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Use of metrics to quantify IMRT and VMAT treatment plan complexity: a systematic review and perspectives

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Abstract

Purpose: Fixed-field intensity modulated radiation therapy (FF-IMRT) or volumetric modulated arc therapy (VMAT) beams complexity is due to fluence fluctuation. Pre-treatment Quality Assurance (PTQA) failure could be linked to it. Several plan complexity metrics (PCM) have been published to quantify this complexity but in a heterogeneous formalism. This review proposes to gather different PCM and to discuss their eventual PTQA failure identifier abilities.

Methods and Materials: A systematic literature search and outcome extraction from MEDLINE/PubMed (National Center for Biotechnology Information, NCBI) was performed. First, a list and a synthesis of available PCM is made in a homogeneous formalism. Second, main results relying on the link between PCM and PTQA results but also on other uses are listed.

Results: A total of 163 studies were identified and n=19 were selected after inclusion and exclusion criteria application. Difference is made between fluence and degree of freedom (DOF)-based PCM. Results about the PCM potential as PTQA failure identifier are described and synthesized. Others uses are also found in quality, big data, machine learning and audit procedure**.**

Conclusions: A state of the art is made thanks to this homogeneous PCM classification. For now, PCM should be seen as a planning procedure quality indicator although PTQA failure identifier results are mitigated. However limited clinical use seems possible for some cases. Yet, addressing the general PTQA failure prediction case could be possible with the big data or machine learning help.

Keywords: modulation indices, plan complexity, volumetric modulated arc therapy

1. Introduction

Fixed field-intensity modulated radiation therapy (FF-IMRT) and volumetric modulated arc therapy (VMAT) have become common in radiation oncology treatments of gynaecological, prostate, and head and neck (H&N) tumours [1]. Compared to older techniques, the estimated advantages are dose conformation improvement, dose escalation potential, simultaneous integrated boost feasibility or highest organ at risk sparing performance [2]–[6]. At this time, publications relating to commissioning [7], treatment planning [8], associated quality assurance (QA) [9], clinical implementation [10][11], dose prescription and reporting [12] have been emitted, making this technique widespread.

In association with this technique a dedicated QA program [13][14] is needed, and a distinction between linac QA (LQA), pre-treatment QA (PTQA) and patient-specific QA (PSQA) could be made. Linac QA is related to the linac capacities of conducting accurate FF-IRMT or VMAT beams delivery by, for example, realizing specific multi-leaf collimator (MLC) tests [15][16]. Performed before the start of treatment, PTQA relies on the criteria-based validation of beam delivery detector acquisition. Last, PSQA is related to an in-vivo measurement made during treatment with detectors such as diodes or through EPID-transit solutions.

A report was recently published on methodologies and tolerance limits [17] permitting the harmonisation of PTQA practices and establishing consistent and comparable criteria among institutions. As the origins of PTQA failure could be uneasy to identify between dose calculation (TPS, dedicated software), dose delivery (linac) or dose measurement (detectors) [18], most of the time re-planning is necessary.

Moreover, PTQA – and specifically the gamma pass rate (γ_{pass}) index [19][20] – correlates weakly with dose-volume histogram (DVH) variation [21][22] and may not substantially detect clinically relevant errors [23]. Pre-treatment QA failure identifiers could then be considered as less time-consuming than linac-occupation approaches and would represent a benefit for radiation oncology departments.

So, a VMAT or FF-IMRT plan could be considered as the simultaneous variation of different degrees of freedom (DOFs) combined with fixed-physical properties (FPPs). A DOF corresponds to all achievable beam discrete values which varies during deliverance like dose rate, gantry rotation speed and monitor units (MU) per control point (CP) [24], and FPPs to constant parameters such as MLC properties (for example leaves transmission, edge shape and motion limitations), linac properties (such as beam energy and maximum gantry rotation speed) or plan specificities (for instance CP number). The beam fluence depends on both DOF and FPP combinations, and its fluctuation may be seen as its complexity.

Variables could quantify DOF variations such as the overall leaf travel (OLT), which represents the total distance (in mm) travelled by an MLC leaf during beam delivery. Given the simple variable employment, OLT is a basic DOF calculation; however, to go further, some authors have proposed plan complexity metrics (PCMs). These metrics are DOF and FPP-based calculation results and could be seen as beam complexity quantification. One of the potential uses of PCMs could be their PTQA failure prediction capacities.

