QA procedures needed for advanced RT techniques and its impact on treatment outcome

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Abstract. The radiotherapy process is reviewed briefly and potential risks or pitfalls are identified. The focus is on modern advanced modalities in radiation therapy such as IMRT, VMAT, gating and tracking and also for the unknown to come. Existing methods, or quality controls (QC), or with better word barriers, are introduced at important steps of process with the purpose of prohibiting errors to continue through the process and thus avoiding an unwanted erroneous irradiation of the patient. The soft branch of quality assurance (QA) such as peer-review is also a major component of today’s process and its safety. The importance of knowing your QCs is pointed out. The role of dosimetry method i.e. 3D-dosimetry is reviewed. Staff have to be working with awareness and alertness that can reduce most of the risks. Having comprehensive protocols known by all involved together with well-trained staff at the department with dedicated functions and responsibilities will further reduce the risk for unintended irradiations of patient. Having a well-designed QA system with the appropriate barriers have the possibility of producing high quality radiotherapy, which will also result in better outcome for the patients. The international head and neck trial illustrates very well the importance of accurate radiotherapy.

1. Background
Radiotherapy is evolving fast with new technologies and modalities launched frequently by vendors and by research groups. Today we have commercially available dynamic delivery of rotational intensity modulated treatments e.g. RapidArc, VMAT and Tomotherapy. Intensity modulated radiotherapy (IMRT) is today the standard modality at many departments. We also have systems that adjust the beam delivery according to the patients motions i.e. gating systems [1] and soon we will also have commercial system tracking the movements of the tumour [2, 3]. We have also seen the incorporation of computerised tomography during treatment with equipment mounted on the linear accelerator i.e. cone-beam CT (CBCT) which have given us new possibilities of increasing the precision and accuracy of the patients position but also the opportunity to adapt our treatment delivery to the target of the day. Selecting the plan of the day based on imaging prior to irradiation is possible today [4-6]. The latest development is the incorporation of MR-imaging with the treatment units. Research groups in Utrecht, The Netherlands [7], Calgary, Canada [8] and Sydney, Australia [9] are...
examples of this. A commercial product Viewray® is also available [10] combining three rotating Co-60 sources equipped with MLC with a MRI system for on-line imaging.

The challenge for medical physicists and other professionals within radiation oncology is to cope with this accelerated process of new modalities and technologies. Especially regarding acceptance and commissioning of the new equipment, but also creating new procedures for the daily work to establish a safe environment for these modalities for patients but also for staff. This pushes our quality management systems to its limits where new quality assurance programs and their quality controls have to be set up and organised. How will we assure that these systems will be able to deliver the accurate and precise absorbed dose (dose distribution) as nicely planned and displayed on our treatment planning stations? We do not only have to do it once, we have to do it for all fractions through the treatment course. In short, the right dose at the right place at the right time. Decision-making is also part of this when we start to think about selecting the best plan for the individual patient from our multi-dimensional environment of modalities. Reports regarding improving safety in radiation oncology has been published during the last 10 years [11-13].

2. New approaches for quality assurance
Radiation oncology cannot continue in the same path regarding quality assurance (QA) and especially not how quality controls (QC) are set-up and performed. The all-mighty model has been to check whatever is possible to check e.g. plans, monitor units, chart checks prior, during and after treatment etc… Even patient specific QA measurement programs have been introduced draining the resources of the medical physics department. Have these programs prevented us from accidents in radiotherapy?

Several severe accidents have been reported the last decade or so (even earlier when technology have passed the users) and some examples are given here (details regarding these accidents can also be found at IAEAs Radiation Protection of Patients website [14]):

- UK, 1982-90: incorrect SSD correction (applied it twice due to lack of knowledge and communication) 1045 patients where under-dosed up to 30%, >492 RT failures (Ash and Bates [15]).
- Spain, 1990: Linac ‘repair’ led to 36MeV e-beam no matter what was programmed. No dosimetry check. 27 patients overdose, 15 deaths [16, 17].
- France, 2004: incorrect MU for dynamic wedge. 23 patients overdosed 20%, 4 deaths [18].
- Glasgow, 2006: incorrect calculation of MU. Planner thought TPS calculated MU/Gy and not MU/fraction. 67% overdose results in death [19].
- France, 2006-7: large ion chamber used for SRS. 145 overdoses [20].
- US, NYC, IMRT without MLC control points, overdose 13 Gy/fraction three times, one patient dead [21].

