Original Article

The Nano-X linear accelerator: A compact and economical cancer radiotherapy system incorporating patient rotation

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Abstract

Rapid technological improvements in radiotherapy delivery results in improved outcomes to patients, yet current commercial systems with these technologies on board are costly. The aim of this study was to develop a state-of-the-art cancer radiotherapy system that is economical and space efficient fitting with current world demands. The Nano-X system is a compact design that is light weight combining a patient rotation system with a vertical 6 MV fixed beam. In this paper, we present the Nano-X system design configuration, an estimate of the system dimensions and its potential impact on shielding cost reductions. We provide an assessment of implementing such a radiotherapy system clinically, its advantages and disadvantages compared to a compact conventional gantry rotating linac. The Nano-X system has several differentiating features from current radiotherapy systems, it is [1] compact and therefore can fit into small vaults, [2] light weight, [3] engineering efficient, i.e., it rotates a relatively light component and the main treatment delivery components are not under rotation (e.g., DMLCs). All these features can have an impact on reducing the costs of the system. In terms of shielding requirements, leakage radiation was found to be the dominant contributor to the Nano-X vault and as such no primary shielding was necessary. For a low leakage design, the Nano-X vault footprint and concrete volume required is $17m^2$ and $35m^3$ respectively, compared to $54m^2$ and $102m^3$ for a conventional compact linac vault, resulting in decreased costs in shielding. Key issues to be investigated in future work are the possible patient comfort concerns associated with the patient rotation system, as well as the magnitude of deformation and subsequent adaptation requirements.

Introduction

Radiotherapy is a cost effective treatment for cancer. However, it has high initial costs associated with its establishment, such as the purchase of linear accelerators and the construction of specialized shielded rooms (vaults) (1). Numerous reports have emerged on the worldwide lack of linear accelerators and the annual rise in cancer incidence will spark a growing crisis (2-4). Solutions are required to reduce the cost of systems and vaults without compromising on radiotherapy delivery accuracy.

Radiotherapy is moving towards image-guided four-dimensional radiotherapy (4DRT) which compensates for anatomic changes during treatment improving treatment delivery accuracy and outcomes (5). The requirements of this technology are: [1] real-time intrafraction imaging of changes in anatomy using onboard or in-room kV and/or MV imaging systems (6); [2] real-time position monitoring/tracking, possibly with the use of implanted markers, to identify any changes of anatomy (6); and [3] real-time treatment adaptation to compensate for the real-time changes in the anatomy using either beam adaptation systems such as dynamic leaf collimators (DMLC) (7,8) and beam gating (9) or couch adaptation systems (10). The development of technologies to allow the implementation of adaptive RT in the clinic setting are ongoing (11,12), and recent clinical implementation of adaptive RT has been established for prostate cancer (13).

Based on the above requirements, we propose a method of introducing cost savings in the design of an advanced technology radiotherapy system and vault. Given the necessity of a rotation system in radiotherapy, a more economical approach in terms of engineering is to rotate the smallest component, the patient, rather than the gantry (14). The potential costs savings of utilizing this design are in its engineering efficiency, compact system design and minimal shielding requirements, as it allows the use of a fixed beam linac, we have called the design the

Nano-X (Nano = small, X = X-ray). A rotating gantry linac design is heavy, bulky and necessitates primary shielding in the ceiling and two side walls (other than the floor). Limiting gantry rotation will minimize shielding costs (14).

Economical conventional rotating gantry linacs presently on the market are the Elekta Compact (Norcross, GA) and the Varian Unique (Palo Alto, CA), which are single energy 6 MV linear accelerators and can fit in relatively small vault footprints with cost savings in the concrete volume required. The recommended and commonly used internal space (excluding shielding) requirements for a treatment vault is 6.1 × 6.7 m^2 (15,16), however the smallest internal vault footprint found in the literature was for a Varian Silhouette linac, 4.9 × 5.8 m^2 (17).

