

BEAM QUALITY FOR PROTON THERAPY AT C.P.O.

Samuel Meyroneinc, Jean Gosnet, Jean-Claude Boucault,
Catherine Nauraye, Régis Ferrand, Alejandro Mazal
Centre de Protonthérapie d'Orsay, BP 65, 91402 Orsay, France

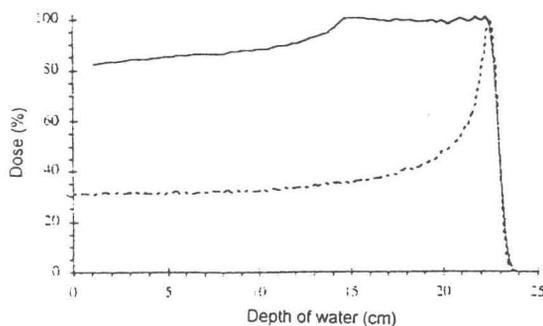
Since 1987, the beam of the synchro-cyclotron is tuned and adapted for medical treatments. The first eye treatment was realized in 1991 and from this date the Centre de Protonthérapie d'Orsay (C.P.O.) accumulates experience for the beam control. Beside the classical discussions on the parameters settings of the machine and the beamline, the overall problem of accuracy of the beam must also take into account the medical and the end-line uncertainties. The aim of this article is more to inform cyclotrons people about the protontherapy application than to give expert numbers about the complex problem of accuracy in protontherapy.

1. Introduction

1.1. Protontherapy - CPO

The major advantage of the proton beam in radiation therapy is in the characteristic curve of energy loss in matter called "Bragg peak" (fig. 1), which corresponds to a high dose deposition at a particular depth at the end of the range. In addition, protons have also a small lateral scattering. The synchrocyclotron SC200, designed in 1957, and upgraded in 1975 by Institut de Physique Nucléaire, is fully used since 1991, by the Centre de Protonthérapie d'Orsay (C.P.O.). The C.P.O. is a special hospital institution supported by four majors oncological centers of Paris (Institut Curie, Institut Gustave Roussy, Centre René Huguenin, Assistance Publique des Hôpitaux de Paris)[1][2]. Since the beginning, more than 1100 patients have been treated for ophthalmological or intracranial tumors at CPO.

Fig. 1 : the native and the spread out Bragg peak



1.2. The beam accuracy

Because of its advantage and its cost, the medical utilization of a proton beam is dedicated for treatments which require precision. This raises questions about the precision required for each feature of the beam. At the present time, the new designed facilities fully devoted to protontherapy application (MGH at Boston, Loma Linda, etc ...) have already included these requirements in their specifications [3][4][5]. Instead for C.P.O., an old physics research machine associated with a passive scattering system to shape the beam

[6][7], we are regularly confronted with accuracy considerations concerning the accelerator, the beam delivery and the treatment conditions.

The aim of this discussion is to evoke the general accuracy of each step of the overall treatment process, in order to know the real needs for the beam at CPO.

2. Clinical and treatment planning considerations

2.1. The imaging system

One of the first step in the radiotherapy procedure is in the acquisition of anatomical data for treatment planning (IRM,CT). The resolution and the accuracy of the data depends on multiple factors (deformations, voxel size, slice thickness, calibration, ...), but the related uncertainties in the treatment planning process are in the 1-3 mm range.

The contouring of the tumor realised by the physician seems to be more affected by uncertainty. Beside the human arbitrary character of this operation, there's also the natural spreading character of the tumor. Uncertainty in some cases can reach 5mm or more.

But when a clinical target is defined, it includes the clinical uncertainties and the subclinical microscopic disease. Additional margins are added to define a "planning target volume" to take into account organ movements, uncertainties in patient set-up and on beam geometry [8].

2.2. The treatment planning

The "treatment planning" process includes the choices and evaluations (by a software simulation) of the dose delivered to the patient. The compromise is of course to deliver a particular dose to the tumor by minimizing the dose in healthy critical parts. Due to the Bragg peak abrupt shape, accuracy has to be considered sometimes in dose (Gy) and sometimes in distance (mm). The lateral uncertainties are within 2 mm [6]. The distal accuracy (dose in depth) seems to be a harder problem, because of the complex diffusion effects due to the heterogeneity of the tissues [9] [10]. Works done at P.S.I. give an estimate of 1.4 mm error for intracranial localisation [11].

