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PROTON BEAM THERAPY AND IMPLICATIONS FOR HOSPITAL DESIGN IN AUSTRALIA

By James Gungl

ABSTRACT

Proton Beam Therapy (PBT) is a cutting-edge radiation therapy technique which allows ionising radiation to be delivered in a precise and controlled manner for the treatment of cancer. The technology is a significant advancement over conventional X-ray based radiotherapy that is typically administered by LINAC machines. PBT uses protons to deliver the radiation treatment, which allows the peak radiation dosage to be directed at a tumour site and significantly reduce radiation damage to the surrounding healthy tissue.

Demand for PBT treatment is increasing worldwide, with over 70 PBT facilities now operational and a further 40 in construction. While Australia currently has no operational PBT facilities, feasibility and planning studies are currently being undertaken in a number of states and it appears likely that a PBT facility will be constructed within the next few years.

This article presents a discussion on the design challenges which may be faced by healthcare engineers in the development of an Australian PBT facility to accommodate this advanced medical technology.

WHAT IS PROTON BEAM THERAPY

Proton Beam Therapy (PBT) is a form of external beam radiation therapy which utilises ionising radiation to destroy cancer cells. External beam radiation therapy has traditionally been administered to patients via Linear Accelerator (LINAC) machines, which deliver high energy X-ray beams to damage the DNA of cancer cells, to kill them or limit their reproduction. The X-ray beam, while highly effective in destroying the cancer cells, also deposits energy along the path of beam travel meaning patients may also be subjected to radiation damage to healthy tissue in the path that the beam enters and exits the body. This entry and exit dosage limits the use of this treatment technique around sensitive areas of the body such as the brain, eye, and spinal cord.

The major advancement Proton Beam Therapy provides over traditional LINAC based radiotherapy is that the radiation dosage can be precisely controlled to administer the dosage more locally at the tumour site, and significantly reduce the exposure to the surrounding healthy tissue.

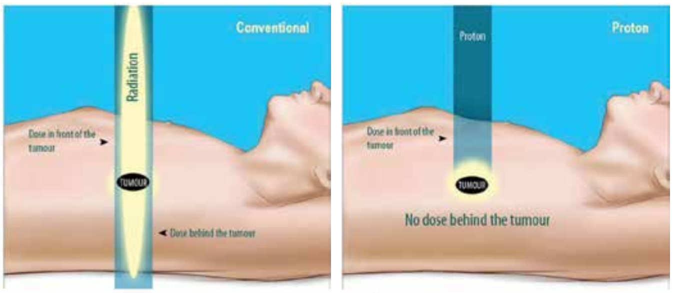

Figure 1 – Comparison of radiation dosage paths between PBT and conventional X-ray radiotherapy (source: http://www.proton-cancer-treatment.com/for-patients/advantages-of-proton-therapy/).

As evidenced by its name, PBT utilises protons to deliver the radiation dosage to the tumour site. The charged proton particles enter the body travelling at a very fast velocity, losing energy as they begin to travel through the body. The protons exhibit a phenomenon called a Bragg Peak, whereby the energy lost by the particle peaks significantly just before the particle comes to rest. During the administering of proton beam therapy, the radiation therapist can adjust the depth in which this peak occurs so that the maximum radiation dosage is precisely applied to the location of the tumour, with effectively no radiation dosage occurring behind the tumour site.

This controlled application of radiation dosage allows PBT to be utilised in areas of the body where traditional X-ray based radiation therapy would be unsuitable due to risk of significant side effects from radiation exposure, as indicated in Figure 2. Limiting

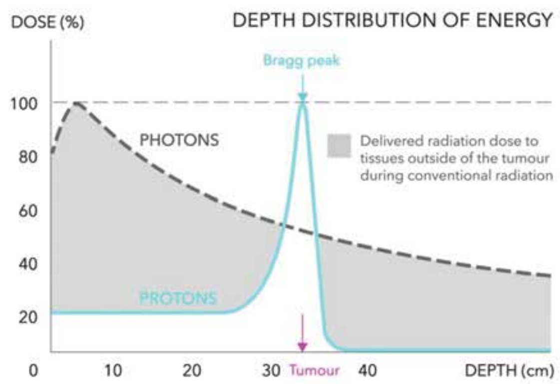

Figure 2 – Delivered radiation dosage for PBT and conventional X-ray/ photon radiotherapy (source: http://www.proton-cancer-treatment.com/ proton-therapy/principles-of-proton-therapy).

radiation exposure to healthy tissue is also a major consideration for paediatric cancer treatment, to minimise long term radiation risks for developing children.

