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Original Research Article

Assessing the impact of adaptations to the clinical workflow in radiotherapy using transit in vivo dosimetry

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ABSTRACT

Background and Purpose: Currently in-vivo dosimetry (IVD) is primarily used to identify individual patient errors in radiotherapy. This study investigated possible correlations of observed trends in transit IVD results, with adaptations to the clinical workflow, aiming to demonstrate the possibility of using the bulk data for continuous quality improvement.
Materials and methods: In total 84,100 transit IVD measurements were analyzed of all patients treated between 2018 and 2022, divided into four yearly periods. Failed measurements (FM) were divided per pathology and into four categories of causes of failure: technical, planning and positioning problems, and anatomic changes.
Results: The number of FM due to patient related problems gradually decreased from 9.5% to 6.6%, 6.1% and 5.6% over the study period. FM attributed to positioning problems decreased from 10.0% to 4.9% in boost breast cancer patients after introduction of extra imaging, from 9.1% to 3.9% in Head&Neck patients following education of radiation therapists on positioning of patients' shoulders, from 6.1% to 2.8% in breast cancer patients after introduction of ultrahypofractionated breast radiotherapy with daily online pre-treatment imaging and from 11.2% to 4.3% in extremities following introduction of immobilization with calculated couch parameters and a Surface Guided Radiation Therapy solution. FM related to anatomic changes decreased from 10.2% to 4.0% in rectum patients and from 6.7% to 3.3% in prostate patients following more patient education from dieticians.
Conclusions: Our study suggests that IVD can be a powerful tool to assess the impact of adaptations to the clinical workflow and its use for continuous quality improvement.

1. Introduction

In-vivo dosimetry (IVD) is recommended in radiotherapy to avoid major treatment errors and to improve accuracy, as elucidated in several reports [1–5]. IVD using Electronic Portal Imaging Device (EPID) images has become routine practice in a growing number of clinics in recent years. Many groups have reported the capability of EPID IVD to detect dosimetric deviations due to multiple sources, as well as the dosimetric advantages of using IVD: the Netherlands Cancer Institute has published multiple reports showing the importance of EPID IVD [6–10], other groups investigated the sensitivity and specificity for the detection of errors [11–17]. For a comprehensive literature review on electronic portal imaging for radiotherapy dosimetry the reader is referred to van Elmpt et al. [18] and McCurdy et al. [19].

Recent versions of EPID, increased computer power and fully automated EPID-based systems make it feasible to perform dosimetric patient specific quality assurance (PSQA) on a large scale. This extended usage opens possibilities to not only detect individual errors, but to use the data as a tool to evaluate the quality of treatment procedures and hence as an input for continuous quality improvement. In literature there is very limited data on this subject. Celi et al. [20] performed an analysis of the measurements per linac and energy over a two-year period including a more detailed examination per technique and treatment site over a six-month period. The prostate study revealed that beams and arcs with out-of-tolerance IVD results tended to have more complex modulation and a lower exposure of the points of interest. By

Abbreviations: IVD, In-vivo Dosimetry; FM, Failed Measurements; H&N, Head&Neck; EPID, Electronic Portal Imaging Device; VMAT, Volumetric Modulated Arc Therapy; PSQA, Patient Specific Quality Assurance; HU, Hounsfield Units.

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analyzing the long-term PSQA data of prostate Volumetric Modulated Arc Therapy (VMAT) plans, Mans et al. [21] revealed an under-dosage gradual increasing to about 2 % in 3 years correlated with plan complexity and coinciding with changes in clinically applied planning techniques. They also presented a procedure to investigate long-term trend analysis of PSQA data to identify any change with time and to find in a systematic way the reasons for it. The method of statistical process control (SPC) could be very useful for assessing results, as described by Fuangrod et al. [22] and Esposito et al. [23]. Establishing tolerance limits using the SPC technique can be quite labor-intensive though and this method has not been used by our group.

To our knowledge, none of the groups have evaluated the impact of changes made to the clinical workflow on the results of their IVD measurements. In the current paper the long-term PSQA data of a large cohort of patients with multiple pathologies is analyzed and correlated to adaptations in the clinical workflow. The aim was to demonstrate the capability of EPID IVD to assess the impact of adaptations to the clinical workflow and hence the possibility to use the bulk data of a longer period of time for continuous quality improvement rather than merely the detection of individual errors.