2.3. The radiobiology efficiency

Major uncertainties are commonly suspected on the real Radiobiological Efficiency (R.B.E.) because of the variety and complexity of the tissues and treatment schemes (doses, fractionation, ...). The reference procedure is performed with cells which are quite far away from human tissues complexity. The experimental values for in vivo and in vitro RBE related with protontherapy are in the range 1 - 1.2. [12][13]

3. Dosimetry and end-line considerations

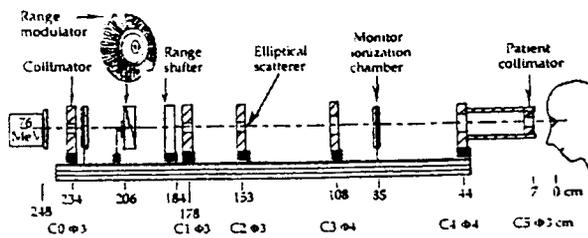
3.1. Dosimetry quality control of the beam

The dosimetry measurement of the beam must be with specific tolerances in relation with the modulated Bragg peak shape. At CPO, the limits are 2% for the dose variation (for the absolute dose or for the dose variation on the spread out Bragg peak) and 1mm for the range.

3.2. Accessories

The beam is conformed to the tumor shape by the use of collimators, modulators, scatterers and compensators (fig.2)[6][7]. Each modification of the beam introduce uncertainties which are hardly to be prestimated theoretically. At CPO, an experimental database has been built to anticipate all these effects during the planification of the personalized line.

Fig 2 : the ophthalmological line of CPO



3.3. Patient positioning

The patient positioning system is based on the implantation of opaque clips in the eye or on the base of skull detectable by radiographs during the positioning procedure [14]. Measurements on the precision has been done at CPO for the eye treatment [15] and the result gave an uncertainty less than 0.5 mm. Others studies made at Boston [16] for the intracranial treatment give a 1mm precision for a seated position.

The major problem for the positioning seems to be in the movement of the patient inside the contention mask (2 mm)

or in the mobility of the organ treated (ex : scanner images are done in a layed position and the treatment is realized seated).

3.4. The routine uncertainties

The actual treatment line of CPO is not automatized (personalised absorbers and modulators) : we have also to switch energy daily between the intracranial treatment configuration and the ophthalmological configuration. These two factors are sources of mechanical and human mistakes. Even with a quality assurance procedure, this point is crucial. The time and the effort devoted to quality controls in protontherapy are still one of the most important components of the daily activity of the staff.

4. General accuracy considerations

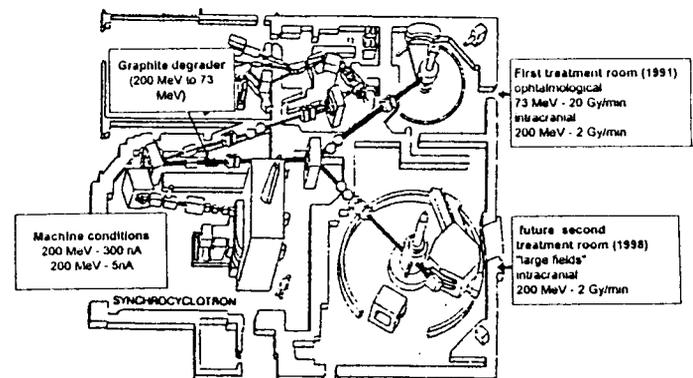
After this general description of sources of unaccuracy, some general remarks can be done on this complex problem :

- The uncertainties are systematic or aleatory. In case of single session treatment, each uncertainty has a direct incidence on the final accuracy. In a fractionned scheme, the uncertainties with a random distribution (usually gaussian) are less influent.
- the general discussion about accuracy must be also considered as a clinical problem (results of long-term tumor control) and not only as a problem of exact physics.

