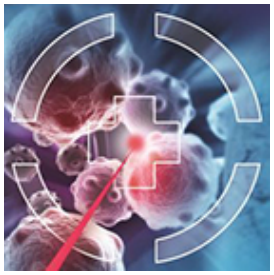

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A Modular Control System for Treating Moving Targets with Scanned Ion Beams: Design, Development, and Preliminary Test Results

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Introduction
Lung and other thoracic cancer survival rates have shown limited improvements despite generally more effective local control rates. Scanned particle beam therapy has the potential for dose escalation while sparing healthy tissue, but it requires a practicable solution to the longstanding problem of the adverse effects from the interplay of moving ion beams and moving tumors. We designed and implemented a modular dose delivery system to synchronize moving tumors with scanned ion beams for safer and more effective treatment of late stage lung cancers and lung metastases. This capability will enable subsequent clinical studies to evaluate the role of scanned ion beams in treating moving tumors. The objective of this study is to confirm that a modular dose delivery system which synchronizes the motion of tumors and scanned ion beams can irradiate tumors with portability, safety, and dosimetric accuracy, while sparing surrounding healthy tissues.

Methods and Materials
A modular motion-synchronized dose delivery system (M-DDS) was designed, developed and tested at GSI Helmholtz Centre for Heavy Ion Research and Centro Nazionale di Adroterapia Oncologica (CNAO). The operation of the M-DDS and its subsystems, including the timing, beam request, detector, magnet, memory, and motion mitigation systems, was validated to ensure the M-DDS, when integrated into the treatment control system, functions according to design specifications. This as done by testing the transmission, reception, timing, and synchronization of signals used by each subsystem. Integration tests were performed by delivering test-case library of 10 3-dimensional (static) treatment plans, which together comprise a complete plan for a moving tumor. Additionally, the interlock and safety systems within the M-DDS were tested by inducing a series of critical and non-critical errors.
Finally, the quality of delivered dose distributions was assessed in simple geometries by considering dosimetric uniformity and conformity. Simple geometries were delivered to a 2-dimensional ionization chamber array detector and radiochromic films mounted on a sinusoidal moving platform. Various plans designed for 1, 3, 6, and 10 respiratory states were delivered to investigate the degree of motion compensation and the extent of residual motion within a single motion state. The delivered geometries were assessed for delivery quality via gamma index analysis with a 3%/3mm criteria.

Results
The modular M-DDS subsystem functionality, motion mitigation functionalities, and treatment delivery were experimentally verified, including synchronization of timing events, magnet interfaces, beam request software and beam monitors. Loading of treatment plan libraries into dynamic random access memory (DRAM) and synchronous delivery, where treatment sequence is directed by the detected motion state was verified. Duty cycles of 80-95% were achieved for these deliveries. The performance of a critical component of DDS safety, the gating system, was also verified at both GSI and CNAO. Complete beam disruption was possible with the chopper magnet, while residual intensities on the order of 10 % of full intensity compromised experimental results at GSI. At both facilities, rapid gating was verified.
The delivered geometries were assessed for delivery quality via gamma index analysis with a 3%/3mm criteria. 6 and 10 motion phase plans for 40 and 20 mm amplitude motion showed >95% gamma index pass rates for 50x50mm squares at CNAO. A homogeneity of 90% was measured for 50x100mm rectangles at GSI. Dose outside the target region showed a rapid fall-off, comparable to static plans.

Summary

Preliminary results have validated the basic functionality and feasibility of the implemented motion mitigation strategy. Further tests, including clinical safety and more complex phantoms are necessary to translate this strategy to lung or pancreas cancer patients.

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