To date, a substantial amount of literature exists since one of the earliest contributions, which was made by the Webb team with the introduction of the modulation index (MI) in 2003 [25]. Giorgia [26] continued with this approach with the first MI-PTQA failure correlation tests. In 2010, McNiven [27] introduced the modulation complexity score (MCS) as a different PCM combination. Yet, many other authors have contributed to this research field, and PCMs were heterogeneously formalised. A semantic issue also appeared because words such as metrics, modulation indices or plan complexity score are becoming common and often refer to the same concept. Therefore, a systematic review, such as the one presented here, should constitute an interesting approach not only to provide a homogeneous overview of already published PCMs and to discuss their known PTQA failure prediction abilities, but also to address their other potential uses.

2. Material and Methods

According to preferred reporting items for systematic reviews and meta-analyses (PRISMA)'s recommendations for systematic review [28], published articles were identified in April 2019 through a Medline PubMed search using a combination of ('VMAT' OR 'IMRT') AND ('complexity' OR 'modulation') AND ('index' OR 'metric' OR 'metrics' OR 'indices' OR 'score'). No date range was applied, and only English-written and peer-reviewed articles were considered. Inclusion criteria were as follows: articles with new DOF or fluence map-related PCM explicit formulas or articles involving treatment with PCM adaptation from existing metrics. Exclusion criteria were review and optimisation function modification articles. First, published PCMs are reviewed with the following aims: to class, synthesise and homogenise the formalism and to qualitatively describe the influence parameters (1). Second, the main results dealing with the PCM PTQA-failure prediction abilities are described (2). Third, PCMs' other uses are presented (3).

3. Results

The PubMed search yielded 163 results, of which 159 are original, while 4 are review articles. After applying both inclusion and exclusion criteria, only 19 articles were selected [15], [25]–[27], [29]–[44].

(1) Review of existing plan complexity metrics

The classification, synthesis and qualitative evaluation of already published PCMs can be differentiated according the metrics' relate to a beam fluence map (MI, MI_G, PIMV, FMC, FD, ASM, IDM, CTR, VAR, COR, S [Table 1]) or to a DOF-based calculation (MI_S, MI_a, MI_{SPORT}, DC, M, MCS, MCS_v, oMCS, MFA, CAM, EAM, C/A, SAS, MAD, CLS, CAS, PA, PI, PM, PMU, MLC_{velo}, ALPO [Table 2]).

(2) Main results regarding the link between PCMs and pre-treatment QA failure

Results are synthesised in Table 3. A total of 23 correlation tests were found in the literature. With the exception of Götsted [42], none of them found a significant and strong correlation between PCM and

PTQA results, but such a correlation was obtained for MLC complexity tests. Despite this, some other results were also found.

For FF-IMRT, after the Webb MI [25] adaptation, Giorgia [26] realised some correlation tests between MI_G and EPID $\gamma_{3\%/3mm}$ and argued in favour of fixing an MI_G threshold at 19. Park [38] added three other PCMs (MI_s, MI_a, MI_t) to the MI family, arguing that they focus on mechanical parameter variations under the assumption that abrupt mechanical variations increase delivery uncertainties. A correlation analysis was performed between MI_s, MI_a, MI_t, MCSv, LTMCS and MI_{SPORT} and γ_{pass} rates (3%/3mm, 2%/2mm, 1%/2mm and 2%/1 mm) from 2D diode array forty planar dose distribution acquisitions. The significant obtained Rs values for MI_s, MI_a and MI_t with 2%/2 mm criteria were -0.637, -0.648 and -0.660 respectively, and with 1%/2 mm criteria, those values were -0.662, -0.668 and -0.675 respectively. It should be noted that the MI_s values were greater for H&N than for prostate, which is a result also found by Li [32], confirming intuitive thought on the greater complexities of H&N plans.

McNiven tested the link between different localisations of the FF-IMRT MCS and $\gamma_{3\%/3mm}$ and $\gamma_{2\%/1mm}$ pass rates acquired on a 2D diode array [27]. First, it was demonstrated that MU and MU/CP are weakly correlated with MCS because of the higher amount of information contained in MCS compared to intuitive basic PCMs such as MU or MU/CP. Second, results indicated that MCS could have a threshold effect, and beams higher than 0.8 MCS were identified as robust (100% specificity). Masi [33] completed this work by adapting MCS for a VMAT plan (MCS_v) and particularly studied the CP angular sampling impact. A Pearson correlation test was performed between LT, MCS_v and $LTMCS_v$ and local $\gamma_{3\%/3mm}$ and $\gamma_{2\%/2mm}$ pass rates on a bi-planar diode array. A significant correlation was found for 4° CP sampling, and those PCMs were found to be possible PTQA failure identifiers while using threshold values. It was also found that a finer angular sampling increased γ pass rate results but lowered the correlation.