2. Materials and methods

The study was conducted at the Iridium Netwerk, a radiotherapy facility in Belgium with 10 linear accelerators: a mix of Varian Clinac, TrueBeam and TrueBeam STX (Varian Oncology Systems, Palo Alto, Ca, USA). Two treatment planning systems were used to create plans: RayStation (RaySearch Laboratories, Stockholm, Sweden) for stereotactic plans and Eclipse (Varian Medical Systems, Palo Alto, CA, USA) for all other types of plans. An automated web-based system was installed early 2017, for both pre-treatment and in-vivo QA based on EPID measurements (PerFRACTION™, part of SunCHECK™, Sun Nuclear Corporation (SNC), version 1.7 since October 2017, version 2.0 since May 2018, version 2.2 since November 2019, version 3.1 since April 2021). This study included the data of all patients treated between September 2018 and August 2022: DICOM data were pushed to the server, images were actively retrieved, and calculation and analysis occurred automatically in the background. Failing measurements were checked daily by the responsible physicists as well as by the physicians and appropriate actions were taken. The study was approved by the scientific committee and patient consent was waived.

Transit EPID integrated images were generated standardly the first three days of treatment and weekly thereafter. More measurements were performed sometimes due to technical problems or when patient follow-up was needed. The parameters for 2D gamma analysis depended on the type of treatment. The templates for this were designed to make a distinction in tolerance levels depending on the treatment site. These tolerances were empirically determined as described in a previous publication from our group [24] and have not been altered since, offering the advantage that results could be safely evaluated and compared over the years. An overview of the parameters for gamma analysis can be found in Table 1.

Results are reported for 84,100 transit IVD measurements of patients treated between September 2018 and August 2022, divided into four yearly periods. Failed measurements (FM) were divided per pathology and into four categories of causes of failure to assess the influence of adaptations to the clinical workflow: technical, planning and positioning problems, and anatomic changes. The categories of causes of failure have been assigned using the comments and notes that were made by the physicists and physicians for each failing measurement. If failure was due to more than 1 reason, the most contributing cause, according to the physicist, was assigned. Technical problems included software bugs, wrong imager position, problems with imager calibration and interrupted beams causing missing dose in the image. Planning problems included errors in body contouring, skin flash tool planning, Hounsfield units (HU) assignment, CT's with artefacts or wrong HU used for planning. Positioning problems included amongst others shoulder positioning, arm positioning, issues related to the breath hold technique and problems with immobilization devices. Examples of anatomy changes included weight loss, tumor growth or shrinkage, breast swelling and pneumonia.

Some adaptations to the clinical workflow were investigated in detail: the introduction of extra imaging for the boost in breast cancer after the first year, the education of radiation therapists (RTT's) on positioning of patients' shoulders in head & neck cancer (H&N) after the first year, more patient education from dieticians for prostate-, rectum-, upper abdomen- and esophageal cancer patients after the first year, ultrahypofractionated breast RT in five fractions with daily online pre-treatment imaging replacing a 15-fraction scheme in the second year and immobilization with calculated couch parameters and a Surface Guided Radiation Therapy (SGRT) solution (C-RAD) in the third year.

3. Results

The number of failed measurements (FM) gradually decreased over the years with 15.7 %, 13.3 %, 10.5 % and 9.0 % of FM in the first, second, third and fourth year respectively of which 6.2 %, 6.8 %, 4.5 % and 3.4 % were technical problems and 9.5 %, 6.5 %, 6.0 % and 5.6 % were caused by patient related issues, which were subdivided in planning problems, positioning problems and anatomic changes (Fig. 1).

Table 2 shows the results of the measurements for the investigated pathologies. Relevant numbers related to the investigated adaptations to the clinical workflow are highlighted.

FM attributed to positioning problems in boost breast cancer patients decreased from 10.0 % in the first year to 4.9 % in the second year after the introduction of extra imaging. FM attributed to positioning problems in H&N patients decreased from 9.1 % in the first year to 3.9 % in the second year following education of RTT's on positioning of patients' shoulders. FM related to anatomic changes in rectum and prostate patients have been reduced from 10.2 % and 6.7 % in the first year to 4.0 % and 3.3 % in the second year respectively, following patient education from dieticians. No difference was observed for stomach and esophageal

Table 1
Summary of empirically determined parameters for gamma analysis of in-vivo transit dosimetry results.