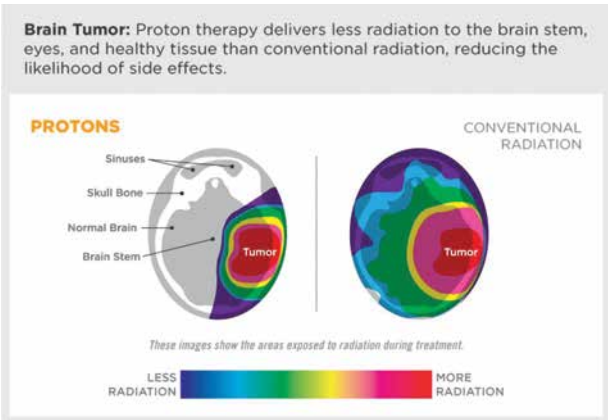

Figure 3 – Comparison of radiation exposure between PBT and conventional X-ray radiotherapy (source: http://www.provisionproton. com/about-proton-therapy/advantages-of-proton).

While there are clear advantages of PBT over traditional X-ray based radiation therapy options, the technology and infrastructure required to produce, distribute, and apply the protons beam for use in patient treatment is of a scale and complexity unlike any other medical equipment seen in today's modern hospitals.

HOW DOES PROTON BEAM THERAPY WORK

A patient receiving a PBT treatment will typically have very little appreciation to the scale and complexity of the supporting infrastructure behind the walls of the treatment room and back of house areas of the facility.

The PBT treatment generally occurs with a patient entering a treatment room and being positioned on a treatment couch, which is then precisely moved into position inside the treatment area.

Figure 4 – PBT Patient Treatment Room at the Children's Hospital of Philadelphia (source: http://www.newswise.com/articles/proton-therapy-carries-precise-potent-punch-against-children-s-cancers).

