couch Procurement and Scanning Control System Design for the Pion Radiotherapy Program

SYMBOL : MP-3

MAIL STOP: MS-844

COLLECTION Dr Off Files
BOX No. B-10, D105
FOLDER MES 200 1/3/75-3/31/75

As you know we have been concerned with couch procurement for some time. We believe we have been unable to communicate the following points successfully to the Cancer Center staff:

1. Significant engineering constraints exist in the selection of a suitable couch system and engineering judgments must be made.

2. The magnitude of effort - engineering, software, possible building modifications, and budgetary - that will be required to get a properly working couch scanning system is considerable.

3. There is possible risk and danger to patients from a poorly designed couch or couch control system.

4. The time required to implement a patient scanning system is considerably greater than the procurement time for a commercial couch and will be somewhat dependent on how readily the couch can be modified to meet the requirements.

Accuracy and Safety

In a scanned beam situation such as we are planning and which is required to take maximal advantage of the superior dose localization properties of pions, the accuracy and reliability with which the prescribed dose is delivered to the patient is directly dependent on the accuracy and reliability with which the treatment couch velocity can be controlled. This couch velocity must be controlled by the prescribed dose, by the instantaneous pion beam intensity and by the thickness of the tumor volume being treated which may vary along the length of the scan. (The thickness of the treatment volume is dependent on the momentum distribution of the beam which is planned to be controlled by a variable thickness absorber scan motion - Don Liska's device - or by a dome or ridge filter.) Velocity should be controlled to an accuracy of 1% or better, we believe. (In most radiation therapy an overall goal of 5% accuracy in dose is accepted. Several uncertainties on the order of 1 to 2% enter into achieving a total uncertainty of 5% in good conventional therapy.)

Similarly the accuracy and reliability with which the treatment volume can be shaped is directly dependent on the accuracy and reliability

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with which couch position and scan direction can be monitored and controlled. We believe horizontal couch position should be controllable to one millimeter accuracy. On a couch such as the Varian with long longitudinal travel this corresponds to a percentage accuracy of 0.075%. This accuracy is not reliably attainable with the potentiometer techniques commonly used to sense position on commercial treatment couches.

In arriving at the one millimeter accuracy requirement we consider a tumor next to a critical structure such as the spinal cord or optic nerve which can be well localized with diagnostic x rays where one wishes to treat the entire tumor and yet miss the critical structure. In many cases one would be able to place protective collimation on the patient's skin surface but one can easily visualize cases where the tumor goes not only to the critical structure but actually over and past it. Here if one were using a device such as Liska's variable thickness energy degrader to control penetration it would be necessary to know couch position accurately. The cost of failure here might be the patient losing his sight, becoming paralyzed, or losing his life to an inadequately treated cancer. The experience of one of us in doing actual clinical treatment planning with electron beams indicates that it would be undesirable to have to allow for much more than one millimeter uncertainty in patient position in such cases when other errors and beam edge unsharpness are considered. Somewhat similar concerns exist when abutting fields or when restarting a scanned treatment which was interrupted part way through. (One might try to achieve about 5 mm total uncertainty in knowing the collimated beam edge position - beam edge being defined as the 50% isodose line for example. Again, as in the dosimetry situation, several errors must be summed. Physics input is needed as to how "sharp" a beam edge may be obtained with good collimation.) The accuracy requirement is one which we need to know and which should of course be specified by the radiation therapists. Unfortunately we have not had the opportunity to discuss it with them.

A great deal of attention must be paid to analyzing failure modes in the couch and couch control system and evaluating their possible safety consequences. About two years ago a patient was killed in Boston when a relay stuck on a commercial treatment couch. In this particular case, the accident occurred during patient setup using the manual control buttons when the elevation motor stuck "on" in the elevate mode. The patient was crushed to death by the collimator while the setup technician watched helplessly. (Nine years ago one of us modified three new couches of the brand involved in the Boston accident to avoid such problems and wrote several letters about the situation but the manufacturer did not take action. One safety problem in it was corrected only after one of the vendors own service people suffered a crushed hand demonstrating the anti-collision device! Even standard commercial products must be reviewed.) Our system will be far more complex and inherently more prone to component failures. The design must be very carefully reviewed to insure that there is only the most minimal chance of component malfunction resulting in patient injury.

