IGRT and motion management during lung SBRT delivery.

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Abstract

Patient motion can cause misalignment of the tumour and toxicities to the healthy lung tissue during lung stereotactic body radiation therapy (SBRT). Any deviations from the reference setup can miss the target and have acute toxic effects on the patient with consequences onto its quality of life and survival outcomes. Correction for motion, either immediately prior to treatment or intra-treatment, can be realized with image-guided radiation therapy (IGRT) and motion management devices. The use of these techniques has demonstrated the feasibility of integrating complex technology with clinical linear accelerator to provide a higher standard of care for the patients and increase their quality of life.

1. Introduction

Lung Stereotactic Body Radiation Therapy (SBRT), or stereotactic ablative body radiotherapy (SABR), is a radiation therapy technique that delivers large ablative doses to the tumour with fewer fractions than conventional radiation therapy. The high biological dose delivered to patients requires a high conformal dose distribution around the tumour with minimal exposure of surrounding healthy tissues. However, lung tumours are subjected to motion, which complicates the provision of high accuracy targeting during treatment delivery. Failure to adequately account for uncertainties due to motion can cause geographic miss and inaccurate dose coverage, such as underdosing the target and/or overdosing surrounding organs-at-risk (OAR) [1-4]. For these reasons, it is a desideratum of modern radiotherapy to manage tumour motion, trajectory irregularities, deformation and patient repositioning during lung radiation therapy.

Image-guided radiation therapy (IGRT) is the image-based guidance of radiotherapy delivery and a sub-set of the motion management strategies clinically implemented to help mitigate motion-related errors [5]. The scope of this chapter is narrowly defined to IGRT and motion management during SBRT delivery of photon beam therapy. The novelty of Magnetic Resonance Imaging (MRI) combined with linear accelerators is detailed in another chapter [6]

and will not be extensively mentioned here. We presuppose that a patient scan has been acquired (e.g. 4D-CT, MRI), and a treatment plan appropriate to the delivery method has been developed. This chapter is then organised into IGRT and motion management technologies that are used in room but prior to the treatment delivery (section II) and those that are used during the treatment (section III).

2. In room pre-treatment IGRT and motion management

Pre-treatment IGRT and motion management techniques available either commercially or in the research phase are summarised below in Fig. 1. Each of these devices are compartmentalised into four domains; kV imaging, MV imaging, optical imaging and treatment couch.

2.1. KV imaging

2.1.1. Conventional kV-imagers and 3D-CBCT

Fluoroscopic imaging devices are offered as standard components for nearly all linear accelerators (linacs). Most C-arm shaped linacs are made available with retractable kilovoltage (kV) source and a detector panel that provide a radiographic image of the patient's anatomy with submillimetre resolution enabling highly accurate positioning relative to a reference setup. The visibility of internal anatomy using kilovoltage x-rays is largely imposed by the Compton cross sections of the targeted tissue in the patient. For that reason, bone and metal (implanted fiducials) are high contrast due to their high attenuation coefficient and can be used as landmarks for patient's positioning, as opposed to soft tissue that have a low visibility contrast.

Another system, the Vero system (Brainlab AG, Feldkirchen, Germany) uses gimballed X-ray sources and imager. The Cyberknife system (Accuray Inc. Sunnyvale, USA) and the ExacTrac X-ray system (ExacTrac optical-tracking system, Brainlab, Heimstetten, Germany) are both systems that entail the use of mounted X-ray imagers and in-floor built detectors.

For rotating X-ray gantry, the 2D images can be reconstructed in three dimensions (cone-beam-computed-tomography, 3D-CBCT). Compared with kV planar images, CBCT provides offers a more complete assessment of patient deformation, rotation, tumour to OAR distances [7,8] and more importantly, a higher contrast visibility of soft tissue. AAPM Task-group 179 recommends quality assurance and iso-calibration tests monthly, to ensure that geometric and image quality remain within tolerance, and daily, for safety (collision check) and laser/image/treatment isocentre coincidence [9]. 3D-CBCT entails the use of fluoroscopic images and gantry rotation to calculate a three dimensional image showing the patient's internal anatomy prior to each fraction and allows visualisation of a range of geometric deviations such as motion-related uncertainties [10]. The main drawback of 3D-CBCT for lung imaging is that the projections from breathing phases are averaged to reconstruct a single 3D scan. Average projection yields blurred regions of interest or multiple diaphragm artefacts [11], potentially providing misinformation regarding actual tumour amplitude and its relative position to the OAR during breathing [12]. These artefacts complicate the task of the clinician to assess the degree of internal motion, deformation and the repositioning of the patient according to the reference set up

2.1.2. 4D-CBCT

4D-CBCT is the reconstruction of time-resolved 2D projections in phase or amplitude bins. Online 4D-CBCT has the advantage over 3D-CBCT of providing daily motion information such as visualising lesions that are near the ribs or diaphragm that might be inside 3D-CBCT blur and identifying baseline shift [13]. Compared with 3D-CBCT, the 4D-CBCT supplementary information on the trajectory-of-the-day keeps the margins around the target small [14] and reduces inter-observer variability for patient positioning [15]. 4D-CBCT was first developed and implemented on a linac by Tagushi et al. [16] and Sonke et al. [17]. Elekta released the first commercially available 4D-CBCT followed by Varian with the Truebeam 2.0.