	Normalization (Local/Global)	Dose Difference Tolerance (%)	Distance Tolerance (mm)	Low Dose Threshold (%)	Passing Tolerance Level (%)
Breast	Local	7	6	20	90
Whole Brain RadioTherapy	Local	7	3	20	90
Palliative treatments	Local	7	5	20	93
H&N and Brain	Global	3	3	20	95
Rectum	Global	5	5	20	93
Other treatment sites with mask	Global	5	3	20	95
Other treatment sites without mask (including lung, pelvis, abdomen,…)	Global	5	5	20	95
Stereotactic 1 mm	Local	10	1	20	95
Stereotactic 2 mm	Local	10	2	20	95
Stereotactic 3 mm	Local	10	3	20	95

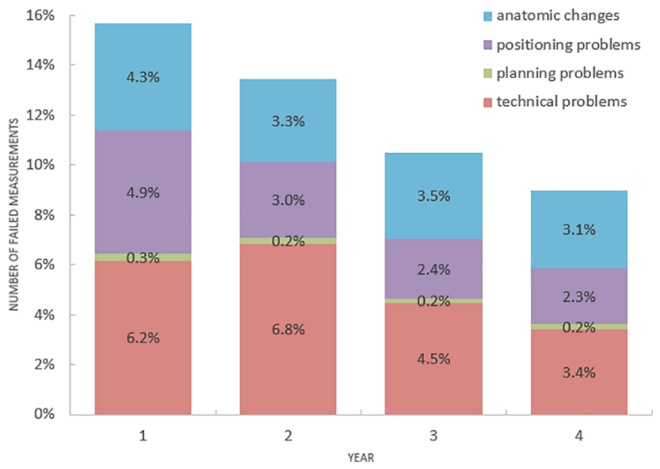

Fig. 1. Overview of the number of all failed measurements over the years, subdivided into four categories of causes of failure: anatomic changes, positioning problems, planning problems and technical problems.

cancer patients.

FM attributed to positioning problems in breast cancer patients decreased from 6.1 % in the second year to 2.8 % in the third year after the introduction of ultrahypofractionated breast radiotherapy with daily online pre-treatment imaging. FM attributed to patient positioning decreased further in the fourth year for most pathologies following the introduction of immobilization with calculated couch parameters and an SGRT solution, with the largest effect seen for extremities where FM due to patient positioning decreased from 11.2 % in the third year to 4.3 % in the fourth year.

4. Discussion

This study investigated if the observed trends in the IVD results over the years could be a result of adaptations to the clinical workflow, or the other way around, if the impact of adaptations could be monitored by IVD. Our results suggest EPID IVD was indeed able to assess the impact of some adaptations to the clinical workflow and can therefore assist in continuous quality improvement.

The most relevant observations of the overview of number of FM over the years (Fig. 1) were that the number of FM due to patient related problems gradually decreased from 9.5 % in the first year to 6.6 % in the second year, 6.1 % in the third year and 5.6 % in the fourth year. Between the first and the second year, there was a decrease of 1.9 % in positioning problems and 0.6 % in anatomic changes. In the third year the decrease was mainly caused by a decrease in technical problems and in patient positioning. The number of planning problems and anatomic changes were about the same. The fourth year showed a further small decrease. The increase of FM due to technical problems in the second year was mainly due to a bug in a new version of the IVD software causing a wrong predicted dose for plans with multiple energies. This bug was solved by the third year, so most of the software problems disappeared. The further reduction of technical problems over the years was mainly due to the gradual replacement of older linear accelerators by new machines. The latter experience less imager breakdowns and are

Table 2
Overview of the results of the measurements for prostate, rectum, upper abdomen, head & neck (H&N), extremities, esophagus, breast and boost breast patients, divided into four categories of causes of failure: technical, planning and positioning problems, and anatomic changes. Relevant numbers related to the investigated adaptations to the clinical workflow are highlighted in different colors: extra imaging for the boost in breast cancer in yellow, the education of radiation therapists on positioning of patients' shoulders in green, patient education from dieticians in blue, ultrahypofractionated breast RT in grey, immobilization with calculated couch parameters and a Surface Guided Radiation Therapy solution in pink.

