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A practical implementation of physics quality assurance for photon adaptive radiotherapy

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Abstract

The fast evolution of technology in radiotherapy (RT) enabled the realization of adaptive radiotherapy (ART). However, the new characteristics of ART pose unique challenges for efficiencies and effectiveness of quality assurance (QA) strategies. In this paper, we discuss the necessary QAs for ART and introduce a practical implementation. A previously published work on failure modes and effects analysis (FMEA) of ART is introduced first to explain the risks associated with ART sub-processes. After a brief discussion of QA challenges, we review the existing QA strategies and tools that might be suitable for each ART step. By introducing the MR-guided online ART QA processes developed at our institute, we demonstrate a practical implementation. The limitations and future works to develop more robust and efficient QA strategies are discussed at the end.

Keywords: Adaptive radiotherapy, Quality assurance, Image guided radiotherapy

1 Introduction

Photon adaptive radiotherapy (ART) has drawn great attention over the last two decades [1–4]. During the ART processes, an adaptive plan based on treatment day anatomic feedback following imaging guidance is generated to optimize the ratio of normal tissue sparing and target coverage. Many clinical and research studies have showed potential benefits of ART. New tools, technologies and software solutions are continuously being developed to aid the ART planning and treatment processes [2–6].

As shown in Fig. 1, a typical ART workflow [7] includes 8 major steps – daily imaging and localization, image registration, image segmentation, dose prediction with the original plan, setup for adaptive planning, plan re-optimization, adaptive plan evaluation and plan delivery. Each step could contain multiple sub-steps. The successful execution of each step is essential to ensure a safe and robust delivery of the adaptive plan.

ART can be realized either offline or online. For an offline ART, the imaging based anatomical feedback is assessed offline and the adaptive plan will be used for the subsequent treatment fractions. For an online ART, the adaptive plan is prepared immediately after the daily image acquisition with patient remaining in the treatment position, and is delivered immediately after plan evaluation and quality assurance (QA). Because time is a very important limiting factor for online ART, a high level of automation for each online ART step is highly desired and the developments of new protocols, software tools and personnel trainings are required.

To ensure safety and quality, QA measures are recommended for most radiation therapy (RT) procedures. Many guidelines and publications have recommended and discussed machine-specific QAs and patient-specific QAs for the standard RT procedures [8–10]. However, it is challenging to apply conventional RT QA processes to ART, especially to online ART. This is mainly because: (1) the processes of patient setup, image acquisition, image registration, contour

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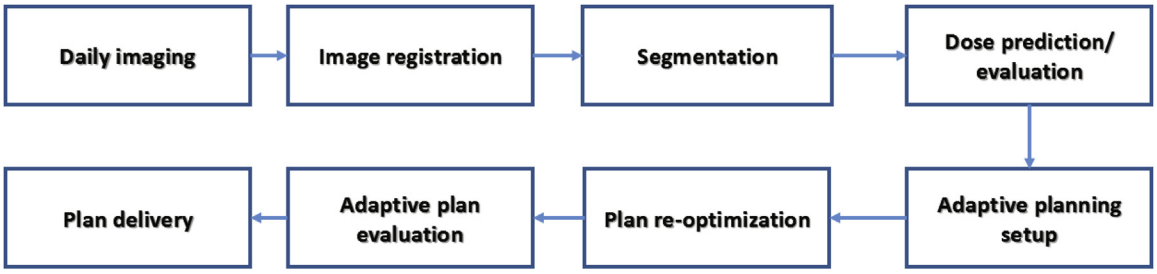

Figure 1. A typical ART workflow that contains eight major steps.

delineation, treatment planning and treatment delivery must be executed rapidly and only allow very limited time for plan evaluation and physics QAs. (2) With the patient being on the treatment couch during an online ART, it is impractical to perform measurement-based pre-treatment QA for the adaptive plan. (3) ART is generally considered riskier [11] than standard RT, therefore extra QA procedures are required to detect ART-based errors which are not well-handled by current QA tools (to be explained in the following sections).

In this paper, we will introduce the risks and QA challenges associated with the ART processes, then review the possible QA strategies for each individual ART steps. By using the online MRI-guided ART QA processes developed at our institution as examples, we will demonstrate the clinical implementation.

2 Materials and methods

2.1 Risks of the ART processes and QA challenges

Risk analysis is often performed to guide the development of QA strategies for a particular RT process. However, the traditional way to develop quality management strategies via analysis of recorded treatment errors is not applicable to ART at this moment [12] because no such data exists. For new processes like ART, prospective approaches such as failure modes and effects analysis (FMEA) [13] can be applied to identify the potential failure modes and to quantify risks of each step. Appropriate QA strategies and tools can be then implemented to reduce risks and to avoid critical failures. One such pioneer study was done by Noel et al. [11], who described a general ART workflow from simulation to treatment delivery, and determined failure modes associated with each ART step and calculated the risk-priority-numbers (RPNs). As shown in Fig. 2, the flow diagram lists the sub-processes of ART and the failure modes per sub-process (shown in parenthesis). The "+" or "−" sign indicates an increased or decreased RPN of each step compared to the corresponding step in regular RT, with a higher RPN indicating a higher risk. Multiple steps are unique to ART, for example, contour generation, electron density map editing based on the scan of the treatment day, etc., and lead to new failure modes. The final failure modes and effects analysis (FMEA) in Noel's study revealed 13 new and 30 common critical failures (shown in bold symbol in Fig. 2). The ART RPNs increased for 38% of the failures with 75% attributed to failures in the ART segmentation and planning processes. Table 1 lists the nine most critical failures and their associated steps. These results demonstrate that ART is riskier than the standard RT, and it is necessary to develop appropriate QA strategies to reduce the new and the common risks.

2.2 ART QA challenges

There are five core steps for online ART: (1) daily imaging, (2) structure segmentation/contour delineation, (3) evaluation of the initial plan on the anatomy of the day, (4) plan re-optimization and evaluation, and (5) treatment delivery. All steps are performed with the patient in the treatment position. Ideally, a thorough physics QA shall be performed at the completion of each step to check the aspects covered by the step. Examples of important aspects include accuracy of delineations of target and organs-at-risk (OARs), integrity of treatment plan parameters, plan quality and accuracy of the calculated dose. However, two additional major challenges are associated with ART QA over the QA for traditional non-adaptive RT: much shorter time scale for QA and dose verification.

2.2.1 QA efficiency

Time is the key for online ART because any additional delay will increase the overall uncertainties of patient's anatomy or position. More importantly, without efficient QAs the whole ART process would not be possible. For standard RT or offline ART, timing is not a major limiting factor, and the contour delineation, plan integrity, plan consistency and plan quality can be checked manually at relatively slower paces. The manual plan-check processes are relatively laborious and inefficient by relying on the RT team members (radiation oncologists, medical physicists, dosimetrists, and therapists) to apply their knowledge to detect errors and inconsistencies in the plan parameters. It is very difficult for patients in poor overall conditions to hold still through a lengthy online ART process. It is obvious that the classic slower QA processes