In this study, we describe the design and shielding requirement of the Nano-X linac and its potential cost savings compared to a compact conventional linac. The experiences and challenges of patient rotation in radiation oncology and neurology are expanded on in the discussion section.

Materials and Methods

The Nano-X system design criteria

In the design of an economical cancer radiotherapy facility, a principal aim was to decrease the size of the current compact radiotherapy system and vault. In order to do this, we applied three *a priori* criteria: [1] the system design would utilize minimal space and cost approaches in hardware engineering and building; [2] the designed system's delivery should match current standards best practice in low energy systems range, i.e., enabling interfraction and intrafraction (real-time) imaging using MV and kV imaging systems, respectively, as well as delivering intensity modulated radiotherapy (IMRT) and volumetric modulated arc therapy

(VMAT) and [3] the system design should fit with the progress of radiotherapy technology development, i.e., enable the delivery of real-time adaptive radiotherapy.

Addressing criteria [1] A compact economical solution

Patient rotation system: The rationale for a patient rotation system rather than gantry rotation is to reduce the vault footprint and cost. To enable radiotherapy, the same functionality of gantry rotation and control needs to be considered in the patient rotation system, e.g., angular position, rotation speed and acceleration and control of the dose delivered and dose rate. By using the same functionality as a rotating gantry and changing the frame of reference, a rotating patient system enables IMRT and VMAT delivery. A patient rotation system prototype design with full rotation (360°) in the superior-inferior axis and translational motion in the superior-inferior direction is shown in Figure 1. Further developments could include additional rotational and translational degrees of freedom. The patient has whole body support through medical grade restraint systems along the couch length. Other immobilizing mechanisms such as vacuum cushions could be used.