first year	Prostate	Rectum	Upper Abdomen	H&N	Extremities	Esophagus	Breast	Boost Breast
Number of measurements	3380	872	426	2719	154	674	5110	1637
% passed measurements	84.6%	79.2%	80.3%	83.3%	70.8%	73.4%	85.8%	84.5%
% technical problems	7.1%	7.9%	7.0%	4.8%	12.3%	9.3%	6.3%	3.7%
% planning problems	0.0%	0.1%	0.7%	0.0%	1.3%	2.2%	0.2%	0.0%
% positioning problems	1.5%	2.5%	3.3%	**9.1%**	12.3%	**8.8%**	6.6%	**10.0%**
% anatomic changes	**6.7%**	**10.2%**	**8.7%**	2.8%	3.2%	**6.2%**	1.0%	1.9%
second year								
Number of measurements	3049	706	430	2392	137	658	5234	1171
% passed measurements	89.3%	91.5%	84.4%	90.6%	82.5%	73.3%	86.5%	76.9%
% technical problems	6.9%	3.7%	4.0%	2.5%	4.4%	8.7%	6.3%	16.6%
% planning problems	0.0%	0.1%	0.9%	0.0%	2.2%	0.0%	0.0%	0.0%
% positioning problems	0.4%	0.7%	2.3%	**3.9%**	6.6%	**5.2%**	**6.1%**	**4.9%**
% anatomic changes	**3.3%**	**4.0%**	**8.4%**	3.1%	4.4%	**12.9%**	**1.1%**	1.6%
third year								
Number of measurements	2287	672	404	2031	125	536	4703	621
% passed measurements	89.1%	90.6%	80.2%	91.4%	81.6%	76.3%	94.5%	89.5%
% technical problems	4.9%	3.9%	6.2%	1.2%	6.4%	8.8%	2.4%	3.9%
% planning problems	0.1%	0.0%	0.0%	0.0%	0.8%	0.0%	0.0%	0.0%
% positioning problems	0.4%	0.7%	2.7%	4.4%	**11.2%**	3.2%	**2.8%**	5.3%
% anatomic changes	5.5%	4.8%	10.9%	2.9%	0.0%	11.8%	**0.3%**	1.3%
fourth year								
Number of measurements	2845	721	338	2326	188	504	4965	1006
% passed measurements	91.9%	92.8%	77.8%	88.3%	93.1%	84.5%	95.3%	92.9%
% technical problems	3.5%	4.4%	9.5%	1.5%	1.6%	4.8%	1.8%	0.7%
% planning problems	0.3%	0.0%	1.2%	0.0%	0.5%	0.0%	0.1%	0.0%
% positioning problems	0.7%	0.6%	1.8%	6.2%	**4.3%**	1.4%	2.4%	3.9%
% anatomic changes	3.6%	2.2%	9.8%	4.1%	0.5%	9.3%	0.5%	2.5%

equipped with a more stable type of imagers, the imager position of the aS1000 imagers not being corrected mechanically during VMAT and hence less stable than the aS1200 imagers.

Most studies found in literature analyzing IVD results on a large scale, report deviations of the same type of causes and order of magnitude [5,22,25,26,27] but none to our knowledge, have evaluated the impact of changes made to the clinical workflow on the results of their IVD measurements.

After the first year, analysis of our results showed a large number of positioning issues for extremities, boost breast patients and Head & Neck (H&N) patients. Therefore, some changes to the clinical workflow were introduced: after the first year extra imaging was applied for boost breast and extra education was given to the RTT's to pay attention to proper positioning of the shoulders. After the third year immobilization with calculated couch parameters was introduced and an SGRT solution was installed on all treatment machines aiming at reducing the number of failed measurements due to positioning issues, especially for extremities.

To evaluate the impact of these changes in the workflow, FM of these pathologies were analyzed in more detail. FM attributed to positioning problems in boost breast cancer patients decreased from 10.0 % in the first year to 4.9 % in the second year (highlighted in yellow in Table 2). The large number of technical problems in the second year was caused by a software bug where the dose prediction of plans with multiple energies, which is often used for boost breast plans, was wrongly calculated. This bug was solved in the third year. The number of positioning problems almost stayed the same in the third year, so the improvement in patient positioning is likely to be caused by the use of extra imaging. FM attributed to positioning problems in H&N patients decreased from 9.1 % in the first year to 3.9 % in the second year (highlighted in green in Table 2). This number is gradually getting worse in the third and the fourth year. We are currently looking into this thoroughly to see if retraining the RTT's is needed or if there could be other reasons, for instance small changes in immobilization strategies. After the introduction of immobilization with calculated couch parameters and an SGRT solution in the third year, FM attributed to patient positioning decreased further for most pathologies, with the largest effect seen for extremities where FM due to patient positioning decreased from 11.2 % in the third year to 4.3 % in the fourth year (highlighted in pink in Table 2).