The image quality of 4D-CBCT is dependent on the binning strategies and the type of CBCT reconstruction algorithm. Binning strategies are grouped either by phase or by displacement. Phase binning divides the breathing cycle into discrete phases relative to an arbitrary origin (i.e. end of exhalation), while displacement uses the magnitude of displacement to discretise the breathing signal. Phase binning was shown to be more clinically relevant, with a more accurate and clearer representation of small moving structures but the method is weakened in the presence of baseline shift [18]. On the other hand, displacement binning has the advantage to be less sensitive to variation in breathing patterns during the acquisition but the quality of reconstruction is influenced by interbin image quality variation and large projection angular gaps [18]. The reconstruction of CBCT is also heavily dependent on the reconstruction algorithm clinically in use. The current clinical reconstruction algorithm is the Feldkamp-Davis-Kress (FKD) algorithm or the McKinnon-Bates (MKB) algorithm, the latter mostly used for fast reconstruction. Both algorithms suffer from streak artefacts and a considerable amount of noise [18]

There is active research towards an enhanced version of 4D-CBCT to decrease the imaging dose per acquisition and reduce the streak artefacts. Dose reductions are obtained with hardware enhancement by varying the gantry speed [19,20], acquisition and imaging frequency [21] on a patient-specific basis in response to the patient's respiratory signal, with reported ~50% reduction of image dose. Streak artefacts can be reduced by implementing an iterative reconstruction algorithm [22]. Iterative algorithms are limited clinically by their requirements for long and intensive computation. However, they provide a higher image quality when constraints are applied to the similarity between the image to be reconstructed and higher quality prior image.

2.2. MV imaging

2.2.1. Electronic Portal imaging device (EPID)

The EPID was developed to provide a fast and accessible tool to replace film dosimetry. For most C-shaped linear accelerators, the EPID is a retractable panel that can be deployed at different distances and is typically used as a quality assurance tool on modern linacs for verification of modulated deliveries. For older linacs without on-board imagers, the EPID remains the go-to tool for pre-treatment patient setup. Its use in the beam-eye-view is particularly well appreciated by clinicians since both the image and the therapeutic MV beam share the same isocentre with projection having less distortion from metal artefacts compared with kV imaging.

The inconvenience of MV X-ray imaging is that high energy photons have low tissue-density differentiation, resulting in 2D images with lower contrast-to-noise ratio than kV images. Average dose per image is as high as 3–7 cGy, compared with the kV system of 0.1–0.3 cGy per images. Better image quality will improve the potential for patient positioning prior to treatment using the MV frames. For that reason, efforts have been made to investigate the detectors' response using high efficiency materials [23-26] and enhancing reconstruction algorithms with MV-CT and MV-CBCT [27-29].

2.2.2. Fan beam MV-CT with tomotherapy

As part of the IGRT techniques utilised before treatment, fan beam MV-CT is available in the helical Tomotherapy Hi-ART system (Madison, Wisconsin, USA, HI-ART II). The MV beam rotates around the patient in a fast and helical manner, much like a third-generation helical CT would (i.e. both X-ray tube and detector rotate). Tomotherapy is the only commercial product that currently utilises the MV imaging device in the narrow beam geometry as a computed tomographic device. Length in the cranio-caudal (CC) direction is user dependent but the field-of-view in the other directions is restricted to ∼40 cm. The fan-beam MVCT imaging dose is typically in the range of 1–3 cGy per scan [30] depending on the length of the patient to be imaged. We like to utilise.

2.2.3. MV-CBCT

MV-CBCT utilises the EPID to provide reconstructed 3D images prior to treatment. Lower energy settings than treatment MV is commonly used, 2.5 MV on the Varian Truebeam linac and 1 MV for the Siemens linear accelerators. Acquisition and reconstruction are performed in less than 2 min with a typical dose between 2 and 9 cGy but motion blur and low density differentiation can reduce the image quality. Studies aiming to enhance the image quality utilised the MV-CBCT on thoracic scan in a gated rotation acquisition method, where the gantry rotations are stopped and started when the tumour reaches the gating threshold [31], or fast acquisition, by combining kV and MV projections during approximately 15 s breath-holds [32]. For the latter, the gantry needs to rotate only 90 degrees and reduces the acquisition time to ∼15 s, achievable throughout one breath-hold. This has been automated to be performed clinically [33], with patient positioning set up shown to be equivalent to conventional IGRT techniques [34]. Additionally, MV-CBCT was shown to be feasible for rapid dose planning in urgent palliative situations [35].