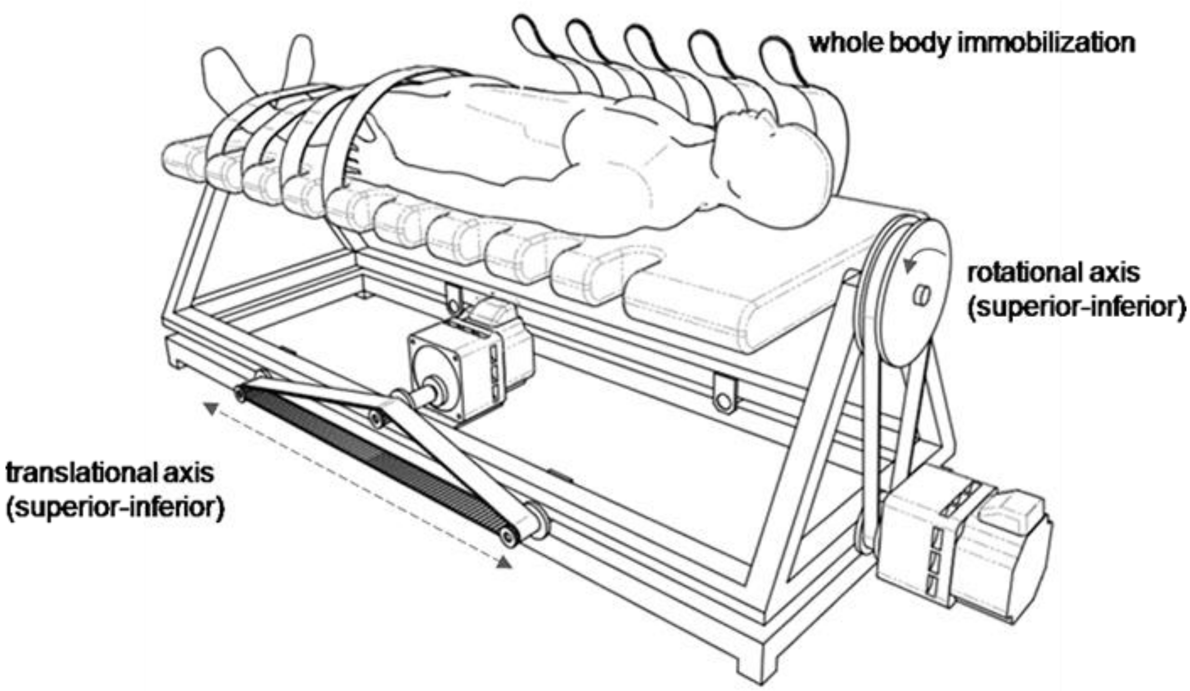

Figure 1: Prototype patient rotation system design with 360^0 rotation in the superior-inferior axis and translational motion along the superior-inferior axis. The center of rotation is approximately about the patient center of mass.

Fixed vertical linac: Using a patient rotation system, the Nano-X system design utilizes a 6 MV fixed beam vertical linac. Linear accelerators with varying leakage factors are available. For example, the S-band Varian Linatron-M has leakage factor options ranging from standard 10^{-3} to 10^{-6} (Varian Linatron; Varian Medical Systems, Palo Alto, CA). In this study, we investigated leakage factors of 10^{-3}, 10^{-4} and 10^{-5}.

Addressing criteria [2] Designed to deliver current standard of care

A modern linac needs to offer image guided radiotherapy (IGRT), IMRT and VMAT solutions. kV and MV imaging systems are integrated in the Nano-X system design to facilitate IGRT. For IMRT and VMAT, by using rotational symmetry of the patient and gantry, as well as the multileaf collimator, IMRT and VMAT could be delivered.

Addressing criteria [3] Real-time adaptation to tumor motion

In patient rotating systems the issue of accounting for organ deformation will be of greater concern as larger degree of motion will be experienced due to the rotation. As a result it is important that the Nano-X system is equipped with real-time tumor positioning and motion tracking, as well as tumor motion adaptation technologies (18). Tracking technologies dealing with real-time motion during treatment are currently being developed. It has previously been demonstrated that a single kV x-ray imager integrated with DMLC adaptation can be used to track translational tumor motion with 2 mm geometric accuracy for conformal, IMRT and VMAT IMRT-class treatments (11,19).

Equipment space requirements

The minimal internal vault space required for safe clinical operation of the equipment was calculated. Equipment not required to be in the room was modeled to be kept outside of the vault, including storage. The internal vault space required for the Nano-X system was compared to a conventional compact linac system.

Shielding design considerations and total vault footprint

The shielding requirements for the Nano-X system were calculated using the standard framework for primary, scattered and leakage radiation. The barrier transmission was calculated based on a shielding design goal of 0.05 Gy/year and a workload of 29,000 (Gy/year) which was obtained from the average value of 400 Gy/week for 6 MV accelerators (20,21). The occupancy factor of 10% was used for the ceiling wall and 100% for all other walls (22). The IEC leakage requirements limit leakage factor to 10^{-3} through the source housing (22). In IMRT treatments, the leakage radiation is substantially higher and the IMRT factor can range from two to 10 (22). For these calculations, an IMRT factor of 10 and IMRT utilization of 80% was assumed. This resulted in a workload of 254,000 Gy/year in the calculation of the leakage radiation barrier. The thickness of the barrier was calculated from tenth-value layers (TVLs) based on 6 MV beam energy and ordinary concrete shielding. The linac was modeled at the center of the vault. The vault footprint was deduced and compared to a conventional compact rotating gantry linac system vault footprint for which the same shielding design goals and assumptions were used.

Evaluation of potential cost savings of the Nano-X system

We examined potential cost savings of the Nano-X system compared to a compact conventional system.

Results

The Nano-X system design

The design prototype and a schematic demonstrating the main functional components of the Nano-X system are shown in Figure 2. In addressing the three design criteria, the proposed Nano-X system utilizes a vertical linac, DMLC for intensity modulation and real-time adaptation and kV and MV systems for image guidance. A patient rotation system (Figure 1) is used to achieve multiple beam angles and VMAT treatments.

