

Constructing a clinical decision-making framework for image-guided radiotherapy using a Bayesian Network

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Abstract. A decision-making framework for image-guided radiotherapy (IGRT) is being developed using a Bayesian Network (BN) to graphically describe, and probabilistically quantify, the many interacting factors that are involved in this complex clinical process. Outputs of the BN will provide decision-support for radiation therapists to assist them to make correct inferences relating to the likelihood of treatment delivery accuracy for a given image-guided set-up correction. The framework is being developed as a dynamic object-oriented BN, allowing for complex modelling with specific sub-regions, as well as representation of the sequential decision-making and belief updating associated with IGRT. A prototype graphic structure for the BN was developed by analysing IGRT practices at a local radiotherapy department and incorporating results obtained from a literature review. Clinical stakeholders reviewed the BN to validate its structure. The BN consists of a sub-network for evaluating the accuracy of IGRT practices and technology. The directed acyclic graph (DAG) contains nodes and directional arcs representing the causal relationship between the many interacting factors such as tumour site and its associated critical organs, technology and technique, and inter-user variability. The BN was extended to support on-line and off-line decision-making with respect to treatment plan compliance. Following conceptualisation of the framework, the BN will be quantified. It is anticipated that the finalised decision-making framework will provide a foundation to develop better decision-support strategies and automated correction algorithms for IGRT.

1. Introduction

Decision-making in image-guided radiotherapy (IGRT) requires radiation therapists (RTs) to consider and weigh up many factors within tight clinical time constraints [1]. Choosing the most optimal set-up correction to apply in the presence of residual patient positioning errors adds further uncertainty to the decision-making process. The clinical decision-making processes associated with IGRT have become more complex as on-board imaging and treatment delivery technologies have advanced [2].

We aim to use a systems approach to develop a decision-support framework for IGRT to assist RTs to perform IGRT efficiently whilst ensuring that any applied set-up correction, based on their analysis of the images, will maximise treatment delivery accuracy. A Bayesian network (BN) is a tool ideally suited for developing such a framework and has been previously applied to radiotherapy treatment plan selection [3]. BNs are able to model complex systems such as IGRT decision-making, providing both a graphical map of the process via a directed acyclic graph (DAG) as well as probabilistic quantification of the system knowledge and uncertainty using conditional probability tables (CPTs)



[4]. There are various core and iterative processes in the development of a BN [5]. This paper presents the work to date to conceptualise the BN graphical structure and the outcomes of a review workshop undertaken to begin the process of validating the network structure.

2. Materials and Methods

It is crucial to define the purpose of any BN at the outset in order to determine the outcome of interest requiring decision-support. This outcome is defined as the BN's target node. Key factors that influence the outcome of interest and their causal relationships are then identified and mapped as nodes and directional arcs to create the DAG. Clinical protocols and data from published studies are ideal sources for clarifying important outcomes and their influencing factors for the IGRT decision-making process. The construction of the DAG is an iterative process, where a model is proposed, reviewed and modified until structure confidence is achieved. RTs, radiation oncologists (ROs) and physicists with extensive clinical IGRT experience are able to contribute valuable expertise towards the BN review process.

2.1. Review of IGRT clinical practices and the literature

The starting point for conceptualising the BN was to examine the IGRT practices at a local radiotherapy department. IGRT protocols for prostate and head and neck cancer patients were evaluated as planar and volumetric on-board imaging technologies are routinely used in both the online and offline environments. Decision flowcharts were constructed to map the actions that are taken for typical image matching scenarios. A systematic literature review was then performed to ensure a comprehensive analysis of IGRT practices and technologies. Internet searches were conducted to access texts, technical reports and guidelines published by relevant national and international professional bodies, working parties and regulatory authorities. Searches were also conducted on online databases (PubMed, Embase, ScienceDirect, and the Cochrane Library) for peer reviewed publications. 580 publications met the inclusion criteria after abstract review. However for the purpose of conceptualising the BN, 160 articles, either published in 2012 or those frequently cited, were deemed an adequate sample of current knowledge and expertise of the IGRT technologies and practices. Quantitative and qualitative data was extracted from these publications and tabulated according to technology, technique, tumour, OAR, and study results.

