Laser-Like X-Ray Sources for a New Stereotactic Radiotherapy Paradigm

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INTRODUCTION

Alternative forms of x-ray generation offer brighter, lower divergence, and near-monochromatic x-rays as compared to x-rays generated through the Bremsstrahlung process. Such x-ray generation methods include synchrotrons, however, the large storage ring required for synchrotron operation is impractical for a hospital setting. Inverse Compton (IC) x-ray sources produce x-ray beams of similar quality, divergence, and energy as synchrotron x-ray sources[1]. X-ray generation through the inverse Compton scattering process is illustrated in Figure 1 where optical photons are scattered from MeV energy electron beams to produce x-rays in the keV energy range. The main benefit of these IC sources is they can fit inside existing radiotherapy vaults. However, the available literature on the medical applications of these IC beams is limited. **The purpose of this work was to investigate the properties of IC sources for radiotherapy applications through Monte Carlo Simulations.**

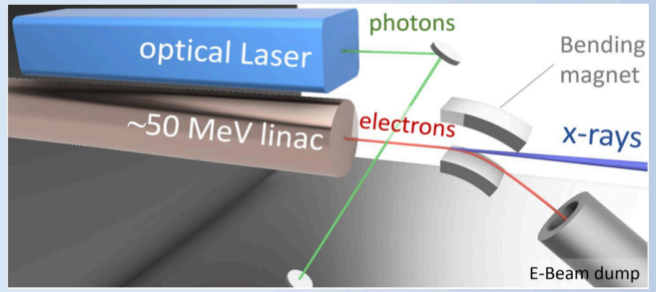


Figure 1: Schematic representation of the IC scattering process.

METHODS

- The egs brachy user code of EGSnrc[2] was used
- The IC source characteristics were obtained from the literature[3-5]. Nominal x-ray energies of 80 keV and 150 keV were considered
- Depth dose and dose profile simulations were performed in a 30x30x30 cc water phantom with and without the presence of a 2 cm bone slab
- The clinical efficacy of the IC x-ray beams was investigated by simulating treatment plans for sites including brain and spine
- The PTV for the brain case consisted of a 3 cm diameter sphere of ICRU 44 brain tissue inside a 20 cm diameter spherical head phantom
- The impact of gold doping was investigated for the brain case for gold concentrations of 0 μg/g to 10 mg/g inside the PTV
- The first spine case consisted of two partial arcs that avoided the spinal cord to treat the half-cylinder PTV
- The second spine case consisted of opposed lateral beams with the isocenter positioned in the center of the PTV
- All IC beam simulations were compared to analogous dose calculations performed in Eclipse™ Acuros® for a clinical 6 MV photon beam