Velocity Range of Horizontal Motions

Another factor to consider is the range of velocity control required on the horizontal motions. One can easily visualize operating over a 15 to 1 range of accelerator intensity and a 5 to 1 range of tumor volume thickness

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resulting in a total velocity range of 75 to 1. Also with most commercial couches it will be necessary to drive both horizontal axes simultaneously at different velocities (see required couch motions section) to achieve scan motion at arbitrary angles. As an example one might wish to scan 15 cm on the x-axis while moving only 1/2 cm on the y axis. This is an additional 30 to 1 velocity ratio. Obviously the total required velocity range is not 30 x 75 or 2250:1 as one quickly finds that the time required for some treatments under some conditions would be totally impractical. A velocity range of at least 150 to 1 does seem desirable though. The brush-type shunt wound motors used on most commercial treatment couches (SHM is the only exception we are aware of) have a useful velocity range of only about 20 to 1. As much as 50:1 can be obtained with some units but with possible "cogging" problems and with torque reduced at low speed to avoid overheating. Suitable velocity range can be gotten by replacing the motors with either d.c. servo motors or stepping motors but the motor power available per unit volume is less with these types of motors and sufficient space must be available to mount them. Also the gear ratio between the driven shaft and the patient motion must be adaptable to the speed range of the new motors.

If stepping motors are used they may be very noisy unless they are properly mounted with suitable vibration isolation. Another problem with stepping motors operating over a wide speed range is avoiding resonance conditions where uneven stepping is apt to occur. This is primarily dependent on the frictional and inertial properties of the load. Any motors used must be rated for continuous duty - normal use of treatment couches requires only intermittent duty. If fan cooled motors are used the 7000 ft altitude of Los Alamos must be considered - the lower air density at this altitude requires about 30% greater air moving capacity to achieve the same cooling.

Required Couch Motions

If we achieve the planned "fan beam" tune, the pion stopping region in the patient will approximate a horizontal "sausage" shape up to 15 cm in length. This "sausage" volume lies in a fixed orientation in the horizontal plane (controlled by the physical alignment of the beam line). For a given tumor volume there usually will be an optimum angle at which to scan the patient through the "sausage" to minimize loss of pions in collimators and to do the treatment with the minimum number of scans (usually one). The rotation motion of most commercial couches is a rotation table mounted on the floor (centered on the beam axis). This rotation table would be used to align the angle of the "sausage" relative to the tumor.

In essentially all cases one would want to "scan through" the "sausage" at a right angle to its axis. Scan direction is thus fixed relative to the room since the "sausage" is fixed. Unfortunately the x and y horizontal motions on all of the commercial couches which we are aware of are mounted on top of the rotation turntable and are thus not fixed relative to the room. To scan at right angles to the sausage will then usually require driving both x and y motions simultaneously at different velocities. This problem could be overcome by fixing the x and y motion drives to the floor and putting the rotation motion on top. (This might complicate setups somewhat because the center-of-rotation no longer stays aligned with the central beam axis.) The additional controls to drive both axes simultaneously are almost certainly cheaper than doing a mechanical redesign on a commercial couch.

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(In a December meeting it was proposed to not incorporate a rotation table but to attach patient "modules" to the couch top at arbitrary angles. We believe this idea is impractical. The "modules" would have to be very heavy to hold deflections to reasonable limits. The overhanging torque applied to the couch top would be higher than the standard designs allow, and a clamping method which would provide adequate strength and yet provide precise and easy alignment may not be possible. In any event, it would be very difficult to design.)

Dick Hutson has pointed out that the fan beam is apt to be somewhat asymmetrical along the length of the sausage shaped stopping region and that to compensate for this it may be necessary to do the treatment in two parts rotating the patient 180° between them. If this is true the length of longitudinal travel required is greatly increased.