2.2. BN structure development

The decision flowcharts and the data extracted from the literature review identified that there are multiple outcomes of interest in the IGRT decision-making process, requiring multiple interacting target nodes. An object oriented BN (OoBN) format was used to create sub-networks relating to the various target nodes. A dynamic component using several OoBN time slices was used to model the sequential decision-making required to assess accurate delivery of the treatment plan as the patient's treatment progresses [4]. A prototype DAG for the BN was then manually constructed by mapping the key factors associated with the different target nodes. Input nodes were used to allow evidence relating to the IGRT process, such as IGRT modality (e.g. planar 2D kilo-voltage (kV) imaging with fiducial marker matching), tumour site and its associated organs at risk (OAR), to be specified in the network.

2.3. BN review

A workshop was conducted where an RT, RO and physicist reviewed the prototype IGRT decision-making BN. Prior to the workshop a list of the network nodes (50 in total), their function and definitions, was provided to the participants. These were reviewed at the beginning of the session to determine whether the outcomes of interest and key influencing factors of the network had been correctly identified. Yellow sticky notes with the target nodes and their key factors written on them were then used to independently construct the BN. The prototype BN was then examined so that missing or redundant nodes, or incorrect directional arcs, could be identified.

3. Results

3.1. Conceptualisation of a prototype BN structure

The multiple outcomes of interest identified for the IGRT decision-making process were measurement or assessment uncertainty, determining the probability of accurately delivering the treatment plan in the presence of residual errors in the online environment and, on-going assessment of treatment delivery compliance with the treatment plan, given the treatments delivered to date. Figure 1 demonstrates the prototype dynamic OOBN DAG created to model the relationship between the target nodes used to represent these various outcomes of interest. An IGRT technology and technique assessment sub-network, and separate online and offline IGRT decision-making sub-networks were linked by their target nodes.