Thus to have a safer radiotherapy environment in the future we have to change our way of thinking and look at what we are doing from a new perspective. We need a more process-oriented approach.
Figure 1. The wheel of improvements for guiding quality management.

Referring to figure 1, we have to look at our radiotherapy process with an approach of identifying potential risks, define and set barriers to assure that potential deviations from the intended treatment plan never reach the patient.

One needs a team made up of representatives of all professionals in radiation oncology who identifies the risks in the radiotherapy process. Identified risks can be assessed and shared within the radiotherapy community. At the identified control points, QC or barriers are set up to prevent errors from disseminate further through down the line. All QCs must be monitored and to have defined tolerances and action levels. Control and evaluation of the effectiveness is mandatory to maintain a potential of improving the radiotherapy process. Finally we have to learn and feedback our experiences etc and fine-tune our QM/QA system.

Effective tools for this do exist in other fields such as aviation, nuclear power, off shore and also from the manufacturing industry. For short we have a) process mapping (identify the main processes and their sub processes), b) identify the processes which are more error prone using established methods as FMEA (Failure Mode and Error Analysis) and RCA (Root Cause Analysis) [22, 23] c) identify measures (QC or barriers) for control [24] and d) using SPC (Statistical Process Control) to determine tolerance and action levels for QC based on measurements [25-27].

Figure 2. Example of a crude process chart for radiation therapy. The fences indicate safety barriers or QCs between the different sub-processes.

Additionally, one must also have control of the barriers set up in the process and an effective way is to score/report actual and potential deviations thru e.g. an Incident Learning Systems (ILS). Today we have several systems for anonymous reporting thus allows us to get information on risky steps in the process. These are the international system SAFety in Radiation Oncology (SAFRON) [28] and the recently announced US system from ASTRO/AAPM Radiation Oncology Incident Learning System (RO-ILS) [29] and the Canadian National System for Incident Reporting: Radiation Therapy (NSIR-RT) [30]. A lot of national systems exist too e.g. the UK has a very comprehensive reporting system within healthcare including radiation oncology [31] as well as local systems [32, 33]).
predecessor to these were the Radiation Oncology Safety Information System (ROSIS) set up in 2006 within a web environment and which received around 1000 reports in a short time (Cunningham et al [34]).

**Figure 3.** Quality assurance with its two sides - the soft branch which covers all the decisions taken in a patients process and the hard branch with all technical QC as dosimetry checks, plan checks etc.

One must remember that the severe events in radiation oncology that we know so well from literature and from various lectures on safety is only the tip of an iceberg. In daily practice deviations from the intended process occurs frequently, but our QC or barriers catch and corrects them i.e. keeps the process within its limits. This emphasis the use of an ILS for potential advert events too. We have a great opportunity to learn from these.

It is not only the technical part of a QM or QA system that is important, the soft part with an environment that has an open, no-blame, just culture and an organisation that sees all mistakes as an opportunity to learn and improve is even more important.

Peer-review of decisions taken in radiotherapy is another important part of a modern QM system, (figure 3). One can consider this as the soft side of the system compared to all the technical (or hard) QC that exists to assure the dosimetry. This soft part of the system includes e.g. decision to treat (in our case with radiation), prescription, treatment modality, volume(s) delineation, modality, treatment plan etc. All these steps involve a lot of subjective decisions by all professionals especially radiation oncologists. Marks et al have discussed this further [35].

Similar to peer-review of the soft branch in radiation oncology it is also of importance for the medical physics to have a system of internal and external audit of the commissioning process. For example, a linear accelerator should never be clinical before an external audit been taken place. For internal audit one should also consider to always having two medical physicists performing acceptance and commissioning [36].

3. The role of 3D dosimetry
Dosimetric QC is one of the major activities the clinical medical physicist is involved in regarding improving the safety within radiation oncology. This can of course be performed in many ways but the topic here is the role of 3D dosimetry. Today we have more or less three methods for 3D dosimetry:

- 3D detectors.
- 2D detectors which are complemented with reconstructions to 3D.
- Calculations based on either pre-planning data or data collected during the treatment or a combination.

