D.C. Hansen, *Improving Ion Computed Tomography*, Ph.D. dissertation, Aarhus University, Experimental Clinical Oncology, Aarhus, Denmark, 2014.
http://pure.au.dk//portal/files/83515131/dissertation.pdf.

Abstract

Radiotherapy using ionized particles, known as particle therapy, provides a more accurate and gentle treatment than conventional radiotherapy using x-rays. This is mainly due to the finite range of the particles inside the patient, resulting in the patient receiving no, or very little, dose downstream of the tumour. The accuracy of particle therapy is however limited by the precision with which the particle range can be predicted inside patients. Currently this is done based on x-ray computed tomography (CT) scans, but the inherent physics of the problem limit the precision to about 3.5%.
One of the alternatives that have been proposed to solve this, is the use of ion computed tomography (ion CT). Ion CT uses the treatment beam in particle therapy to do imaging through measurement of the energy loss, and is able to achieve sub-percent precision. It does however have several limitations, including the limited range of the particles, restricting the scanned objects to a diameter of $30 - 37$cm, depending on the facility.
In this PhD dissertation, several of these limitations are addressed. A new algorithm, combining ion CT with x-ray cone-beam CT has been developed, which helps compensate for the limited range. With the new algorithm, high quality images could be reconstructed even in cases where ion CT projections could only be obtained in 50% of the angular interval.
Accurate simulation of ion CT is highly dependent on the models of nuclear fragmentation. These were studied in the Monte Carlo code SHIELD-HIT, and the models were adjusted to experimental partial cross sections. When compared with experiments measuring nuclear fragmentation in water, the models were found to be accurate for carbon ions, but with some deviations for neon.
For ions heavier than protons, the doses for ion CT reported in literature are too high to be of clinical use and in several cases larger than an actual treatment dose. It was unclear whether this was an inherent limitation of using these heavier ions, or simply the result of the experimental procedure used. A methodology for comparing the dose from ion CT with standard CT was developed and used to compare different ion at clinical dose levels. It was found that protons allowed for the lowest imaging dose, but at higher doses, similar to x-ray CT, helium and carbon ions gave images with less noise and better resolution. It was concluded that helium is a good candidate for ion CT, as it gave the best compromise between dose and image quality.
Another proposed solution to the problem of range estimation in literature is dual energy x-ray CT, which allows a more accurate range calculation than conventional x-ray CT. A detailed comparison was made between ion CT using protons and dual energy CT. While dual energy CT showed a significant improvement over standard x-ray CT, it still showed deviations in the order of 1.0%. Proton CT on the other hand showed maximum deviations of 0.3%