Younge [45] introduced the M PCM and performed a receiver operating characteristic (ROC) analysis for 649 previously treated plans completed by 62 plans for which PTQA failed. This allowed for the

selection of a threshold value of 0.180 mm^{-1}, which led to the true positive rate of 44% for correctly identifying PTQA failed plans and to the false positive rate of 7%. According to these results, the implementation of overall plan screening was set up in the clinical workflow, and plans that were too complex were excluded because of their PTQA-failure risk.

Valdes [46] tested 78 metrics on 498 IMRT plans and suggested that $\gamma_{3\%/3mm}$ local dose/DTA and 90% threshold PTQA failures have five origins: MLC leaves transmission, leaf end leakage, jaw transmission, tongue and groove effect, and charge particle disequilibrium. It was found that the most relevant metrics to describe the passing rates were the MU factor (MU per Gy), the small aperture score (SAS), the irregularity factor and the fraction of the plan delivered at the corners of the 40-cm x 40-cm field. Indeed, according to Valdes, the higher these values were, the lower the PTQA passing rate was.

Park [47] tested the correlation of MIs, MIa, MIc, MCS, PA and PI for 202 failure occurrences of FF-IMRT with PTQA on two different linacs and with both Mapcheck2 and Archeck. The author found that PI was the best PTQA failure identifier and concluded by arguing that '*the PI value could support the verification of IMRT plan delivery accuracies before patient treatment and reduce resource consumption in the clinic, as it can be calculated at the planning level.'* Lastly, Glenn [48] studied the relationship between 16 PCMs (including MU, MCS, PI, MI_s, MI_a and MI) on H&N plans and found no significant correlation between PCM results ($r_s = \pm 0.30$) and $\gamma_{7\%/4mm}$ radio-chromic films measurements or single-point thermo-luminescent dosimeter (TLD) dose.

(3) Other PCM uses

Data statistics and machine learning

Palaniswaamy [49] developed in-house software to monitor the statistical trends of PTQA results differentiating radiotherapy localisations. By setting the specific-site PTQA tolerance, false positive and false negative results were reduced. Valdes [46] pooled over 78 variables, which included PCMs and FPPs (such as dosimetric leaf gap, leaf transmission and SAS), and applied a self-developed

machine-learning algorithm to predict the PTQA γ_{pass} rate. This could be seen as a virtual PTQA, as the team was able to realise an *a posteriori* predictability of PTQA results with a 3% confidence level.

Audit perspectives and comparison of centres

Nelms [50] used a DVH-based PCM set to quantify clinical practice variations and potential technology parameter dependence. It was demonstrated that a user's skill seems to be more important than technology or demographic user characteristics (such as years of experience). McGarry [51] compared 39 VMAT γ_{pass} rates obtained from 34 different centres, as these plans were created from type 1 or type 2 TPS. A significant finding ($p < 0.01$) was that type 2 TPS created poorer plan quality (higher MCS and MU) and that type 2 had a lower gamma pass rate than type 1 TPS plans when comparing them on a multi-detector.

Hernandez [52] developed an in-house program to generate plans with different complexity indices and compared 100 VMAT plans from two institutions. As stated, it was not possible to use PCMs as PTQA failure identifiers. It was also found that some PCMs addressed the same information, as they are correlated, thereby leading the author to plead for their careful use in multi-centre comparison.

4. Discussion

(1) Review of existing PCMs

Quality has become one of the major interests of radiotherapy teams [53], especially for patient safety [54]. While medical physics work is increasingly being divided between physicists, dosimetrists, nurses, technicians and medical physicists, clinical involvement should remain a strong reality, especially in QA and risk assessment [55]. To this end, PCM use in a clinical workflow could offer three relevant tools. First, for each FF-IMRT or VMAT plan, a PCM comparison with other similar plans (such as localisation or Linac) would permit one to upgrade the safety of the planning procedure by setting limits and producing knowledge on 'abnormal plans'. Second, PCM use offers a 'common language' between team members, allowing for scientifically based discussions about many topics such as PTQA failure, planning procedures and education. Third, PCM plan quantification should be

seen as an evidence production, making it an indicator of the quality of clinical practice. All of this could also be seen as contributing to the confidence of the radiation therapy team.