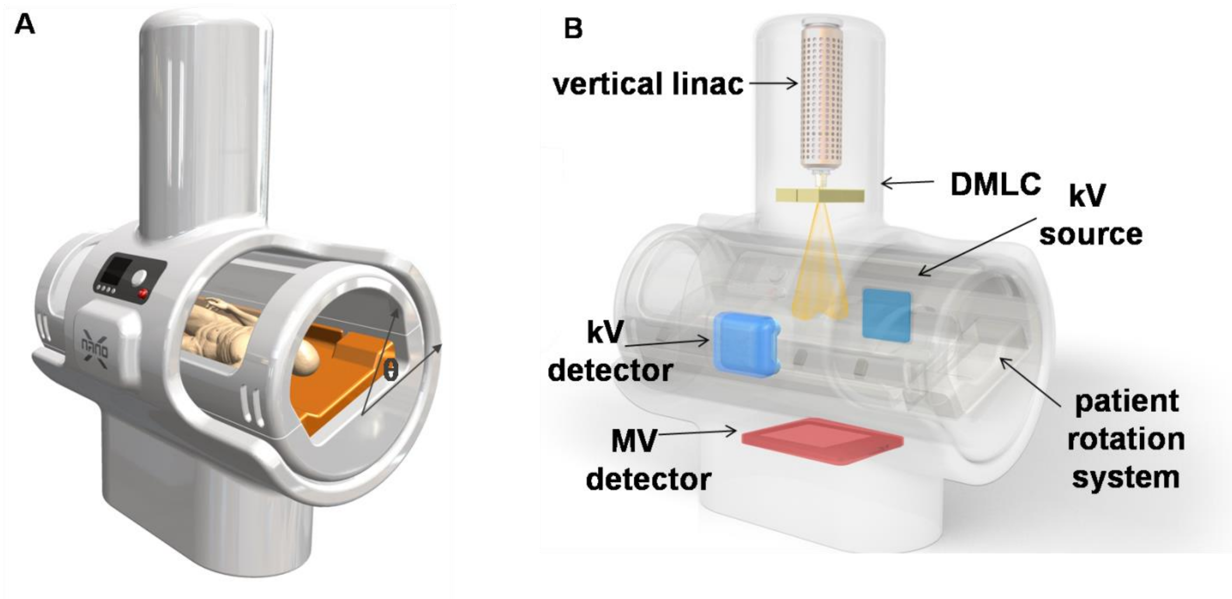

Figure 2: (A) Proposed Nano-X prototype design. (B) Schematic of the Nano-X main functional components, showing the vertical linac, DMLC for intensity modulation and real-time adaptation, kV source and detector and MV detector for image guidance and the patient rotation system for multiple beam angle and VMAT treatments.

Equipment space requirements

An estimate of the internal vault space required for the Nano-X system is 3(L)×3.7(W)×3(H) m^3 where the length of the room would be governed by the couch extension, approximately ± 0.5 m, the width of the room by the width of the couch (with imaging systems attached) and the height of the room by the whole system height, 2.7 m.

Required shielding and total vault footprint

The conventional rotating gantry linac requires both primary shielding and secondary shielding in the vault, with the primary barriers located in the ceiling and the side walls. In a conventional rotating gantry linac vault, the worst case secondary radiation is associated with the scattered radiation just beyond the primary barriers (15). The secondary barriers were required to be 1 m thick. The vault size and shielding for the Nano-X and a conventional compact linac system are shown in Figure 3.