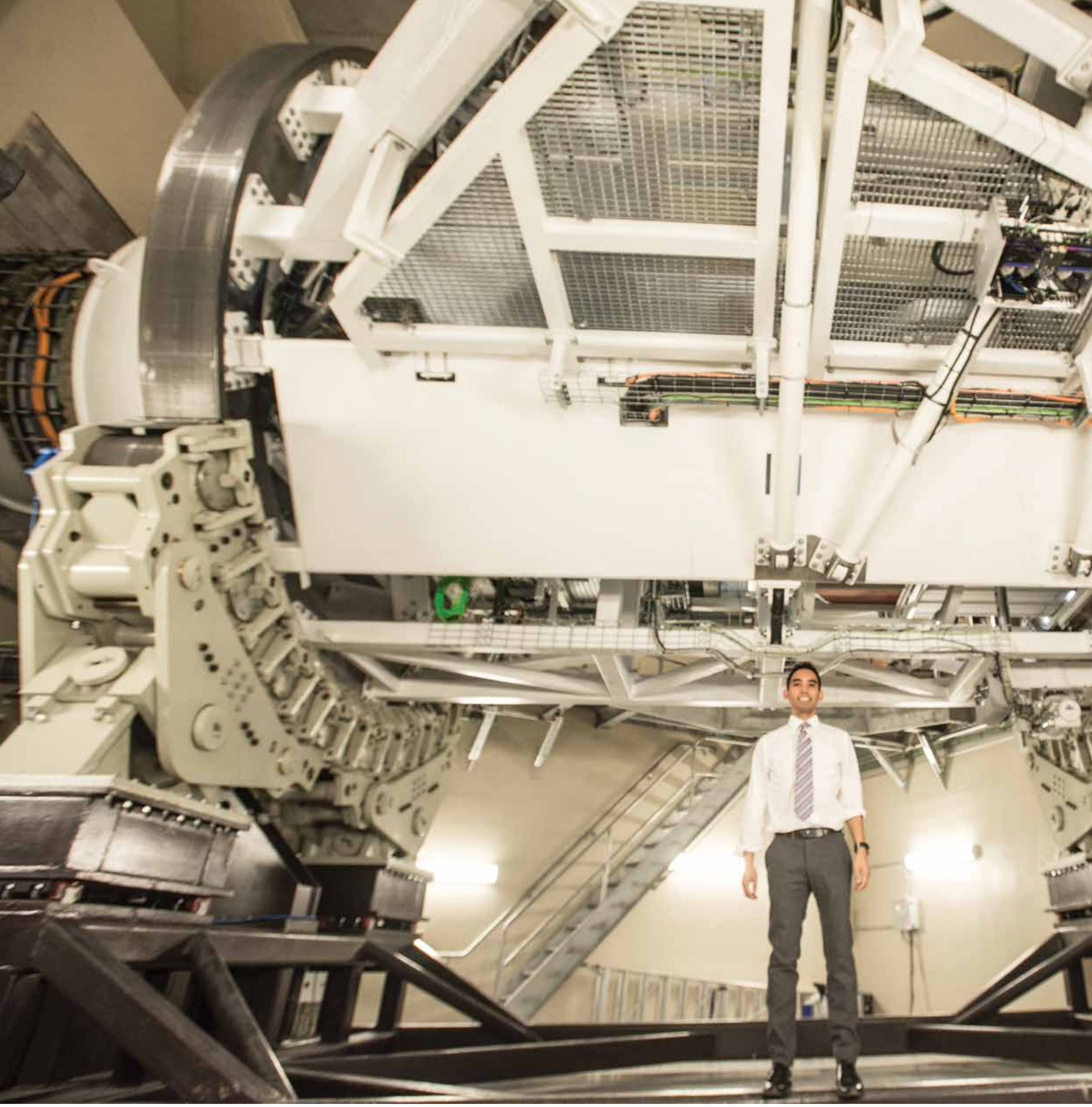

Figure 5 – PBT Gantry at the Texas Centre for Proton Therapy (source: http://www.texascenterforprotontherapy.com).

To direct the proton beam to the correct position to impact the tumour, most PBT facilities utilise a 360 degree rotating gantry to allow the delivery position of the beam to be adjusted to any point around the patient. The patient's view of the gantry is generally limited to the rotating element seen in white surrounding the patient couch in Figure 3 above. The physical structure of the gantry behind the treatment area is extremely large. Individual gantries for each treatment room can weigh up to around 200 tonnes each and require a three storey void to accommodate the structure.

The proton particles are generated by an ion injector which uses an electric field to separate hydrogen atoms into negatively charged electrons and positively charged protons. Protons are transported through a vacuum tube into a linear accelerator to accelerate the protons and significantly increase the proton's energy. The protons then enter a particle accelerator, such as synchrotron or cyclotron to further increase the energy of the protons by accelerating the particles to a speed of up to 200,000 km per second or around 70% of the speed of light.

Figure 6 – Mayo Clinic synchrotron and linear accelerator assembly (source: http://www.medgadget.com/2011/05/hitachi-proton-beam-therapy-coming-to-mayo-clinic.html).

Figure 7 – Beam transfer line at Texas Centre for Proton Therapy (source: http://www.texascenterforprotontherapy.com).

The high velocity and high energy protons exit the particle accelerator and are transported via a vacuum tube through a beam transfer line at the rear of the gantry rooms. Large liquid cooled electromagnets along the beam line allow the protons to be directed to individual treatment gantries for delivery to each patient treatment room.

The high velocity and energy of the protons is required to allow the radiation dosage to penetrate to required treatment depths within the body. The infrastructure required to generate particles in these conditions requires extremely advanced and high precision equipment, which is not only significant in footprint and energy usage, but is often orders of magnitude higher in capital cost than conventional X-ray based radiotherapy equipment.

Proton Beam Therapy has significant advantages over conventional radiotherapy; however the scale, complexity, and cost to implement these systems has meant that PBT is currently only available at a select number of specialist facilities worldwide. Demand for this treatment continues to grow, and with further advances in equipment technology to reduce the size and cost of the equipment the feasibility of providing these specialist facilities should also continue to increase.