2.3. Optical verification

Optical IGRT systems dedicated to guidance of patient setup have also been developed, such as AlignRT (Vision RT, London, United Kingdom), Catalyst (C-Rad AB, Uppsala, Sweden) and ExacTrac optical-tracking system (BrainLab AG, Munich, Germany). These devices rely on room-mounted optical cameras that verify the patient position and detect gross alignment errors. AlignRT and Catalyst use an infra-red camera that maps the patient surface contours in 6 degrees of freedom without the need of markers while the ExacTrac relies on external markers placed on the patient's chest. The ExacTrac also offers the advantage of integration with a kV radiographic

imaging system to verify the internal markers' position prior to treatment for building a correlation model between external and internal markers.

2.4. Robotic couch

Treatment couch re-positioning is an important intervention made prior to treatment and is closely intertwined with the use of image guidance. The patient is positioned on the couch and aligned manually according to landmarks, tattoo or indexed to immobilisation devices. Following imaging, the couch can be re-aligned in 3 translations and a couch rotation about the anterior-posterior axis (yaw) to match current patient positioning with reference set up. Optimal alignment requires 6D correction including the roll and pitch to account for patient internal movement and rotation [29,30] to facilitate isocentre shifts. Commercially available 6 degrees of freedom couches include the Brainlab's Robotics 6D couch HexaPOD evo RT (integrated with Exactrac X-ray 6D system), Protura Robotic Patient Positioning System (via Civco Medical Solution, Kalona, USA), and the PerfectPitch couch system (Varian, Palo Alto, USA).

3. Intra-treatment IGRT and motion management

During treatment, a range of devices are available for correction of errors related to motion. Motion compensation intra-treatment is paramount either by tracking the tumour or monitoring and adapting to its position. Fig. 2 summarises the commercial and research applications of the IGRT and non-IGRT motion management techniques available during treatment, from beam-on until end of treatment. In this section, we restrict the analysis to during treatment as offline review can also be processed as an a posteriori treatment quality assurance.

3.1. Dedicated devices for motion management

Several motion management devices have been clinically implemented as therapeutic tools to ensure a safer and more accurate radiation therapy treatment. These devices rely on motion correction in real-time either by adapting the position of the beam, its shape, or the patient couch position. The motion input may vary depending on the specific machine, using kV (with or without radio-opaque markers), electromagnetic transponders or surface markers for the motion of the thorax.

The most prevalent device for motion management with lung tumour tracking is the Cyberknife system commercialised and clinically implemented since 2006 [36]. The Cyberknife is comprised of a six degree-of-freedom robotic arm capable of compensating for the thoracic motion and internal anatomy movement in real-time [37]. Two orthogonal fluoroscopic systems are mounted onto the ceiling with the flat panel in-built into the floor around the treatment couch. The other commercialised device specifically designed for real-time adaptation is the gimballed linac Vero. The Vero linear accelerator is mounted on a ring gantry that rotates both around the patient and on its vertical axis (±60 degrees) with two gimbals that enable the treatment beam to pan and tilt, a feature particularly useful for tumour tracking [38,39]. For the Vero, two kV sources and the flat panel imagers are directly located on the rotating gantry. Both the Cyberknife and the Vero tracking system are supplied with a correlation model, initially built before treatment, based on the detection motion system of an internal (measured using kV

imaging) and external (measured using optical imaging) surrogate motion of the chest wall. The measured external chest motion combined with the correlation model predicts the tumour position, allowing the treatment beam to be shifted accordingly in real-time. For the Cyberknife, the correlation model is frequently verified (typically 30–60 s) and updated using marker segmentation on a single kV image. For the Vero system, the correlation model is verified more frequently than the Cyberknife (1 Hz) but requires treatment interruption to be updated [40]. Studies show that patient survival of the Cyberknife and the Vero are equivalent to standard SABR [41-45]. These studies also confirm that tumour tracking result in lower toxicity issues when compared with standard SABR, with significant increase in dose conformity.

A third technique is dynamic Multi-Leaf Collimator (MLC) tracking for standard linear accelerators. MLC tracking takes a tumour position signal and integrates it with the MLC to reconfigure the aperture in real-time in response to detected motion. MLC tracking is not available commercially but has been demonstrated on Varian [46,47], Elekta [48,49] and Siemens [50,51] linear accelerators. One unique possibility presented by MLC tracking is the ability to adapt to deformation of a target, which might be best utilised within the MR-linac framework.

Couch tracking is another real-time adaptation modality available for the standard linear accelerator where a tumour localisation signal is fed back to re-align the treatment couch [52]. Couch tracking has not been clinically implemented but has been demonstrated as a proof of concept with electromagnetic beacons [53], a topometrical device (Topos, Cyber Technologies, Germany), the respiratory gating system RPM (Varian) and a laser triangulation system (Micro Epsilon, Ortenburg, Germany) [54]. Couch tracking requires a high-precision couch motion system and was shown to be feasibly implemented on most linear accelerators. MLC tracking and couch tracking stand as potentially highly accessible modalities to enable increased utilisation of real-time adaptive radiotherapy [55].

3.2. Tracking or monitoring the tumour motion

kV imagers are an emerging tool for motion management to offer image guidance solutions during treatment. Gating or triggered imaging are available on certain linear accelerators (e.g. Varian Truebeam) with the capacity to monitor the tumour position, either to deliver the therapeutic beam at a specific phage during the patient's respiratory cycle or for real-time quality assurance and treatment accuracy.