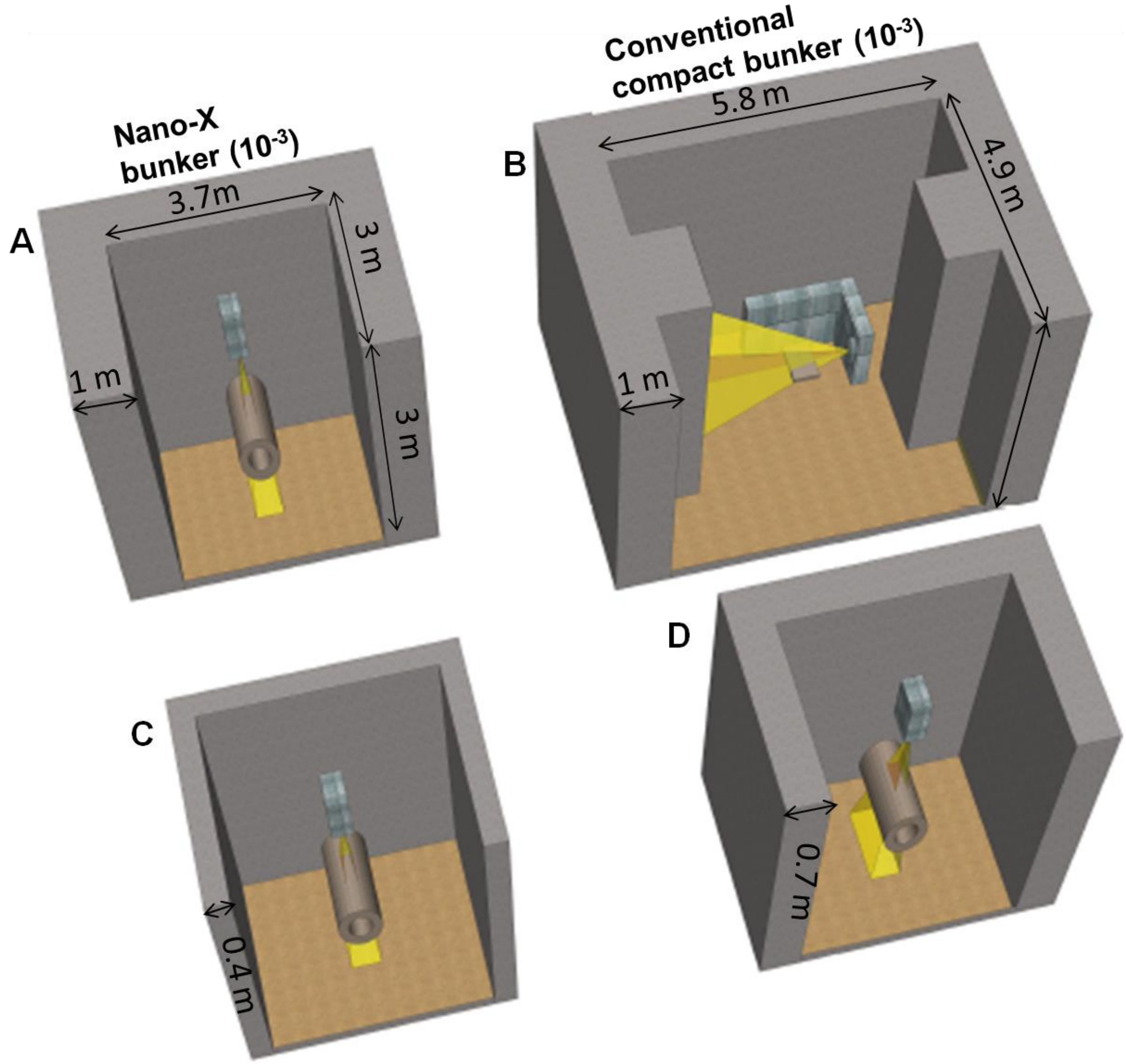

Figure 3: Vault size and shielding for the Nano-X and a conventional compact linac system. (A) Nano-X vault with leakage factor of 10^{-3}. (B) Conventional compact vault with leakage factor of 10^{-3} (C) Nano-X vault with leakage factor of 10^{-5}. (D) Nano-X vault with leakage factor of 10^{-4}. The internal room dimensions and shielding barrier thicknesses are shown.

