
4D offline PET-based treatment verification in ion beam therapy: experimental and clinical evaluation

Christopher Kurz

Dissertation
an der Fakultät für Physik
der Ludwig-Maximilians-Universität
München

vorgelegt von
Christopher Kurz
aus Neuwied

München, den 12.06.2014

Contents

| | | |
|----------|---|-----------|
| 1 | Introduction | 1 |
| 2 | Fundamentals of ion beam therapy | 3 |
| 2.1 | A brief introduction to ion beam therapy | 3 |
| 2.2 | Physical properties of ion beams | 4 |
| 2.2.1 | Energy-loss of ions in matter | 5 |
| 2.2.2 | Lateral scattering | 8 |
| 2.2.3 | Nuclear interactions | 8 |
| 2.3 | Biological aspects of heavy ion beams | 10 |
| 2.4 | Clinical implementation of ion beam therapy | 12 |
| 2.4.1 | Ion beam delivery | 12 |
| 2.4.2 | The Heidelberg Ion-Beam Therapy Center | 13 |
| 2.4.3 | Treatment planning | 14 |
| 2.5 | Uncertainties in ion beam therapy | 16 |
| 2.6 | Organ motion in ion beam therapy | 18 |
| 2.6.1 | Introduction to organ motion | 18 |
| 2.6.2 | Implications of organ motion for ion beam therapy | 19 |
| 2.6.3 | Organ motion management in ion beam therapy | 19 |
| 2.6.4 | Motion monitoring | 22 |
| 2.6.5 | Treatment of moving targets at HIT | 23 |
| 2.7 | Summary | 23 |
| 3 | PET-based treatment verification in ion beam therapy | 25 |
| 3.1 | Production of β^+ -emitter | 25 |
| 3.2 | Positron emission tomography imaging | 26 |
| 3.3 | Clinical implementation of PET-based treatment verification | 29 |
| 3.4 | Implementation of offline PET-based treatment verification at HIT | 31 |
| 3.4.1 | MC simulation of the β^+ -emitter distribution | 32 |
| 3.4.2 | Calculation of the irradiation-induced activity | 32 |
| 3.4.3 | Data acquisition and the Biograph mCT scanner | 33 |
| 3.4.4 | The SimInterface | 35 |

| | | |
|----------|---|------------|
| 4 | Moving phantom studies | 37 |
| 4.1 | Studies on post-irradiation 4D PET monitoring | 37 |
| 4.1.1 | Material and methods | 37 |
| 4.1.2 | Irradiation specific data analysis and results | 41 |
| 4.1.3 | Discussion and conclusion | 57 |
| 4.2 | US-based 4D PET imaging | 59 |
| 4.2.1 | Material and methods | 59 |
| 4.2.2 | Results | 62 |
| 4.2.3 | Discussion and conclusion | 66 |
| 5 | Performance of the Biograph mCT scanner at very low true count rates | 69 |
| 5.1 | Material and methods | 70 |
| 5.1.1 | Phantom imaging and simulation study | 70 |
| 5.1.2 | Application to clinical cases | 72 |
| 5.2 | Results | 73 |
| 5.2.1 | Phantom data: activity quantification, noise and geometrical fidelity | 73 |
| 5.2.2 | Impact of the LSO random background | 75 |
| 5.2.3 | Patient data: activity quantification, noise and range verification . . | 79 |
| 5.3 | Discussion and conclusion | 82 |
| 6 | Clinical feasibility of 4D offline PET-based treatment verification | 85 |
| 6.1 | Material and methods | 85 |
| 6.1.1 | Patient cohort and data acquisition | 85 |
| 6.1.2 | PET image reconstruction | 86 |
| 6.1.3 | 4D dose and activity calculation | 87 |
| 6.2 | Results | 89 |
| 6.2.1 | Patient L1 | 89 |
| 6.2.2 | Patient L2 | 91 |
| 6.2.3 | Patient L3 | 95 |
| 6.2.4 | Patient L4 | 97 |
| 6.3 | Discussion and conclusion | 101 |
| 7 | Conclusion and outlook | 105 |
| A | Additional results of the moving phantom studies | 109 |
| A.1 | <i>Line Mono</i> irradiation study | 109 |
| A.2 | <i>Line Mult</i> irradiation study | 110 |
| B | Additional results of the 4D patient data analysis | 111 |
| B.1 | Patient L4 | 111 |
| | Bibliography | 113 |