5. Beam and machine considerations

5.1. The CPO facility

fig 3 : The CPO facility



The machine always delivers a 200 MeV proton beam. For the ophthalmological treatment (usually the morning) the current extracted is 300 nA and the energy is degraded to 73 MeV by a graphite degrader located in the middle of the beamline. The dose rate for the tumor is about 20 Gy/min. For the intracranial treatment, the current extracted is about

5nA, it goes directly to the optical bench. The dose rate delivered to the tumor is about 2 Gy/min.

5.2. Energy and current considerations

The range of the beam is in direct relation with its energy. For protontherapy, this parameter must be particularly accurate ($\ll 1\text{mm}$). At CPO, the opportunity of using a synchrocyclotron is quite nice since the principle of this machine is to produce stable energy beams. Furthermore the last big magnet before the end-line plays the role of a spectrometer. The only trouble we have on the energy stability is the fact that the main magnet of the machine has a big thermic inertia in direct relation with the magnetic stability. This disable us from delivering a convenable beam during the first 4 hours of the monday startup. We have also to keep this magnet powered during the nights.

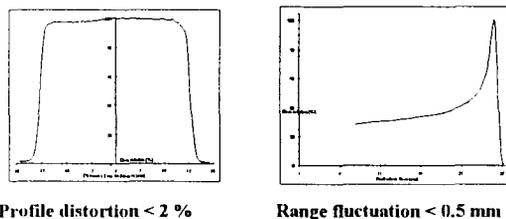
Concerning the current, there are less constraints because the last ionization chamber located at the end of the beam line counts the exact dose delivered. So, we just have to follow roughly the dose rate prescribed and we accept variations of 10 % in the current.

5.3. Experimental approach to follow dosimetry requirements

Beside the considerations on the energy and the current produced by the machine, the main discussion for both energies deals with the size and the position of the beam at the entrance of the treatment room. Because of the complexity of the beam line, we decided to have an experimental approach of the problem.

We have first defined the acceptable variations for the dosimetry references : Bragg profile and lateral profile (fig. 4). Then we measured the effect induced by variations of each of elements of the beamline (field for the big magnets and currents for the electromagnetic channel, the steerers and the quadrupoles). Finally, through our automation and supervisor network, we can detect any fluctuation of the parameters out of the bounds.

Fig 4 : dosimetry requirements for fluctuation dues to machine or beamline



5.4. The daily control of the beam

The startup procedure :

- machine parameters are set to preset values

- dosimetry : normalisation of the Bragg (thin absorber) , normalization of the position by tuning on a vertical magnet and a horizontal one, rough ajustement of the current (ion source delay and shutter)
- personalized dosimetry

The permanent survey of the beam :

- in-line (intrusive) : the monitoring ionization chamber. This is a multisector chamber which informs in case of any fluctuation in the position of the beam.
- off-line (indirect) : readout of the control beamline parameters and real-time comparaison with the acceptable margins (cf §5.3.).

5.5. S.C. 200 specificity and projects

The synchrocyclotron is an old and sophisticated machine. It requires an heavy maintenance programme for keeping its reliability. Concerning the control, many improvements has been done since 1990 to automatize the control. During the nuclear physics time the tuning required many hours, indeed the operations were done manually and the accuracy expected was higher. Actually the startup or the energy modification of the beamline take about 30 minutes.

It must be also mentionned that the " physics time " has left to the operators some " feeling touch " in the tuning of the machine which is not always good for the reproducibility of the beam.

The actual projects in relation with the accuracy of the beam are :

- implementation of diagnostics in the beamline
- automation : upgrade in the electronic technology devoted to the readout of the parameters, programmable absorber, programmable multi-range modulator.

5.6. Summary of the machine considerations

The synchrocyclotron have enough possibilities to deliver an accurate beam for our actual application. The only critical point is in the reproducibility in the position of the beam. We manage this point by a general experimental approach.

Concerning the organization, the best way to obtain an adequate beam is to involve technical staff both in machine and dosimetry instrumentation.

6. Conclusion

This general overview shows that accuracy of the beam delivery is only one of the step in the loop of the protontherapy accuracy. Of course, technical uncertainties in the treatment delivery can not be justified using the argument of large uncertainties in others fields ; in particular because the actual spread out of protontherapy technics will probably improve weak links.

At CPO, we manage the constraint of reproducibility of the beam by an experimental approach.

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