The Cyberknife and the Vero systems take advantage of the set of orthogonal kV-imagers and optical tracking of external markers. The Cyberknife system includes the Synchrony Respiration Tracking System [56,57], a tracking system that reads the Light-Emitting Diodes (LED) chest motion input, correlates it with internal motion, and synchronises the beam accordingly with a latency of approximately 115 ms [58]. For the Vero, the correlation model is similarly built with a system latency for the infra-red markers of approximately 50 ms [39]. This is a much faster response time than any other devices because the beam is mounted on gimbals that provide a fast mechanical response of the therapeutic beam to be re-oriented. Both the Cyberknife and Vero

rely on the high contrast of implanted gold markers, like the coiled gold Visicoils (IBA, Louvain-la-neuve, Belgium) to guide adaptation.

The Brainlab Exactrac Adaptive Gating system is a device used for patient positioning and intra-treatment tumour motion monitoring. Its principle is similar to the Cyberknife and Vero as it takes advantage of a kV imaging system and chest motion to build a correlation model. Instead of tracking the tumour, it monitors the tumour position and irradiates at a selected cycle of respiration, during free breathing or deep inhale breath hold (DIBH) [59,60]. Compared with continuous tumour tracking, the Exactrac gating system has the disadvantage of increased treatment duty cycle, treatment time and imaging. The kV-imagers are mounted on the ceiling and floor and work independently from the on-board imaging device of the linear accelerators. The system is compatible with Vero and most Varian linear accelerators as an integrated platform.

kV-based tracking generally relies on in vivo implanted markers as a surrogate to track tumours within kV images acquired during treatment. There are several challenges limiting the utilisation of kV marker based tracking for lung SABR including the potential of marker-induced toxicity [61-63], marker migration [64] and surrogacy errors between tumour and markers (external or internal markers) [65]. Markerless tumour tracking, where automated soft tissue matching is performed without implanted markers, has the potential to negate these issues. It must operate under the conditions of adequate internal landmark visualisation and surrogacy by the kV-imaging system or a correlation model coupled with a robust prediction algorithm. For patient not amenable for fiducial placement, Cyberknife proposes alternative registration landmarks such as spine tracking [66], carina [67,68] or direct tumour tracking [69] with the Xsight lung tracking system. Soft-tissue matching using MLC tracking has been tested in a feasibility study using offline kilovoltage projections based on a Bayesian approach [70]. Quality assurance for markerless tumour tracking may also pose some challenges and require specialist and possibly patient specific motion phantoms.

3.3. MV imaging

3.3.1. MV tumour tracking

Lung megavoltage tumour tracking is predominantly a type of markerless tracking, based on the tumour or surrogate landmarks featured onto the EPID. To our knowledge, MV tracking has never been clinically implemented on linear accelerators. It was tested as a proof-of-concept using the “STiL” algorithm combined with MLC tracking to visualise and adapt the conformal MLC that is shaped according to a 3D printed tumour inside a deformable thoracic phantom [71]. With SBRT and modulated plans, one problem is that the tumour is not continuously visible on the images and its visibility can be obstructed by the diaphragm, ribs or heart. Also, the use of modulated fields complicates the tasks where the lesions are often obscured by the MLC.

3.3.2. EPID-based Intra-treatment dose verification

EPID-based in vivo dosimetry is the verification of the cumulative dose by comparison with the reference planned dose. EPID-based in vivo dosimetry is a system that flags major errors resulting from large clinical deviations such as machine fault, human error or large and unnoticed patient movement during treatment. A recent study from the Netherlands showed the effectiveness of this system [72] claiming that 1 in 300 plans required the inspection of a medical physicist to address clinical relevant deviations. Several countries have now integrated EPID-based in vivo dosimetry as part of their compulsory protocols. Commercial products currently available are the EPIDose (Sun Nuclear Corporation, Melbourne, FL), Portal Dosimetry system (Varian Medical Systems, Palo Alto, CA), EPIgray (DOSIsoft, Cachan, France), and Dosimetry Check (Math Resolutions LLC, USA). However, with the current increase in biological dose used for SBRT fractionation, post-delivery analysis is not suitable for avoiding radiation-induced toxicities. Real-time EPID-based dose verification can mitigate these issues. Although never implemented for the lung, the use of the EPID for real-time dose verification ("WatchDog") has been clinically tested on a cohort of 28 patients with head-and-neck and prostate cancer [73] allowing for both real-time dosimetric and geometric quality control.