OPERATIONAL PROTON BEAM THERAPY FACILITIES

Current estimates are that in excess of 100,000 patients have now been treated worldwide with Proton Beam Therapy.

As of February 2017, there are currently over 70 PBT facilities in operation worldwide, with the majority of these facilities located in North America, Japan and Europe. A further 40 facilities are in construction.

Australia has no operational PBT facilities, with the closest facilities in our region being located in China, Japan, and South Korea. At this time only a very select number

Figure 8 – World distribution of operational PBT facilities (source: http://www.proton-cancer-treatment.com/proton-therapy/proton-therapy-around-the-world/).

of Australian patients have access to PBT treatment, having to travel overseas for treatment, funded by the Federal Government at a cost of around $200,000 per patient.

In recent years there has been significant interest in PBT technology from a number of organisations in Australia. Master planning and feasibility studies are currently being undertaken across sites in Victoria, Queensland, South Australia, and New South Wales, with these facilities at various stages of planning and development.

Proton Therapy Australia, a Sydney based company established in 2006, were one of the first groups to explore the implementation of PBT in Australia. In 2014 they signed an Alliance with The Mater Health Services to collocate a facility in Queensland, with an aim of having an operational facility within the next few years.

South Australia has also expressed an aspiration to provide the nation's first PBT facility, with plans to develop a second South Australian Health and Medical Research Institute (SAHMRI) for this purpose in the Health and Biomedical precinct adjacent the new Royal Adelaide Hospital facility. The facility is estimated to require investment of approximately $280M and is in the process of securing funding to undertake the project at present.

In late 2016, the Victorian government committed $50M to progress the planning for a PBT facility in Parkville, Melbourne, to be operated by the Peter MacCallum Cancer Centre. The Parkville location is particularly favourable due to its proximity to the recently completed Victorian Comprehensive Cancer Centre, as well as the Royal Children's Hospital.

It seems highly likely then, that within the next few years Australia will have its first operational Proton Therapy facility. In order to get to this point, there will be a number of planning and design challenges to be faced by local healthcare engineers to ensure any new facility can accommodate such an advanced and unique medical treatment system.

IMPLICATIONS FOR PBT FACILITY DESIGN IN AUSTRALIA

Design Planning

There is no 'one size fits all' when it comes to the architectural and building services planning for PBT facilities. There is significant variation between different equipment vendors for room sizes, locations, shielding requirements, and supporting building services infrastructure. The technology utilised by different manufacturers in their PBT systems varies too. Particle accelerators in some PBT system utilise a contained cyclotron and others favour a synchrotron arrangement; the two technologies having significantly different requirements for supporting power and cooling infrastructure. Most PBT facilities therefore require early engagement of a PBT vendor with the facility being specifically designed around the individual requirements of the chosen system.

Radiation Shielding

One of the most significant design challenges for the implementation of PBT is providing sufficient radiation shielding to limit the exposure of patients and staff to within safe levels. The radiation generated by the PBT equipment generally requires a specialist radiation physicist to be engaged as part of the design team to assist with the calculation of required shielding wall thicknesses and provide guidance on allowable room entry locations. PBT facilities are often located beneath ground level; however they still typically require concrete shielding walls between 2.5m to 3.5m thick to protect adjacent clinical areas from the PBT infrastructure. Construction implications of achieving wall thicknesses of this magnitude needs to be carefully considered by the structural engineer and construction team.

Structural Design Challenges

The constructability of forming thick shielding walls up to 3.5m is an important consideration for the structural engineer responsible for the design of the surrounding structure. Analysis of local concrete composition, particularly in regards to residual water content, may also be necessary for consideration in shielding calculations by the radiation physicist.

The precision required to transport the highly energised proton particles along the beam line requires the floor flatness and deformation of the installation to be completed within an extremely fine tolerance. Any deviations long term can have significant implications to the accuracy and efficiency of the system.