RESULTS

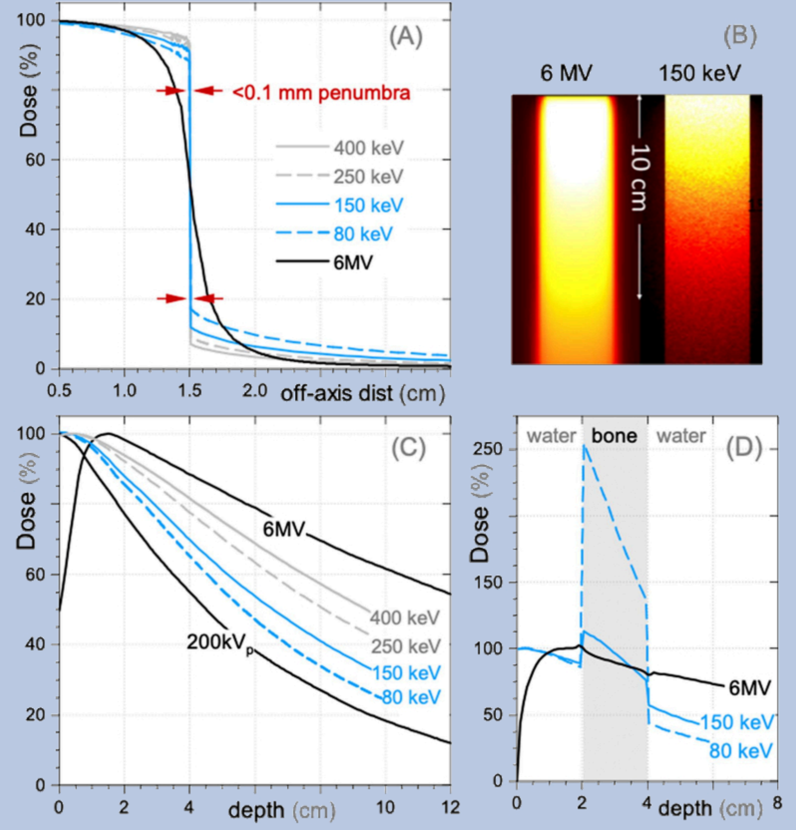
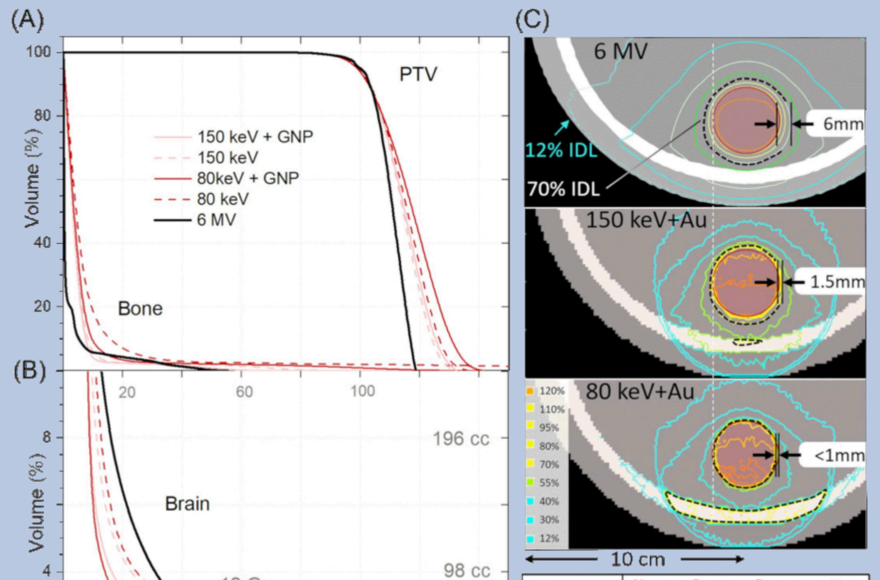


Figure 2: A) Simulated dose profile of a 3 cm-wide IC beam compared to a the clinical 6 MV photon beam model. All profiles were normalized to the central axis and the referenced penumbra values represent the lateral distance between the 80% and 20% dose levels. B) Colorwash dose slice of the clinical 6 MV and 150 keV IC beams in water (depth is vertical). C) Depth-dose curves for the 6 MV and IC beams at four energies, and a filtered 200 kVp Bremsstrahlung beam (Philips RT250 orthovoltage)[6]. D) The depth dose-curves in an inhomogeneous water-bone-water phantom with the 2 cm ICRU 44 bone slab centered at 3 cm depth.



(D)	V_{12Gy} (cc)	D_{max} PTV	D_{max} Bone	CI (Paddick)
80 keV	28.0	133%	243%	0.85
80 keV + GNP	*0.8*	*141%*	*135%*	*0.95*
150 keV	21.6	132%	97%	0.88
150 keV + GNP	*4.6*	*132%*	*69%*	*0.95*
6 MV	38.9	118%	55%	0.78

Figure 3: A) and B) are example DVH's for the single hypothetical brain metastasis case with corresponding axial slices shown in C). Five calculations are shown across three photon energies: 80 keV, 150 keV, and 6 MV. All calculations were normalized to 95% coverage of the PTV by the 20 Gy prescription dose. The two keV energies were simulated with and without GNP's present inside the target volume. For the slices shown in C) the "6 mm'', "1.5 mm", and "<1 mm" are referring to the distance between the 70% and 110% isodose lines. The dashed black curves in C) indicate the 70% isodose line. D) a table showing the V12 of normal brain tissue, D_{max} in the PTV and skull, and the Paddick CI[7].