3.4. Electromagnetic transponders

As a non-imaging based motion management technique, the use of electromagnetic transponders for lung tumour tracking is potentially the most advanced. This system uses non-ionising alternating current electromagnetic radiation to locate and continuously track small devices. It relies on a set of electromagnetic transponders (bronchoscopically or percutaneously) inserted in the vicinity of the lung tumour to be wirelessly detected by a detector placed above the patient chest during treatment (Fig. 3). Electromagnetic beacons for real-time tumour tracking in radiation therapy are commercialised by RayPilot (Micropos Medical AB, Gothenburg, Sweden) and the Calypso Anchored Beacons System (Calypso, Varian Medical system). Both products are suited for use on conventional linac. Micropos rely on wired beacons that are intended to be retracted after treatment. Although this technique has demonstrated its feasibility for prostate, the use of Micropos for lung has never been tested. The Calypso beacons are permanently implanted near the tumour. For lung insertion, Varian provides an improved version of regular prostate beacons with a five legged nitinol stability feature to facilitate anchoring within small airways [74]. The Calypso beacons for lung are approved for gated lung SABR and motion monitoring for data acquisition and analysis by numerous Government Regulatory bodies, such as the TGA in Australia and FDA in the USA. The use of the Calypso beacons is also conceivable for lung SBRT gating and couch tracking [75].

Our current clinical trial treats patients with lung tumours on a Trilogy Varian linac (Varian Medical Systems, Palo Alto, CA) using electromagnetic beacons inserted around the lesions [47]. Other groups have integrated the use of Calypso on a Siemens linac as a proof-of-concept but not to treat patients as yet [51]. The beacons are tracked in real-time with sub-2 mm position accuracy [76] and the beam is adapted using MLC tracking. This is the first and only institution treating patients with MLC tracking for lung SABR [47]. Patients (7/7) were successfully implanted, each with three beacons placed around the tumour, with positive dosimetric impact [77]. The underlying system latency of the MLC tracking system is approximately 220 ms [78] and is balanced with a kernel density-based method to predict the future target position [79].

3.5. Optical imaging

Optical imaging can be used to monitor the patient's abdomen or thorax for the patient's positioning, therapeutic beam gating or real-time monitoring of lung SBRT. Although it has the advantage of being non-ionising and non-invasive, its main challenge is to provide an accurate correlation between external markers and internal motion despite potential tumour hysteresis.

Optical imaging gating devices like the RPM system entail the use of an infra-red camera that illuminates a block covered with reflective markers positioned onto the patient's abdomen. AlignRT (Vision RT, London, UK) and Catalyst (C-Rad AB, Uppsala, Sweden) map the patient surface contours. Other devices using reflective markers are the Cyberknife, Vero and ExacTrac, all described in an earlier section as they require regular fluoroscopic images to update the correlation model. The combination of optical imaging and kV imaging can improve this correlation with regular model updates during monitoring of the chest motion. All of these devices are used to monitor the patient's abdomen or chest motion during DIBH, free-breathing gating or tumour tracking and detect unwanted patient movement like coughing and sneezing. It has been shown that DIBH combined with optical imaging decreases the dose to mediastinal structures as the inflated lung is caudally displaced away from the heart [80,81].

3.6. Breathing control devices

Breathing control devices aim to manipulate the patient's breathing pattern. They directly interact with the patient's airflow with facial masks or restrict thoracic motion using devices to block the motion of the abdomen. Commercialised products that interact directly with the patient's airflow through the mouth or nose are the Active Breathing Coordinator (ABC) device (Elekta AB, Stockholm, Sweden) and the SDX (Dyn'R, Toulouse, France). The ABC is a spirometer device dedicated to the practice of semi-voluntary breath-hold. It is connected to a balloon valve that blocks the patient air flow in several DIBH until the field is delivered, usually requiring two or three breath holds for the entire delivery. The SDX is also a spirometer device, however the patient is expected to perform breath-hold on their own with a pair of goggles providing instructions as a visual aid. The volume of air intakes is recorded from a flow sensor and converted into analogue signals. The signals are analysed by the SDX software that triggers the linac beam when the patient breathing curves reaches the breath-hold zone.

A large clinical trial (STIC 2003) with 403 patients demonstrated significant dose reduction for patients that were treated with ABC or SDX compared with free-breathing or RPM gating technique [80]. Study showed that significant increase in lung volume were found with breathing control devices which resulted in noticeable higher dosimetric benefits compared with RPM gating techniques [82].

Another device, the Continuous Positive Air Pressure (CPAP device), is currently being tested for its potential clinical use in lung radiation therapy [83,84]. The original clinical use of the CPAP device was to avert blockage of upper airways for patients suffering from sleep apnoea. A continuous pressurised air flow is delivered to the patient's airway by pumping air into the

patient's mouth or nose. The hypothesis is that continuous pressurised air results in a hyper-inflated lung which stabilises the diaphragm and increases the distance between the tumour target and OAR (e.g. Heart).

Other types of breathing control devices employ abdominal compression. Abdominal compression may be applied with several devices to mechanically restrict the motion of the abdomen during respiration. Since forced shallow breathing reduces the respiratory motion, dose escalation is permitted and beneficial for SBRT treatment. Compared with others forms of tracking or patient monitoring, the use of abdominal compression retains the advantages that its implementation is easy and accessible on linear accelerators and significantly reduces the cranio-caudal motion. Abdominal compression is increasingly popular. A survey in 2013 showed that abdominal compression was used in 51% of clinical centres in the USA [85].