The only fully 3D dosimeter in radiotherapy is the radiosensitive gel/plastic system, which are either read-out in a MRI system or in an optical laser scanning CT-like system. These system have displayed application and feasibility in many situations e.g. VMAT, RapidArc, protons, gating,
tracking, protons [37-41] However, there is none (to the author’s knowledge) reports regarding its role either in commissioning or in standardised and periodical QC measurements.

Regarding 2D systems many efforts have been reported using portal imaging systems integrated with the linear accelerator for dosimetry [42-45]. The concept is to use the transmitted fluence information and after appropriate corrections for different scatter sources and several other methods (e.g. back-projection) calculate the absorbed dose distribution within the patient. One institution that has implemented this fully is the NKI in Amsterdam who today do 3D dosimetry reconstruction of the dose distribution for all patients treated i.e. about 6000 patients annually. This group has also reported what type of deviations etc they have found during clinical practice of 3D-dosimetry (Mans et al [46, 47]). The conclusion was that about 4% of the treatments were associated with some kind of deviation from the original plan. Some of the methods also combine this with a 3D cone beam CT during treatment and thus basing the calculations on the information obtained.

The third method for 3D dosimetry is calculations based on the delivered treatment e.g. the 4D Monte Carlo simulations of continuously variable beam configurations by the group from British Columbia [48, 49]. The idea is to use the recorded data of the delivered treatment from the linacs log files. Their system also has the possibility to calculate the planar dose distribution to a detector plane either at the entrance or at the exit side. A system based on these principles may replace today’s patient specific measurement based QC as many clinics still are performing (see also figure 4).

**Figure 4.** The Monte Carlo based 3D verification system at Skåne University Hospital. The data (DICOM RP – plan, RD - dose, RS - structures and CT slices) from the OIS (Oncological Information System) including all log files from the delivery are exported and converted to input files to the linac simulation package (BEAMnrc) and the resulting phase spaces are communicated to the DOSXYZnrc system to calculate the absorbed dose distribution in the patient. These files are then exported back to the OIS for evaluation (From Cronholm and Nordqvist personnel communication 2014).

### 4. Quality assurance metrics

The fast adoption of the gamma analysis method for patient specific QC is probably well accepted by the radiation oncology community, however, one must point out that this method is maybe not adequate for all situations it have been applied to. There is a belief that the gamma analysis with its standard criteria of 3 % global dose difference and 3 mm (3G/3mm) is applicable in many situations. For example using these criteria for commissioning have been nicely summarised to be dis-advantages (Nelms et al [50]) Several serious errors may be hidden within this “standard” criterion, which maybe would be obvious if other evaluations methods would have been used. Thus one has to know and
understand the particulars dosimetry system completely, including its limitations, before applying it to a particular validation task (Schreiner’s 1st commandment [51]). A typical example of this are the conclusions from the above-cited paper; “Overreliance on the insensitive metric is counterproductive to quality improvement and can lead to the sense of complacency among the clinical physicists.” And “IMRT and VMAT commissioning, along with product validation, would benefit from the retirement of the 3%/3 mm passing rates as a primary metric of performance, and the adoption instead of tighter tolerances, more diligent diagnostics, and more thorough analysis.” (Nelms et al [39]).

In the future we maybe also see systems that ask for the operators consent before a diagnostic or therapeutic procedure is started. One can just imagine the situation in NYC when the MLC control points were missing if the system would have asked the therapist “Do you want to deliver 13 Gy with these setting on the linac” before the person pressed “BEAM-ON”?

5. Clinical outcome

Several examples show that good radiotherapy matters. For example, the clinical study TROG 0.2.02 HeadStart that compared two different drugs in combination with radiotherapy showed no difference between the two arms neither in overall survival or local control (Rishin et al [52]). More than 800 patients were included from 89 institutes in 16 countries. After re-evaluation of each patient’s treatment plan regarding the compliance to the treatment protocol one excellently showed that significant difference existed between outcome (overall survival and/or local control) and the compliancy to the treatment-plan protocol (Peters et al [53]).