(2) Main results regarding the link between PCMs and PTQA failure

Careful consideration is required when addressing the PTQA γ_{pass} problem and one should be aware of what is relevant in PTQA failure. This was well described by Crowe [56], who investigated the action level and PTQA-device dependence and concluded that the use of a $\gamma_{3\%/3\mathrm{mm}}$ score for PTQA is widespread despite concerns about the suitability of the γ evaluation, and who suggests that a 3%/3mm is not sensitive enough. Moreover, Nelms [57] argues for the retirement of this criteria because of its inability to detect systematic errors. It is to say that every correlation test and predictability remain dependent on detector characteristics [58] and their weak capacities to accurately distinguish acceptable from unacceptable plans [59]. Further evaluations must be considered with this PTQA sensitivity problem. This review does not establish a clear general correlation between PCM and PTQA performance and failure. Indeed, while most of the results indicate a significant link, it was contrasted with a weak correlation. Furthermore, these results should be seen as institution-dependent and published PCM values for threshold or limits should be used carefully. The different TPS, anatomical localisation, PTQA measurement, analysis protocol or statistical correlation methods could explain these results. Therefore, with this actual state of the art, users could create their own PCM correlation for self TPS, anatomical localisation, 2D or 3D PTQA measurement, gamma criteria and threshold. So far, someone who is considering setting up a PCM as a PTQA failure identifier should quantify his own thresholds, limits and prediction capacities. Therefore, one should then consider setting up all Table 1 PCM calculations – especially MI_S, MI_a, MI_{SPORT}, M, MCS, MCS_v, MFA, CAM, EAM, SAS, MAD, CLS and PI – and then establishing correlation with their own PTQA results, with a special focus on SAS, PI, MCS and MI because of their estimated higher potential. These recommendations should allow the user to utilise a PCM as a PTQA tool and to compare his own results with the literature data.

From these previous considerations, it seems too early to affirm that a sufficient amount of data exists to prove that PCMs could replace PTQA for general cases. Nevertheless, it appears that their use can provide interesting results for clinical use [60].

(3) Other perspectives on the use of PCMs

Data statistics and machine learning

Many databases relying on surveillance, epidemiology, demographic or diagnosis are now used in radiation oncology [61], and progress capacities could depend on their reliability. The objective relies on the ability to establish predictive models, and there is a strong need for high data quality to construct these bases [62]. As Mayo [63] wrote, it should be common for clinics to have the ability to rapidly gather datasets to address practice quality improvement for routine or translational research. In this perspective, one of the potential uses of PCMs could be related to the creation of dedicated databases. As the inputting information into these databases should be user-friendly and low in terms of time consumption for an easy clinical workflow implementation, it should preferably be carried out with an automatic procedure. As we are now in an era where radiation oncology data are generated daily, these databases could be employed to study the relationship between PCMs and dosimetry indices, treatment planning homogeneity, clinical outcome, mechanical component state or QA results. A data mining algorithm could also be developed to guide the analysis of these datasets and perhaps to find patterns that the human cannot detect. Even more promising, machine learning in radiotherapy [64] could be a way to develop or create new PCMs or a PCM pool that could resolve the PTQA failure problem in general cases.

Audit perspectives and comparison of centres

Radiation oncology [65] and, more precisely, dosimetry audits are now common processes in many countries, and they permit the evaluation of clinical practice heterogeneities between centres on themes such as TPS modelling and measurement accuracy [66][67], independent dose measurement with non-standard detectors [68] or independent peer quality control [69]. In this perspective, another potential role of PCMs could be to compare centres' propensity to deliver high or low complex plans

by introducing them into these audit processes. Assessing knowledge on delivered plans with PCM score distribution would allow for a comparison of centres' practices. On the other hand, benchmarking PCM score varieties could permit one to fix limits for further clinical assay. It could also help centres to conduct an auto-evaluation of their own practices.

5. Conclusion

The aim of this work was to list and synthesise available PCMs thanks to a systematic review methodology. As the development of such variables was sensibly guided by the PTQA failure problem, a discussion about the link between available PCMs and this issue was in favour of an institution-dependent process because of the TPS, the anatomical localisation, the PTQA measurement, the analysis protocol and the statistical method dependence. So, this work plead for setting up data collection of plan PCMs in institution, and vendors as TPS manufacturers are encouraged to provide this type of tool. More specifically, SAS, PI, MCS and MI should be especially considered because of their sensitivity and their occurrence in the studies. For the use of PTQA failure identifiers, a self-PCM correlation should be made with consideration for TPS, localisation and gamma criteria of 2%/2mm. Finally, other PCM uses seem to have the potential to aid in answering this problem and to open new research fields in machine learning or audit processes.