One form of abdominal compression is a paddle pressed against the patient's abdomen, just below the ribs, using an arch system with screws to regulated the force of the paddle [86]. For this type of system, commercialised products are the Stradivarius abdominal compression paddle system (Qfix Systems, Avondale, PA), or the ONEBridge (Civco Medical Solutions, Kalona, IA) that comes in various sizes of respiratory plates. Another type of abdominal compression device, the pneumatic belt, applies pressure uniformly against the abdomen using an inflated belt controlled by a pump and a gauge. Commercialised products are the Stradivarius compression belt (Qfix), ONE Respiratory Belt (Civco Medical Solutions, Kalona, IA) and Omni V SBRT solution system (Bionix Radiation Therapy, Toledo, Ohio, US). It is worth noting that clinical centres have also designing their own custom-built external compression devices either for research purpose or to answer for their own specific needs [87,88].

Despite abdominal compression, patients may still experience upper body motion. Full thoracic motion restriction can be utilised to mitigate this problem. The BodyFIX system (Elekta, Medical Intelligence, Schwabmuenchen, Germany) is a dual-vacuum whole-body immobilisation device in which the patient is placed in a vacuum bag and the patient's lower body, abdomen and thorax are wrapped in clear plastic. The air between the plastic, patient and the vacuum cushions is then evacuated [89,90]. Compared with the abdominal compression paddle, both techniques performed equivalently, although applying uniform compression to the body of the patient with the BodyFIX system was reported to be more comfortable [90]. Another type of body immobilisation is used with the Orfit SBRT body mask (Orfit Industries Nv, Wijnegem, Belgium). The body mask helps to immobilise the patient and is attached along specifically made slots. This technique is reported to be effective for treating patients with spinal metastases [91].

Objectives and implementation differ between centres depending on the strategies in place, clinical objectives of the centres and the type of patients treated. Forced shallow breathing with abdominal compression was shown to be most effective for patients with tumour motion exceeding 5 mm in free-breathing [92], or 13 mm for gating [93,94], with significant reduction in the cranio-caudal direction with the paddle compared with free-breathing [95] specially for lower

lobe lesions [96]. However the reported residual excursion with the compression belt raises concerns about the tumour amplitude reproducibility [95].

3.7. Respiratory belt

The use of a respiratory belt wrapped around the patient's abdomen for monitoring or gating has also been tested. The most widely available systems are the Anzai belt (AZ-733V Anzai) manufactured by Siemens and the Bellows belt (Philips Medical System, Cleveland, OH). Respiratory belts are equipped with a strain gauge coupled with a sensor to record pressure variation induced by the chest stretching during breathing. The two-dimensional data is sent to the controller that triggers the beam according to the patient's amplitude. Small groups of patients were treated with the respiratory belt [97,98] with evidence that gating provides a constant treatment quality control, depth dose and beam profile [99,100]. Respiratory gating with a belt or optical imaging remains a popular motion management technique with approximately 31% of centres in USA using this with lung radiotherapy treatment [85].

3.8. Audio-visual biofeedback

Coaching the patient to breathe regularly and/or showing them their respiratory trace for active patient control is known as Audio-visual feedback. The use of audio-visual biofeedback from monitoring devices to the patient allows the patient to actively participate in the treatment. The patient directly addresses irregular tumour motion by remaining within a threshold during DIBH or following a regular and predictable breathing pattern that is beneficial for tumour tracking devices. Breathing signals can be obtained from the RPM, belt, optical cameras or other devices providing an analogue output that can be redirected back to the patient. In a systematic review, most studies reported beneficial effects of the use of audio, visual or audio-visual biofeedback compared with free breathing [101].

3.9. Immobilisation devices

Immobilisation of the patient is evidently paramount and can be obtained by locking the patient in a vacuum-lock foam bag, stereotactic frame with wingboard and alpha-cradle, and immobilising their feet and knees. These steps minimise motion or wobbling during CBCT couch shift after the 3D/3D match.

4. Conclusion and outlook

This chapter is a review of the current use of IGRT and motion management techniques available in radiation therapy. It explores the various devices, commercial or still at the research stage, that are currently available for patients treated with lung SBRT. The use of IGRT and motion management prior to treatment are established standardised techniques and their dissemination in clinical practice is ongoing [85]. However, the clinical benefits of motion management during radiation therapy are hard to interpret. Clinical trials generally involve small cohorts of patients, and the treatment strategies between radiotherapy centres cover a large range of fractionations, lung staging or tumour lobe location as well as different treatment techniques (VMAT, IMRT).

Also, comparison of motion management against the absence of motion management is difficult because of the lack of randomised controlled trials. For that reason, stronger clinical data for a large cohort of patients is needed to fully claim the benefits of motion management for lung SBRT.

The rise of MRI-guided linear accelerators may provide a paradigm shift in the way lung SBRT is currently performed. Because of its high tissue contrast, MRI-guided capabilities are far superior to kV-based imaging, with better target and OAR delineations [6]. In addition, it does not require ionising radiation to image the internal anatomy and is therefore safer for the patient.