The QA paper of the Swedish study of accelerated radiotherapy for head and neck cancers (ARTSCAN) showed the importance of having consensus meetings with all involved professionals. (Johansson et al [54]). This is in agreement with the Schreiner’s 2nd commandment - “Engage in the clinical exchange of ideas and knowledge through publication in scientific journals, and, perhaps more importantly, through regular communication, meetings and workshops with colleagues locally, nationally and internationally”[40]. It was also concluded that even if the participating department worked at a high technical level deviations were discovered by the QC procedures and directed the treatment into the correct treatment. The QA team’s conclusion was “the omission of a comprehensive QA procedure is risky”[43] From the report of the clinical outcome of this study one can read “In this study every effort was made to assure a similar quality of the radiotherapy throughout the study and at all centres. It is also possible that a stricter QA-process lead to an improved outcome for the conventional treatment (Rishin et al [41]). This may, in turn, have lead to less potential for improvement in the experimental arm of the study.” (Zackrisson et al [55])

An example where maybe more extensive risk analysis and full three-dimensional end-to-end dosimetry test may have revealed that the margins used for an image-guided treatment protocol for prostate were too optimistically reduced is the paper by Engels et al 2009 [56].

Weber et al [57] have published a compilation of results from several clinical studies where they concluded “These QA data stemming from prospective clinical trials show undisputedly that non adherence to protocol specified RT requirements is associated with reduced survival, local control and potentially increased toxicity.”

Recently a simulation of various QA levels for an head and neck study was published. This study concluded firstly that increased QA level should lead to better patient outcome. Secondly, from a health care perspective it is also cost effective with a higher level of QA since the less number of patients treated for recurrence [58].

6. Summary

The 3D dosimetry systems available at various clinical practical levels will in the future play a larger role due to its possibility of integrating the dose over the whole studied volume. The gel/plastic dosimeter is best suitable for end-to-end tests, at least as long as the read-out system requires a MRI-system. Probably the future will give us clinical systems based on light-based CT scanning systems. The planar Epid based systems are already today suitable for on-line patient in-vivo dosimetry. An
An interesting approach is the Monte Carlo simulations based on the recorded log files from the treatment unit. The most extensive model uses MC calculations of the given treatment and predict the dose in the patient CT-set as well as the planar dose distribution to a detector either at the entrance or at the exit plane.

There is undisputable evidence in the literature that a well-designed QA programme with appropriate and effective QC have the potential of resulting in high quality radiotherapy for the patients. An effective system should be designed where the soft QCs e.g. peer-review are included routinely. This gives radiation oncology the possibility to reach the level of clinical outcome that is possible. In other words we are giving the patients the maximum potential to get the most out of the offered treatment. Thus high quality is synonymous with high patient safety.

