Chapter 2
Motion Compensation in Robotic Radiosurgery

This chapter describes the principles of motion compensation in radiotherapy with a focus on robotic radiosurgery, starting with a brief description of the medical implications. Throughout, special emphasis will be placed on the CyberKnife® system and we will outline the problems originating from the aim of real-time motion compensation. The main current application of robotic radiotherapy is the treatment of malignant tumours while a second, very promising field is the therapy of cardiac arrhythmia, especially of atrial fibrillation. An outline of this project called CyberHeart, and the challenges emanating from it, will be given in section 2.5.

2.1 Medical Implications

As a fully automatic system designed to compensate for respiratory and pulsatory motion as well as for motion of the patient, the CyberKnife (and also the CyberHeart extension) allows for treatment of cancerous regions anywhere in the body. Especially important, due to the system’s possible sub-millimetre accuracy [19, 48], the treatment of previously inoperable or surgically complex tumours has become possible, opening up a new treatment option for a great multitude of patients. The aforementioned problem of latency, however, as well as the notoriously difficult task of determining organ motion using non-invasive imaging methods, is responsible for the remaining inaccuracies and limitations of the system. Especially in those cases where tumour motion is large (i.e. tumours in the central lung or tumours close to the diaphragm) and respiration of the patient is irregular, targeting accuracy might be compromised. Consider the situation depicted in figure 2.1: the clinician determines the cancerous area to be treated (called Gross Tumour Volume (GTV)). This area is expanded to include regions where the cancer might have already spread to, i.e., regions where some cells are cancerous. This is called the Clinical Target Volume (CTV), which is further enlarged to cover imaging and treatment uncertainties (then called Planning Target Volume (PTV)). Usually, certain areas of the body are classified as Organ at Risk (OAR), i.e. regions which should be spared from irradiation.
motion as much as possible. If planning of the radiosurgical treatment is done at one phase of respiration (e.g. on a breath-hold Computed Tomography (CT) scan) and the treatment is delivered while the patient is breathing freely, the treatment beams might not be placed as planned (figure 2.1).

![Fig. 2.1: (a) Typical situation of an Organ at Risk (OAR), the Gross Tumour Volume (GTV) and the Planning Target Volume (PTV) (b) Two treatment beams are shown during one respiratory phase (c) The same treatment beams can hit the OAR during another respiratory phase or might miss the GTV](image)

As a consequence, the PTV is usually selected much larger than clinically required to cope with these inaccuracies. Clearly, this artificial enlargement as well as the inevitable blurring of the dose gradients due to organ motion render certain tumours intreatable without motion compensation. Subsequently, when the OARs are too close to the GTV, the enhanced margin required for Conformal Radiation Therapy (CRT), 3D Conformal Radiation Therapy (3DCRT) and other approaches not compensating for motion, can cause severe difficulties when creating the treatment plan. These difficulties can even be so grave that accurate planning and treatment is not possible, not because the GTV cannot be dealt with, but because the OARs would be in too great danger.

### 2.2 Active Tumour Tracking in Image-Guided Radiotherapy

#### 2.2.1 The CyberKnife

The first system intended to accurately treat tumours anywhere in the human body has been developed from 1987 on by Dr. John R. Adler, Jr., at Stanford University. It was envisioned in [15, 16], initially called *ADLR* [2] and then *Neurotron 1000* [5, 32] and intended for stereotactic radiosurgery of brain tumours. It was first used clinically on June 8, 1994 [3, 63]. The system was subsequently renamed CyberKnife and has been further improved by a collaboration of American and German scientists [4, 6, 7, 10, 41–47]. The system has since been manufactured commercially by Accuray, Inc., and received U.S. Food and Drug Administration (FDA) approval for treatment of stationary tumours (head, neck and upper spine) in 1999.