In the Nano-X system configuration, the primary beam direction is towards the floor, hence only secondary barriers are required in the vault. This assumes that the linac vault is on the lowest level of the building which is almost always the case, otherwise floor shielding would be needed. Unlike in a conventional linac vault, in the Nano-X vault, the leakage radiation is dominant over the scattered radiation when using a standard leakage factor linac head. The required secondary barrier thickness calculated was 1 m. The leakage radiation was made to be below the scattered radiation by the use of a linac head with a lower leakage factor. A leakage factor of 10^{-5} was required to reduce the leakage radiation below the scattered radiation, which resulted in the necessity of a secondary barrier of thickness 0.4 m. Conservative estimates of the shielding requirements for the vaults are shown in Table 1. Note that reducing the leakage factor for conventional linac systems below 10^{-3} does not reduce the shielding requirements as the dominant secondary radiation type is scattered radiation.

Table 1: Comparison of shielding requirements for the Nano-X system and a conventional compact linac system. The vault cost estimate assumes \$8000 per m^2.

System	Leakage factor	Primary barrier	Secondary barrier	Internal vault dimension L × W × H m^3	Vault footprint	Concrete volume	Vault cost estimate	Dominant secondary radiation type
Nano-X	10^{-3}	-	1 m	3 × 3.7 × 3	30 m^2	80 m^3	\$240,000	Leakage
Nano-X	10^{-4}	-	0.7 m	3 × 3.7 × 3	20 m^2	60 m^3	\$160,000	Leakage
Nano-X	10^{-5}	-	0.4 m	3 × 3.7 × 3	17 m^2	35 m^3	\$136,000	Scattered
Conventional compact linac	10^{-3}	Side walls: 1.3 m Ceiling: 1.2 m	1 m	4.9× 5.8 × 3	54 m^2	102 m^3	\$432,000	Scattered
Conventional linac	10^{-3}	Side walls: 1.3 m Ceiling: 1.2 m	1 m	6.7 × 6.1 × 3	70 m^2	131 m^3	\$560,000	Scattered

The vault footprint of the Nano-X system is 30 m^2, which is just over half that of the estimated compact conventional linac vault footprint of 54 m^2 when using a standard 10^{-3} leakage factor as recommended by the IEC (22). Using a machine with a leakage factor of 10^{-5} reduced the vault footprint to 17 m^2. The concrete volume estimates required in the vault construction is 80 m^3 for the 10^{-3} leakage factor and 35 m^3 for 10^{-5} leakage factor for the Nano-X system compared to 102 m^3 for a conventional compact linac.

Cost saving estimates due to Nano-X design configuration

It is difficult to anticipate future system costs which depend on many factors, such as the number of units, place of manufacture, factory set-up costs etc. However, there are many similarities in parts to a conventional linac, such as the linac itself, MLC and MV and kV imaging systems. Therefore, we would expect the Nano-X to cost approximately the same as a conventional linac minus the cost of the approximately 3 ton (23) rotating gantry system plus the cost of the patient rotation system (~150kg) and minus any additional savings from manufacture or service that would be gained by having the main linac components (linac, MLC and imaging systems) fixed rather than rotating.

The shielding requirements

What can be reasonably quantified is the cost of the vault construction, which we estimated to be proportional to the amount of concrete required to build, at a rate of $8000 per m^2. An estimate of the cost of the Nano-X system vault is shown in Table 1. For a standard leakage linac head, the Nano-X ($240,000) saves $306,000 over a conventional compact linac ($432,000). For the Nano-X with a standard leakage factor (10^{-3}), leakage radiation is the dominant factor in the shielding calculations. Further reductions in cost can be made with lower leakage systems e.g., only $136,000 is required for a low leakage (10^{-5}) system.