Vertical travel of the couch is obviously required to adjust for the different thicknesses of patients, ease setup and permit unusual setups, i.e., patients sitting up.

Thus the required motions are x,y,z and rotation, preferably about the beam central axis. All motions should have position transducers. We have not studied the range of travel requirement on each motion; we should review the Cancer Center's specifications on this.

After watching patient setups during the fall it appears to us that limited tilt motion of the couch top would be useful but this does not seem to be offered in any commercial couches.

It should be possible to remove the treatment couch completely and easily to allow setup of large experimental apparatus.

Position and Velocity Transducers

Because of the complexity of the system and the risk to patients of faulty data acquisition, we believe all motions should be equipped with dual digital position transducers and the x and y drives should be additionally equipped with dual velocity transducers. We believe the preferred type of position transducers for accuracy and reliability is the optical disk type absolute shaft position encoder with Gray code output. Similarly velocity can probably be best measured by using an optical disk type rotary pulse generator and using phase lock loop techniques for precise control - probably better than 1% will be achieved. Any commercial couches must be evaluated in terms of how these transducers can be mounted. Such units are available in a variety of case sizes and linear versions are also available. Couch vendors are not apt to be familiar with these devices. The proposed mounting must be evaluated in terms of backlash with respect to the motion being measured. If coupled through a drive screw, the screw linearity must be considered. Failure modes must also be evaluated - for example could a drive pin shear and result in the transducers still being driven but the couch not moving. The procurement and mounting of the transducers is almost certainly most economically done by LASL but will require close liaison with the couch vendor so that proper units can be selected and ordered prior to couch delivery. (Delivery time on components of this type will be several months.)

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Data Needed to Select Drive Motors and to Design Servo System

The system must function as a precise velocity servo on the x and y axes. It would seem highly desirable to make the system function as a position servo on all axes to aid and speed setups. Finally a pendant control should be provided to allow easy positioning manually. To select suitable motors (again we believe economic reasons probably dictate that required motor changes be done by LASL) and to allow the servo design to proceed, we need to know the system friction including some idea of the ratio of static friction to dynamic friction, the amount of backlash in the system, the inertia of the system and the mass of the moved assemblies. Most of this data will probably have to be gotten by making measurements on an actual unit. We also need to know what provisions are provided for brakes and clutches so as to provide controls for these if needed (both the Varian and the SHM couches use electric clutches). Failure modes of these devices should also be determined. Slippage of a clutch must not cause an error in transducer readout. Brake slippage must not endanger the patient, etc.

Control System Design and Philosophy

The risks of improper operation and the complexity of the system dictate a redundant error checking system. Feedback on what is happening is also needed to the control room staff and it should be possible to simulate the treatment ahead of time in some way, i.e., are you really going to do what you think you are.

After discussions with Don Machen, MP-1, we are proposing a control system based on the use of a separate small PDP-11/10 computer ($4000) interfaced via CAMAC and also the use of one, two, or three microprocessors ($1200 each) to handle such items as converting the velocity and direction signals to two velocity components, generating the appropriate drive signals for Liska's energy degrader to obtain reasonably uniform biological response as a function of depth and synchronizing collimator jaw position as a function of couch position and degrader thickness. Elaborate treatment volume shaping such as this implies is a long way off - it won't all happen at once, but the initial system design should allow for expansion to this if it is ever to be achieved in a reasonable time and at a reasonable cost.

We visualize the scan program being developed in the PDP-11/45 main control computer. Close ties to the treatment planning program will have to be developed. It should be possible to "output the scan" on a storage display rather rapidly to provide a visual check of what is to be done. Some method of precisely checking critical points is also needed. When the patient is actually to be treated the program will be down-loaded to the PDP-11/10 on a serial data link. Actual scan control will be done by this computer but the second set of transducers on each axis will be interfaced via a totally independent data path to the PDP-11/45 which will simultaneously run a checking code. Either computer will be able to halt the process in event of malfunction detection.