7. References

1. Korreman S S et al 2005 Radiother. Oncol. 76 311-8
2. Poulsen P R et al 2012 Int. J. Radiat. Oncol. Biol. Phys. 83 e265-71
3. Falk M et al 2012 Med. Phys. 39 1588-94
4. Vestergaard A et al 2014 Acta Oncol. 53 997-1004
5. Leinders S M et al 2013 Int. J. Radiat. Oncol. Biol. Phys. 87 1016-21
6. Heijkoop S T et al 2014 Int. J. Radiat. Oncol. Biol. Phys. (in press)
7. Lagendijk J J et al 2014 Semin. Radiat. Oncol. 24 207-9
8. Fallone B G et al 2014 Semin. Radiat. Oncol. 24 200-2
9. Keall P J et al 2014 Semin. Radiat. Oncol. 24 203-6
10. Web address as of Sept 20 2014: http://www.viewray.com
11. Dunscombe P 2012 Front. Oncol. 28 129
12. Royal College of Radiologist 2008 
   https://www.rcr.ac.uk/publications.aspx?PageID=149&PublicationID=281
13. American Society for Radiation Oncology 2012 Safety is no accident: A Framework for Quality Radiation Oncology and Care,
14. Web address of Sept 22 2014:
   https://rpop.iaea.org/RPOP/RPoP/Content/AdditionalResources/Training/1_TrainingMaterial/AccidentPreventionRadiotherapy.htm
15. Ash D and Bates T 1994 Clinical Oncology 6 214-25
16. Sociedad Española de Física Médica 1991 The Accident of the Linear Accelerator in the "Hospital Clínico de Zaragoza", SEFM, Madrid
17. Medical Management of Radiation Accidents, Second Edition, edited by Igor Gusev, Angelina Guskova, Fred A. Mettle, ISBN 0-8493-7004-3, 2001, CRC Press LLC.
18. Web address as of 12 Oct 2006
   http://www.asn.gouv.fr/sections/rubriquesprincipales/actualites/communiques-presse/2006/accidents-radiotherapie
19. Unintended overexposure of patient Lisa Norris during radiotherapy treatment at the Beatson Oncology Centre, Glasgow in January 2006, Report of an investigation by the Inspector appointed by the Scottish Ministers for The Ionising Radiation (Medical Exposures) Regulations 2000.
20. Borius P Y et al 2010 Neurochirurgie 56 368-73
21. Web address as of Sept 20 2014
   http://www.nytimes.com/2010/01/24/health/24radiation.html?pagewanted=all&_r=0
22. Huq M S et al 2008 Int. J. Radiation Oncology Biol. Phys. 71 S170-3
23. Ford E C et al 2009 Int. J. Radiation Oncology Biol. Phys. 74 852-8
24. Noel C E et al 2014 Med. Phys. 41 081717
25. Rath F 2008 Int. J. Radiation Oncology Biol. Phys. 71 S187-90
26. Nordström F et al 2012 Radiother. Oncol. 102 364-70
27. Pawlicki T et al 2008 Radiother. Oncol. 89 330-7
28. Web address as of Sept 20 2014  
https://rpop.iaea.org/RPOP/RPoP/Modules/login/safron-register.htm
29. Web address as of Sept 20 2014  
https://www.astro.org/Clinical-Practice/Patient-Safety/ROILS/Intro.aspx
30. Web address as of Sept 20 2014  
http://www.cpqr.ca/programs/national-incidents-reporting/
31. Web address as of Sept 20 2014  
http://www.nrls.npsa.nhs.uk/report-a-patient-safety-incident/about-reporting-patient-safety-incidents/
32. Yeung T K et al 2005 Radiother. Oncol. 74 283-91
33. Ford E C et al 2012 Int. J. Radiation Oncology Biol. Phys. 84 e263-9
34. Cunningham J et al 2010 Radiother. Oncol 97 6017
35. Marks L B et al 2013 Practical Radiation Oncology 3 149-56
36. Knöös T (in preparation)
37. Ceberg S et al 2010 Phys. Med. Biol. 55 4885-98
38. Ceberg S et al 2008 Phys. Med. Biol. 53 N387-96
39. Gustavsson H et al 2004 Phys Med Biol. 49 3847-55
40. Juang T et al 2014 Med. Phys. 41 071706
41. Baldock C et al 2010 Phys. Med. Biol. 55 R1-63
42. van Zijtveld M et al 2007 Radiother. Oncol. 82 201-7
43. van Zijtveld M et al 2009 Med. Phys. 36 946-52
44. Mijnheer B et al 2013 Med. Phys. 40 070903
45. Wendling M et al 2009 Med. Phys. 36 3310-21
46. Mans A et al 2010 Med. Phys. 37 2638-44
47. Rozendaal R A et al 2014 Radiother. Oncol. S0167-8140
48. Asuni G et al 2013 Phys. Med. Biol. 58 3535-50
49. Popescu T 2014 International Workshop on Monte Carlo Techniques in Medical Physics. Quebec City, June 2014
50. Nelms B E et al 2013 Med. Phys. 40 111722-15
51. Schreiner L J 2011 Med. Phys. 36 189-91
52. Rischin D et al 2010 J. Clin. Oncol. 28 2989-95
53. Peters L J et al 2010 J. Clin. Oncol. 28 2996-3001
54. Johansson K A et al 2008 Radiother. Oncol. 87 290-9
55. Zackrisson B et al 2011 Radiother. Oncol. 100 41-8
56. Engels B et al 2009 Int. J. Radiation Oncology Biol. Phys. 74 388-91
57. Weber D C et al 2012 Radiother. Oncol. 105 4-8
58. Weber D C et al 2014 Radiother. Oncol. 111 393-9