Discussion

Advantages of the Nano-X system

Approximately 37% of the initial capital required for the establishment of a new radiotherapy facility is associated with the cost of the equipment and vault (24). In this study, we have outlined a new radiotherapy treatment machine design concept, the Nano-X system which has some advantages and disadvantages for use clinically compared to a conventional system. The Nano-X system design combines an advanced light weight compact system and small vault (30 m^2, Table 1) which can potentially be an economical solution to improving the shortage of radiotherapy machines. This system configuration enables cost savings mainly in the shielding. Our calculations show that the patient rotation system can fit into a vault nearly half the size of that needed for a conventional compact rotating gantry system and requires half the amount of concrete. The Nano-X system is able to fit into an even smaller vault footprint, 17 m^2 and requires even less concrete, 35 m^3 (Table 1) when using a lower leakage factor linac. An estimate of the reduction in shielding costs compared to a conventional compact 6 MV linac is approximately $300,000.

These vault footprint estimates are based on utilizing a shielded door rather than a maze in the vault. Whilst the advantage of not using a maze is that the vault footprint can be kept to a minimum, this is balanced by the use of a more expensive shielded door (22). A limitation of the small vault size is that it does not allow long source-surface distance treatments, such as total body irradiation and total skin election therapy.

In high-income countries, the Nano-X's compactness could be appropriate in expensive or space-constrained metropolitan areas to relieve the stress on centralized centers. In rural areas, the economical characteristics of the Nano-X provide a solution to fit with the lower budget per population, and potentially allows for mobile treatments similar to the Tomotherapy on a truck concept.

Major challenges to overcome

Though there may be size and cost savings associated with the Nano-X system, there are major challenges to overcome, and indeed may render the Nano-X impractical. These include patient acceptance of rotation, adaptation technologies to account for patient deformation during rotation, coplanar beam delivery, non-isocentric treatments and patient safety which are discussed below.

The highest priority issues to be investigated in future studies are the patient comfort, claustrophobia and vertigo concerns associated with the patient rotation system. Motion sickness has been reported in studies for fast rotation. In the Human Disorientation Device, 20 pilots-in-training were subjected to horizontal rotations of 10 and 30 revolutions-per-minute (rpm). 'A high incidence of sickness' was observed and 12 of the 20 patients were not able to complete the planned study (25). Similar results were found for a later study of 14 subjects at 20 rpm (26). These studies were performed with much higher rotation than than needed for radiation therapy, where the patient rotation of less than 1 rpm would balance patient comfort and treatment workflow. There are three reasons to hypothesize that most, or at least some, cancer patients would accept slow (<1 rpm) horizontal (roll) rotation:

1. *Radiotherapy patients accept translation:* Three independent groups have studied patient comfort for intrafractional translational motion. Sweeney *et al*. (27) studied 23 patients and D'Souza *et al*. (28) studied 50 patients using a simulated motion pattern. Wilbert *et al*. (29) studied 15 volunteers using correlated and uncorrelated motion. Overall, couch translation is well tolerated and motion sickness was not observed. Indeed, Sweeney *et al*. (27) found, "There is, to our knowledge, no sound data on the subject of potential intolerance to robotic couch motion." These works give us evidence that radiotherapy patients accept translational motion.
2. *Horizontal rotation is used routinely for proton and particle therapy:* The Product Genesis patient positioning device (30) is in routine use for brain cancer patients at the Massachusetts General Hospital Fixed Beam Stereotactic Proton Facility. This device is equipped with five degrees of freedom, two partially rotating axes and three linear translational axes. The couch typically rotates up to 90^0 during patient treatments. 7-10 new patients are treated with this system each week. A single fraction treatment takes ~1 hour with 5-6 beam angles. A fractionated treatment takes ~15 minutes with 1-3 beam angles. Additionally, a partial patient rotating system, $\pm 20^0$, at the Heavy Ion Medical Accelerator (HIMAC) has been used for carbon ion therapy. A literature search failed to find any reported patient comfort or claustrophobia concerns with rotation during radiotherapy.
3. *Multi-plane rotation is used routinely in neurology:* Outside of radiation oncology, a well-known patient rotation system is the Vesticon Omniax system which has complex full-body maneuvers in all three rotational planes. The Omniax (or other similar device) is commonly used to treat benign paroxysmal positioning vertigo (BPPV) which is the most common