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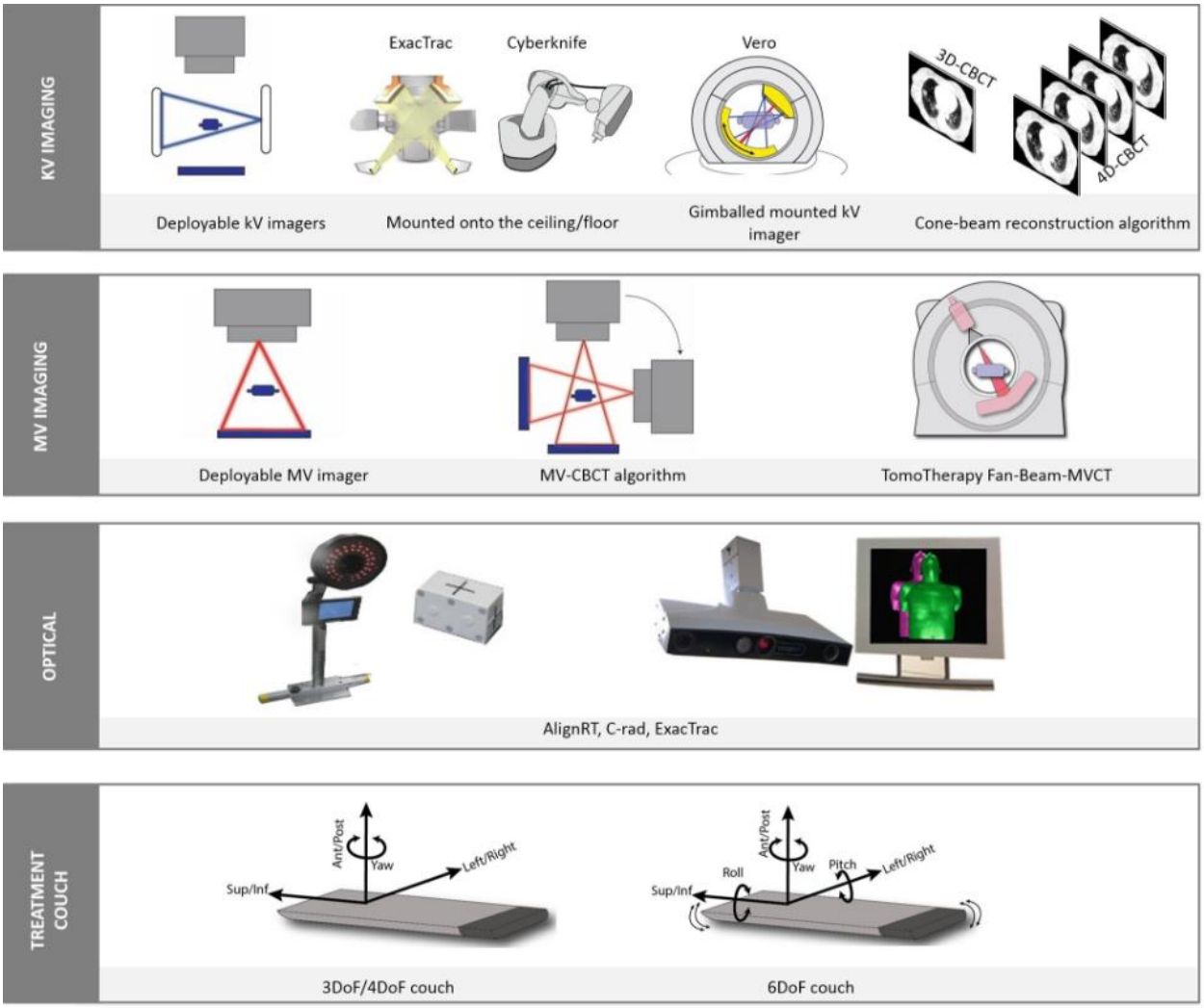

Fig. 1. Summary of motion management techniques available prior to treatment.