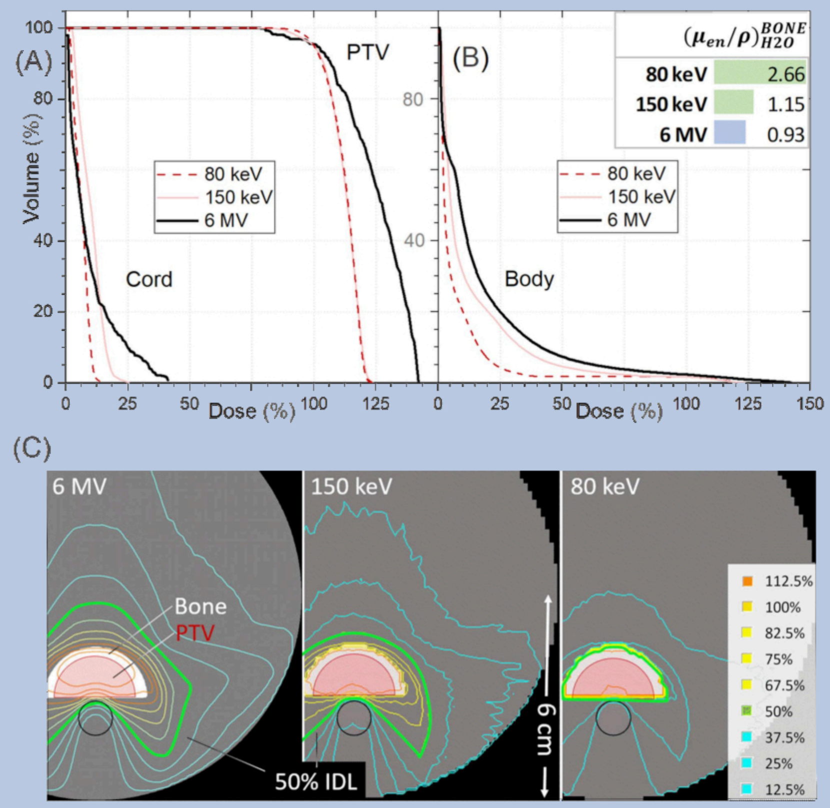


Figure 4: A) and B) are DVH's for the spine case with corresponding axial slices shown in C). Significant dose enhancement in the bone for the 80 keV condenses the 40-100 % isodose lines to overlap within 1 mm. Milder dose enhancement is seen for the 150 keV energy. The sharper 80-20 penumbra of the keV beams also allows better sparing of the spinal cord (black contour).

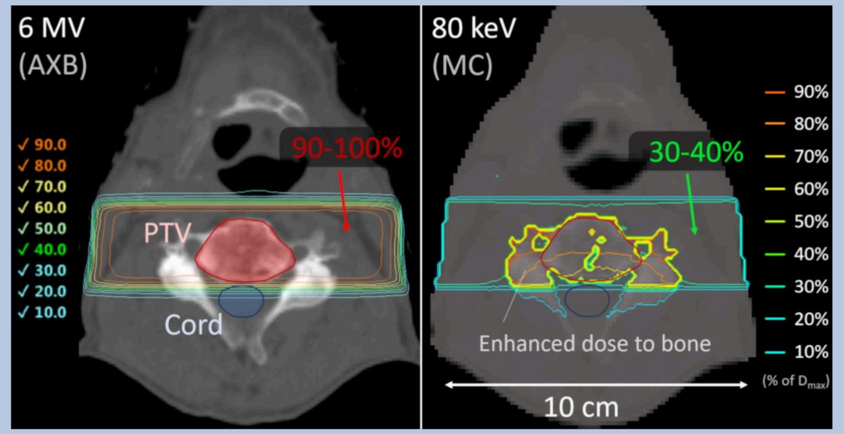


Figure 5: Axial slices of the isodose lines from opposing lateral fields from the clinical 6 MV (left) and 80 keV (right) IC beams for the cervical spine case. Due to the dose enhancement of the IC beams in the bone, the normal neck tissue was greatly spared compared to the 6 MV plan. Furthermore, the sparing of the spinal cord was much greater with the IC beam as compared to the 6 MV beam due to the sharp penumbra inherent to the IC beams.

CONCLUSIONS

- The dosimetric properties of IC x-ray sources were investigated using Monte Carlo simulations
- Simulated penumbra values for the IC x-ray beams were observed to be on the order of tens of microns as compared to several millimeters for the clinical 6 MV beam
- Due to the low divergence and near monochromatic nature of these sources, the depth dose fall-off was found to be between traditional orthovoltage and megavoltage Bremsstrahlung x-ray sources
- Dose enhancement up to a factor of 3.12 in bone was observed for the 80 keV IC beam as compared to 1.05 for the clinical 6 MV beam
- The sharp penumbra and preferential absorption of the IC beams resulted in superior plan quality8 as compared to the treatment plans generated with the clinical 6 MV beam for the sites investigated
- The results of this work indicate that IC x-ray beams are well-suited for stereotactic radiotherapy, which requires sharp dose gradients and tight conformity
- The benefit of IC beams as compared to megavoltage Bremsstrahlung sources increases if the target volume contains high-density, high-atomic number material (e.g., gold doping)

FUTURE WORK

- Future work includes developing an optimizer to be used with the IC beam simulations, which would enable tighter conformity and homogeneity of these beams
- Furthermore, the incorporation of an optimizer would allow for a fair comparison to intensity modulated megavoltage x-ray beams (the current standard of care)

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