vestibular disorder in adults, with a lifetime prevalence of 2.4% (31). Sometimes up to 40 rotations are needed for the treatment of BPPV. A literature search failed to find any reported patient comfort or claustrophobia concerns with rotation for the Omniax, including a 986 patient study (32). Can these results be extrapolated to cancer patients? Although cancer patients are indeed generally in poorer health, and in many cases much poorer health than the general public, balance disorder patients are also generally in poorer health than the general public. Additionally, balance disorder patients by definition have problems with vertigo. Finally, the most uncomfortable rotation plane is pitch when then legs are higher than the head, causing a dramatic change in the pressure and fluid distribution within the body and particularly the brain. For the Nano-X device, only roll rotation is intended for the initial prototype.

Related to the above discussion, there are a number of factors that will determine patient eligibility for a Nano-X treatment. For example patient size, medical co-morbidities, performance status, age and disease site and stage. There will almost certainly be a subgroup of patients who are not eligible for the Nano-X treatment. If the Nano-X is one of several linacs in a facility, then ineligible patients for the Nano-X could be treated on the other linacs. However the proportion of ineligible patients becomes more critical if the Nano-X linac is the sole cancer radiotherapy system in a hospital or indeed a geographic region. Careful design of the final patient transport and rotation system is needed to maximize both patient comfort and the number of cancer sites that can be treated.

Organ motion in conventional gantry rotating radiotherapy treatments is a problem resulting in tumor translation, rotational displacements and deformation (6). In a patient rotating system, the issue of organ motion is likely to be more severe as the rotational motion may introduce larger tumor motion than would otherwise result from treatment using a conventional linac system. This issue would require the incorporation of real-time tumor motion monitoring systems. The development of new technologies which take into account real-time tumor deformation will be necessary (33). Other than organ deformation arising from rotation, organ densities can also change. Lung tissue density has been shown to differ in the prone vs. supine position (34). These changes will also need to be taken into account in treatment planning and delivery.

The current Nano-X system, as envisaged in Figure 2, will not allow for non-coplanar beam delivery. This limitation is common with the current clinical Tomotherapy systems. For the Tomotherapy system, planning studies have been performed for several sites demonstrating that rotation IMRT with co-planar beams gives acceptable plans, and often superior to fixed field non-coplanar IMRT (35-37). Should non-coplanar beams be considered essential, it is possible that the Nano-X design could be adjusted to accommodate some degree of non-coplanar delivery. However, this would add cost which may negate some of the potential economic benefits of the Nano-X system.

The patient rotation system shown (Figure 1) does not allow for translation in the left-right or anterior-posterior directions. Therefore, for non-central lesions, such as peripheral lung lesions, the planning target volume is separate from the isocenter. Such a non-isocentric set-up is common for arc treatments where clearance is an issue. E.g. Ross (38) explain their setup for peripheral lung treatments where 'The isocenter is placed at the lateral midpoint of the table, and vertical midpoint of the patient and immobilization device, approximately 14.5 cm above the table top to allow the gantry full 360° rotation.'

Patient safety issues are also important criteria that need to be addressed in a patient rotation system. Couch safety and an emergency release mechanism are essential. Moreover, the couch needs to be comfortable for treatment times of up to 30 minutes.

Conclusion

A compact advanced radiotherapy system design, 'Nano-X' has been proposed utilizing a patient rotating mechanism. This system design has numerous advantages which can substantially reduce costs associated in the establishment of a radiotherapy facility. Key issues to be investigated are possible patient discomfort, claustrophobia and vertigo concerns associated with the patient rotation system. Through government funding, a prototype Nano-X system is currently being built in Australia.

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