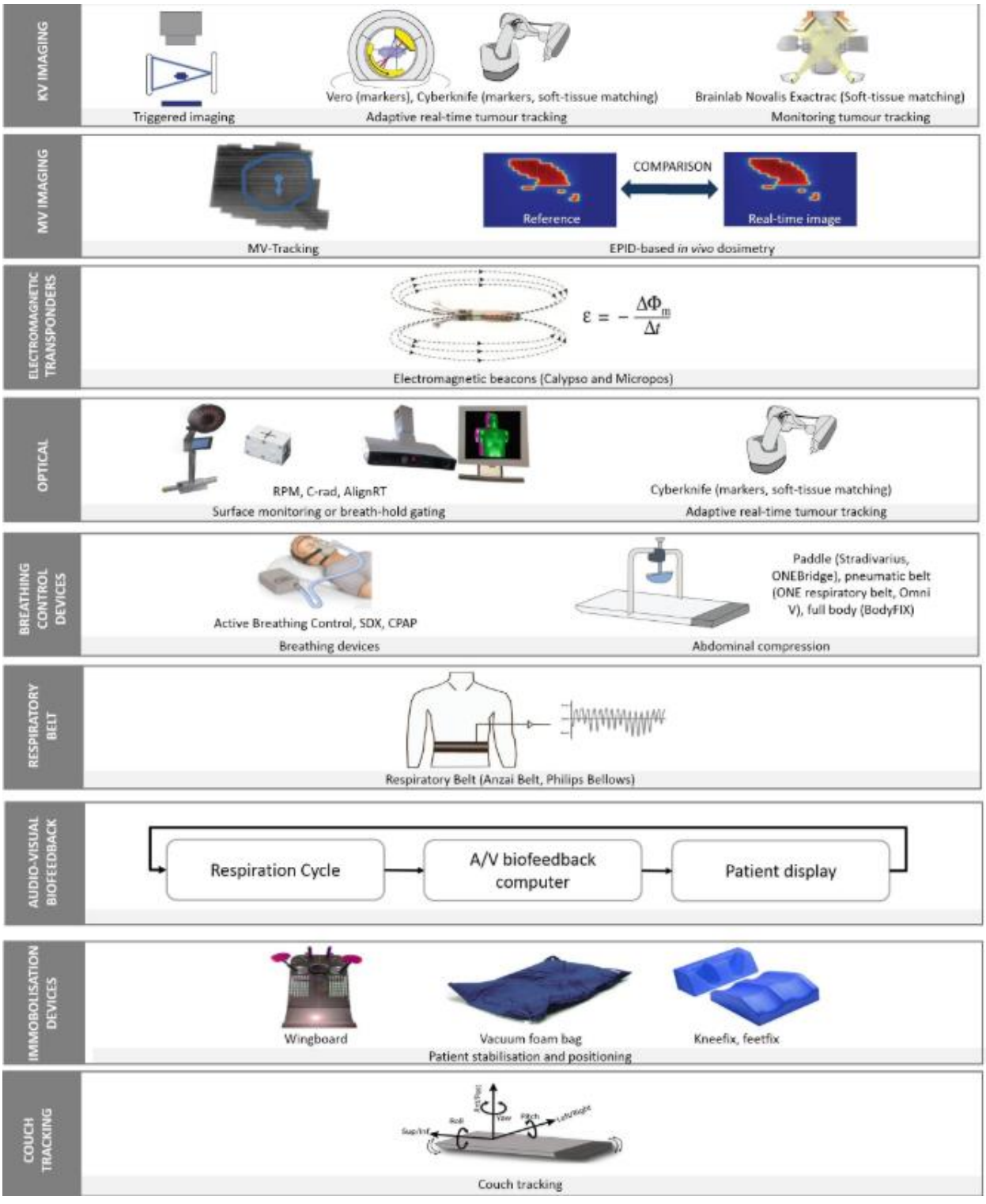

Fig. 2. Summary of IGRT and non-IGRT motion management techniques available during treatment.

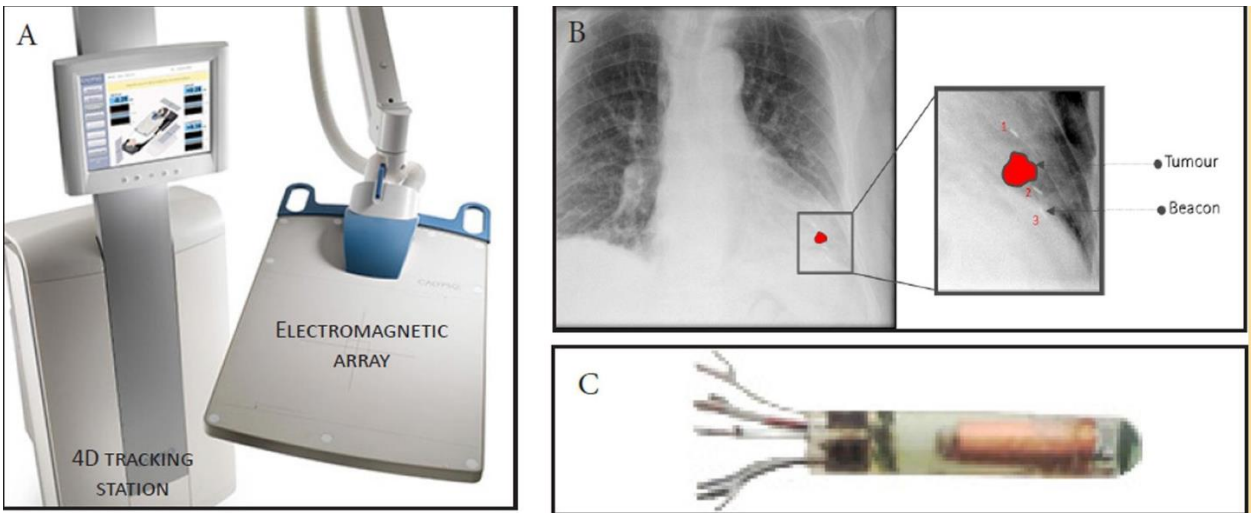

Fig. 3. A) Calypso tracking station with the electromagnetic arm B) fluoroscopic images of implanted beacons within vicinity of the tumour C) lung calypso beacons with the nitinol legs.