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Scheduling and Cost

We believe that if a couch selection is made within the next few weeks, a go-ahead is given on the control system, we have close interaction with the vendor, the couch delivery is no more than eight months ARO, and we make maximum possible use of the available consulting help money that UNM is making available; we can have the couch system ready to start testing by the beginning of 1976 at the earliest. This of course assumes that any needed floor and building modifications can be done on schedule. Close vendor interaction implies being able to inspect a couch immediately upon selection, being able to do necessary tests on a couch before delivery of our unit, and being able to get necessary drawings with accurate dimensions.

Experience has shown that approximately 50% of any software effort is spent in checkout and debugging - thus it is not unreasonable to expect four or more man-months of effort will be spent in checkout of the scanning system after the hardware is finished and installed. Thus it could easily be more than a year from now before any dosimetry studies could be started with the system and still longer before it could be used with patients. To allow intensive work on the hardware system without disruption of the beam schedule it would be desirable to install the first couch in the simulator room and to leave it there until the system is debugged. If two couches were to be delivered simultaneously one might be installed in the treatment room and used with standard motors for fixed field treatment. (We do not believe that starting with very simple scanned volumes in any way changes the couch interfacing hardware requirements.) If we were never to do anything other than very simple shapes the control system philosophy would change. But assuming we will do more complex shapes eventually, we do not think it makes sense to design first a very simple control system and then throw it out and start from scratch to learn about a more flexible system; too much design time and hardware fabrication effort is required for either system.

It would seem highly desirable to get any floor or building modifications needed done before the great shutdown is over to avoid disruption of the experimental schedule later but the time may already be too short to permit that.

A rough cost estimate for a complete scanning control system including collimator controls and drive signals to a variable energy degrader looks like this:

1.	PDP-11/10 computer	$4.0K
2.	16K memory for above	5.0
3.	DL-11 computer to computer serial interface	1.0
4.	CAMAC crate	1.5
5.	CAMAC unibus controller	1.0
6.	Absolute position encoders for couch	8.0
7.	Velocity encoders for couch	2.0
8.	Microprocessors	3.5
9.	CAMAC interfacing modules	4.0
10.	Miscellaneous hardware fabrication (estimate seven chassis at $2.0K each)	14.0
11.	Probable couch motor changes	1.0
	Total	$45.0K

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We believe this is a realistic estimate but we would like to know more about the couch selected before trying to make it more accurate. It does not include the cost of collimator design and fabrication, or the cost of floor or building modifications which might be required.

Comments on Particular Commercial Couches

We believe that to do this project in an economical way it is probably essential that we start with a commercially available unit and that we require the minimum amount of special rework to be done by the vendor. It would seem logical to have surveyed all of the available couches to begin with but this seems not to have been done.

1) Varian Associates

The proposed double pedestal modification of their standard couch appears usable from a controls point of view. There are additional motor synchronization problems to handle and failure of synchronization in the two pedestal elevating motors would cause the unit to self-destruct. The horizontal drive motors would have to be replaced but there appears to be adequate room for this as well as for mounting the position and velocity transducers. Both pedestals have to be driven with the torque required varying depending on how much weight is resting on each pedestal. This would complicate the servo design as well as add to the expense. Complete redesign of the floor rotation bearing would be required to support the additional weight and this would probably allow use of the under floor x-ray tube system desired by Ed Barnes. Removal and reinstallation of the couch would be somewhat complicated but probably could be done in less than an hour. The unit would appear rather cumbersome we believe. Varian could ship standard pedestals almost immediately on which we could work out the motor and encoder changes and mountings and then ship them back for final in-plant assembly. It appears that there would be no problems interfacing with the Varian engineers, they seemed very cooperative. We suspect that the cost of the modifications that Varian would have to make would be very high. Varian could ship the completed systems 5 to 6 months ARO.