Access to skilled local trades in forming the concrete structure and ensuring a quality finish within required tolerance levels has historically been a challenge for the construction of PBT facilities.

areas of the facility being constructed requires careful planning. Plant replacement strategies also need to be developed early in the design to ensure large components such as a cyclotron which may weigh in excess of 100 tonnes can be removed and replaced from the facility if required. The significant shielding requirements and thick concrete bunker walls surrounding the PBT equipment constrain where replacement paths can be provided.

Figure 9 – Construction of gantry shielding walls at Maryland Proton Therapy Centre (source:http://www.schusterconstruction.com/projects/maryland_proton_treatment_center.html).

Figure 10 – Cyclotron lift at Skandionkliniken PBT facility in Sweden (source:http://www.cranestodaymagazine.com/news/heavy-lifting-install-cyclotron-in-sweden-290513/).

Coordination of services entering radiation shielded areas

Given the significant radiation containment challenges associated with PBT facilities, it is essential that all services which need to enter the gantry, beam line and particle accelerator areas need to be carefully coordinated and have entrance locations verified with the radiation physicist.

Typically services must enter treatment areas via the maze entry into the room, requiring a significant amount of ductwork, pipework, and cable trays in a highly congested and confined zone. If a particular service is missed, or cannot be coordinated in the allocated areas, it is typically not an option to core additional penetrations at a later date as any penetration through shielding walls will generally need to be pre-cast, configured in an arrangement eliminating a direct line of sight, and reviewed to be acceptable by the radiation shielding consultant.

Installation, Commissioning, and Plant Replacement

The equipment installation, testing, and commissioning process for the highly intricate PBT components can exceed 12 months. Programming of construction works and the separation of PBT areas from other

Power Quality and Quantity

The PBT equipment often requires dedicated substations, electrical infrastructure and distribution systems to support the energy intensive operation of the linear accelerator, particle accelerator, beam line electromagnets, and gantry actuators. The PBT equipment and supporting services infrastructure may require in excess of 3 MVA of supply capacity; with redundancy, standby power, and UPS infrastructure also key design considerations in the design of the distribution system. Power quality must also be maintained within a fine tolerance including long term voltage variations, imbalance between phases, frequency variations, and harmonics limits.

Process Cooling

The components of the PBT infrastructure generate considerable heat during the production and transport of the protons. Components including the linear accelerator and the electromagnets serving the beam line are water cooled and require dedicated process cooling loops to effectively dissipate the generated heat. Process cooling requirements for PBT equipment can be in excess of 1000 kWr in heat rejection capacity, with requirements varying between individual PBT equipment vendors and being dependent on the number of treatment gantries. Key design considerations for these systems include ensuring water quality parameters such as conductivity are controlled and sufficient redundancy and monitoring capability is incorporated.

Air conditioning and ventilation

Temperature stability and uniformity of temperature distribution is an important design consideration for the air conditioning and ventilation systems given the precision of the PBT equipment. Humidity control must also be considered, particularly to limit any potential for the formation of condensation and to protect bare metal components from corrosion.

Industrial Gases

Industrial gas requirements vary between different PBT vendors, but may require instrument grade compressed air, nitrogen, oxygen, and hydrogen. The transport, storage, and handling of these gases must be carefully planned with the design team and facilities engineers, particularly in the case of hydrogen given its highly flammable nature.

CONCLUSION

With planning and feasibility studies well underway in Australia, it seems likely that an Australian PBT facility will be operational within the next few years. This advanced technology will require Australian healthcare engineers to implement facility design and building services infrastructure solutions unlike those seen in any of today's local hospital facilities.

PBT will be a new and exciting technological advancement when it arrives into the Australian market. Internationally though, there continues to be further rapid development in the field of particle therapy, with a focus on developing this technology to use even heavier particles such as carbon ions. By utilising heavier carbon ions considerably more energy can be deposited into a tumour, to significantly reduce the required number of treatment sessions. The energy, scale and cost associated with generating the carbon ions is magnitudes higher again than that of proton therapy, which has limited this technology to only a handful of specialised facilities around the world. The considerable research and development which is occurring in this field and the clinical benefits which have already been demonstrated will ensure that particle therapy systems will become increasingly relevant to Australian healthcare engineers developing hospital projects in the upcoming years.

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