Analysis of the results after the first year also showed many failing measurements due to anatomic changes for prostate, rectum, upper abdomen and esophagus patients, mostly weight loss and change in intestinal contents. Therefore, the threshold for follow-up and education by a dietician has been lowered. In Belgium, as part of the cancer plan, funding for dieticians by hospitals with an oncology (primary) care program has been granted.

FM related to anatomic changes in rectum and prostate patients have been reduced from 10.2 % and 6.7 % in the first year to 4.0 % and 3.3 % in the second year respectively (highlighted in blue in Table 2). The small number of positioning problems in these patients is probably due to the lower sensitivity of transit in vivo dosimetry for these treatment sites [12,24]. Additionally, a retrospective study was conducted to evaluate if additional help with bladder and rectum preparation in prostate cancer patients by home nurses could improve patients' preparation, but no statistically significant differences could be observed between the test group and the control group receiving the information on bladder and rectum preparation according to the standard protocol [28]. Despite the reduction of FM related to anatomic changes in rectum and prostate patients, there was no noticeable reduction in the number of patient plan adjustments, suggesting the impact of our efforts in that area are still quite limited. Also no difference was observed for abdominal and esophageal cancer patients (highlighted in blue in Table 2). For the esophageal patients in the first year more FM were classified with a cause of positioning problems, but it was seen that these positioning problems are often caused by an anatomic change, which is why the classification has changed after the first year. The overall number of FM didn't have a noticeable change.

Following the publication of long-term results of the FAST Forward trial [29,30], postoperative ultrahypofractionated breast RT in five fractions with daily online pre-treatment imaging was implemented in the second year replacing a 15-fraction scheme. FM attributed to positioning problems in breast cancer patients decreased from 6.1 % in the second year to 2.8 % in the third year and FM related to anatomical changes (breast swelling) have been reduced from 1.1 % in the second year to 0.3 % in the third year (highlighted in grey in Table 2). There is only a very small difference in patient positioning problems between the first and the second year, so it's likely to be the introduction of the 5-fraction scheme in the second year that caused the decrease. Also a retrospective study has been conducted [31] comparing 2 groups of 203 breast cancer patients, one group treated with 5 fractions with daily pre-treatment imaging in 2020, the other group treated in 2019 with 15 fractions. To investigate the influence of the daily imaging, a subgroup was created with the results of the fractions of 15fx-group, after pre-treatment imaging. A large difference in patient positioning problems could be observed between the 5-fraction group and the 15-fraction group. Comparison with the subgroup receiving online imaging showed almost no difference though, indicating the daily online IGRT correction protocol is the main cause of the difference between the 2 groups. Also, the difference in breast swelling as a cause disappeared, indicating that using pre-treatment imaging leading to more accurate positioning, could also bring swollen breasts back within constraints [31].

Limitations of this study are that the data were interpreted retrospectively and that the data are not suitable for further statistical analysis and are therefore hypothesis-generating. The number of measurements and detected problems varied between pathologies, causing a larger standard deviation and confidence interval for e.g. extremities that had a lower number of measurements. Over the years the number of measurements were roughly the same though. To our knowledge, no literature is available on the expected evolution of the number and causes of FM. Given this, we were unable to determine in advance which deviations and improvements would be clinically relevant. Therefore, we described changes in numbers of FM and interpret them in light of changes in clinical workflow. Some of these changes were based on the interpretation of past measurements (e.g., assistance of dieticians, training of RTT's) and others on new scientific data (e.g., publication in implementation of Fast Forward scheme). Each interpretation and decision was made after consultation within a group of physicists, physicians, RTT's and quality managers with expertise. Other reasons for the trends in the results than the ones reported here cannot be excluded. We also did not use SPC techniques to assess results or establish tolerances. Small dosimetric differences due to algorithm problems and systematic deviations cannot be ruled out. Using these methods the sensitivity and specificity of the IVD could maybe be improved. Vendors could facilitate continuous quality improvement using IVD like the ones described in this study and in other studies such as those of Mans et al. [21], Fuangrod et al. [22] and Esposito et al. [23] by providing better access to dashboard possibilities, pre-configured classification options and automatic analysis tools for large-scale data including SPC and Receiver Operating Curves.

Despite the limitations of the study, our results suggest that a broad analysis of IVD results cannot only indicate possible items for improvement but also assess and evaluate the impact of adaptations to the clinical workflow and can hence be a powerful tool in the continuous quality improvement of treatments.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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