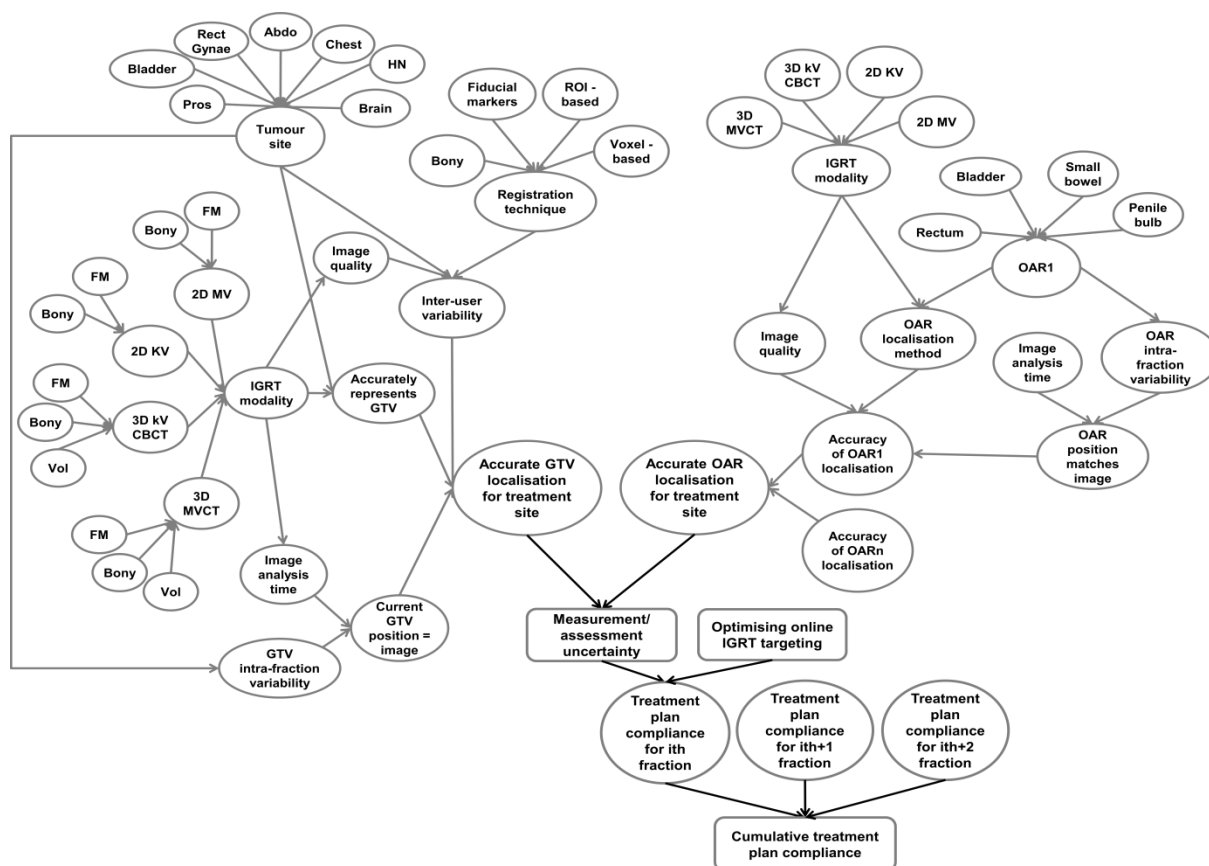


Figure 1. The prototype DAG of the BN. The rectangular target nodes represent the various outcomes of interest in the IGRT decision-making process. The IGRT technology and technique assessment sub-network (target node=Measurement/assessment uncertainty) has been expanded to demonstrate its division into tumour and OAR sub-nets. The treatment plan compliance nodes for individual fractions demonstrate the time slicing component required to assess cumulative treatment plan compliance.

3.2. BN review

The prototype DAG structure was generally accepted by the review process conducted in the workshop. However the role of image quality, radiation dose and patient compliance (including voluntary and involuntary patient-specific issues) in the IGRT decision-making process and their place in the BN structure were key discussion points in the workshop. These factors were considered highly influential in the decision to re-position and re-image the patient in the online IGRT environment. Patient compliance, treatment intent and delivery technique were considered to be key factors to apply

permanent changes to the patient set-up or to adapt the patient's plan in the offline IGRT environment. Consensus was reached that additional weighted nodes could be linked with the target nodes to decision nodes to provide advice different IGRT related interventions.

4. Discussion

The various sub-networks of the BN in effect model the various aspects of uncertainty associated with delivering IGRT treatments, including technology and technique error, and random and systematic setup errors. It is important to note that the BN design has been limited to x-ray based on-board imaging devices as these are the most commonly utilised IGRT technologies [2]. Real-time tracking systems were also excluded as these technologies are relatively new and remain developmental in the broader clinical context.

Further work is required to finalise the conceptualisation of the network structure. While the systematic literature review yielded a high number of studies examining technology and accuracy precision, there are a number of key factors and their role in the IGRT decision-making process that are less widely reported. Examples include image matching criteria to optimise tumour targeting, residual error thresholds, image quality, radiation dose and patient compliance. The necessary inclusion of these factors in the BN is supported by a limited number of publications [6], documents such as the National Health Service IGRT guidelines [2], the departmental IGRT decision flowcharts and the outcomes of the review workshop. Future elicitation workshops and interviews have been planned to utilise the expertise of RTs, ROs and physicists from multiple radiotherapy departments to further refine the placement and function of the factors in question in the BN.

An interesting outcome of the workshop was a discussion on how useful visualising the key factors and their relationships in graphical form was for the individual participants in evaluating both their departmental IGRT practices and their own knowledge-base in this field. The primary aim of a BN is that its target nodes predict an outcome of interest or update beliefs when new information about the system is added to the network. However BNs have also been shown to be beneficial in the evaluation of current standards of practice as well as informing individual practice when they have been developed and applied in other fields [7].

5. Conclusion

The graphic structure of a BN to support clinical IGRT decision-making has been developed and reviewed. Further workshops are required to finalise the BN structure. The BN will then be quantified, using both expert clinical knowledge and data sourced from peer-reviewed clinical studies, to generate the conditional probability tables for the network nodes. It is anticipated that the finalised decision-making framework will provide a foundation to develop better decision-support strategies and automated correction algorithms for IGRT.

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