2) Phillips

We have relatively little information on this unit. We understand that it is built for Phillips by the MEL Equipment Co., Ltd., in Sussex, England and that there are no units installed in North America; only six have been built to date. The large understructure would require building modifications - jackhammering concrete out to lower the sub-floor level and allow the pedestal to go down far enough. In the pictures the x and y motion drive area appears to be very compact and we wonder whether adequate space exists to mount suitable motors and the needed position and velocity transducers. The lifting ram will lift an impressive 870 lbs. in addition to the table top assembly. It is not clear however, what amount of off-axis weight can be supported. Two rotation motions are provided - a floor turntable centered on beam axis and another rotation motion at the top of the lifting ram (but below the x and y motions it appears). This second rotation motion is not motorized and has only a manual lock. The lifting ram comes up near the outer circumference of the floor turntable and the dual rotation motions appear to be necessary to compensate for the very limited transverse (x) motion of the couch top. This x motion is limited to under ± 5 inches from center

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(Varian provides a ± 10 inches of x motion). While the actual travel limits may not prove to be much of a restriction, setup would be complicated by the dual rotations. (Angular alignment of the patient will be quite critical on scanned treatments. A 2° misalignment on a 25 cm scan would result in almost 1.0 cm error on the edge of the field at the end of the scan.) The longitudinal travel of 26" also is limited compared to Varian's 52" and would cause problems if the patient had to be turned 180° to compensate for "sausage" asymmetry.

We have considerable reservations about the ease with which suitable motors and encoder could be fitted to a unit made in England and about how vendor liaison could be handled without actually making a trip to the factory.

The price which we have heard ($48,000 each) seems high to us and 8 months delivery ARO for the first unit, 12 months ARO for the second seems long.

3) SHM Nuclear

This is a new couch of which we saw two units essentially completed in their factory two weeks ago. The units use stepping motor drives which would be usable without motor changes. To us they appeared to meet all of the requirements we are aware of except that of supporting 700 lbs. weight - they are designed for 600 lbs. Deflection at 600 lbs. probably exceeds the 1 mm limit which the Cancer Center has talked about but we believe this 1 mm vertical deflection specification is unrealistic anyway (probably no commercial couch will meet it and we do not understand the need for it).

The motions mirror the standard Varian couch but we did not find out the range of travel. The turntable support is open through the center so an x-ray tube could be installed. If the 600 lb. load limit could be accepted (we believe it could) it appears that the only modifications required would be to mount position and velocity transducers which there appeared to be plenty of room for. No building modifications would be required other than the floor.

We were told the price would probably be under $20,000 each and that delivery could be made on a first unit six months ARO.

4) AECL (Atomic Energy of Canada, Ltd., Commercial Products Division

AECL has probably produced more couches than any of the other vendors. Unfortunately the mechanical engineering leaves a great deal to be desired in terms of precision. The AECL Theratron-80 couches were apparently designed by engineers from England unfamiliar with many standard parts available in North America and many special fabrications were unnecessarily used and poorly executed. They do not seem suitable for our needs. Both Los Angeles County - USC Medical Center and Rush-Presbyterian Medical Center in Chicago have reported severe problems in trying to log position on these units.

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Use of Patient Modules with Commercial Couches

It has been planned to use the patient staging areas to set up patients in immobilization modules and then to transport them on these modules into the treatment room where the modules would key into the couch. This would speed setups. We believe any commercial couch is applicable to this type of arrangement however, a reasonable amount of mechanical engineering effort will be required to make it work smoothly and quickly. The Phillips couch is available with a table top transfer trolley as an option which probably would make implementation of the system easier. We believe that this is not a high priority feature to implement rapidly however, because as long as we operate at the low dose rates which we will probably be at for some time, a few minutes of setup time saved makes only a very small fractional effect on the total treatment time.

MP-3 Staff
Ray Gore, MP-1, MS-828
Don Machen, MS-828
Ed Bush, MS-826
Jerry Wallace, MS-823
Louis Rosen, MP-DO
Don Liska, MS-834
Jim Lindsay, MS-828
Jim Little, MS-828
Val Hart, MS-826
Jim Richardson, MS-828
Chaim Richman, MS-888
Tom Boyd, MS-826
Bob Jameson, MS-834
M. M. Kligerman, Cancer Research and Treatment Center
E. Barnes
Bob Barnard

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