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Table of Content

PCM	Type PCM Name Reference	Formula	Plan Complexity Sensivity
Modulation Index	Original MI Webb,*Phys.Med.Biol., 2003*	$MI_I = \int_0^F Z(f)\,df$ Where $Z_I(f) = Z_{I_x}(f) = \frac{1}{n-1} N_{I_x}(f; \Delta I_x > f\sigma_I)$	Sensitive to the intensity fluence map in one direction, (take account of intensity values changes between adjacent bixels of the fluence map in X direction).
	Adaptation MI_G Giorgia, *Radiat. Oncol., 2007*	$MI_I = \int_0^F Z_I(f)\,df$ Where $Z_I(f) = \frac{\left[Z_{I_x}(f)+Z_{I_y}(f)+Z_{I_{xy}}(f)\right]}{3}$ $Z_{I_x}(f) = \frac{1}{n(m-1)} N_{I_x}(f; \Delta I_x > f\sigma_I)$; $Z_{I_y}(f) = \frac{1}{(n-1)m} N_{I_y}(f; \Delta I_y > f\sigma_I)$; $Z_{I_{xy}}(f) = \frac{1}{(n-1)(m-1)} N_{I_{xy}}(f; \Delta I_{xy} > f\sigma_I)$	Sensitive to the intensity fluence map in three directions, (take account of intensity values changes between adjacent bixels of the fluence map in X, Y and XY directions).
Plan Intensity Map Variation	Original PIMV Coselmon, *Med. Phys.*, 2005.	$PIMV = \sum_{i=1}^{n}\sum_{j=1}^{m}\left(\left\|I_{i,j} - I_{i,j+1}\right\| + \left\|I_{i,j} - I_{i+1,j}\right\| + \left\|I_{i,j} - I_{i+1,j+1}\right\|\right)$	Sensitive to the intensity fluence map in two directions (X and Y).

Fluence Map Complexity	Original FMC Llacer, *Phys. Med. Biol.*, 2001	$FMC = \frac{1}{\sum_{i=1}^{n} I_i} \sqrt{\sum_{i=1}^{n} (I_i - \lambda[I_{i+1} + I_{i-1}])^2}$	Sensitive to the intensity fluence map in one direction by considering the difference between the fluence of a bixel and the fluence of lateral neighboring bixels.
Edge Area Metric	Original EAM Götstedt, *Med. Phys.*, 2015	$EAM = \overline{EAM_k}$ Where $EAM_k = \frac{R_{edge}}{R_{edge} + R_{open\ area}}$	Sensitive to the relative amount of edge region for the MLC aperture. Note that the EAM of a beam is the mean value of all EAM scores calculated for each CP.
Fractal Dimension	Original FD M. Nauta, *Med. Phys.*, 2011. M. Tambasco *Phys. Medica*, 2013.	$FD = \frac{4 - SLP}{2}$ Where SLP is the slope of the plot of $\log(\gamma(h))$ versus $\log(h)$ With $\gamma(h) = c \cdot h^{4-2 \cdot FD} = \frac{1}{2D} \sum_{i=1}^{D} (FS(x_i) - FS(x_i + h))^2$	Sensitive to the structural irregularities of the fluence map at different size scale, by considering the fractal surface variations between neighbor pixels, spaced of a distance h. Note that the mathematical expression is derived from the variogram method.
Angular Second Moment	Original ASM Park, *Radiat. Oncol. Lond. Engl.*, 2014.	$ASM = \sum_{i=0}^{N_g-1} \sum_{j=0}^{N_g-1} GLCM_{i,j}^2$	Metric based on the GLCM that indicates a measure of the homogeneity of a fluence map.
Inverse Difference	Original IDM Park, *Radiat. Oncol.*	$IDM = \sum_{i=0}^{N_g-1} \sum_{j=0}^{N_g-1} \frac{1}{1 + \lvert GLCM_i - GLCM_j \rvert} GLCM_{i,j}$	Metric based on the GLCM that indicates a measure of the local homogeneity of a fluence map.

Moment	*Lond. Engl.*, 2014.		
Contrast	Original CTR Park, *Radiat. Oncol. Lond. Engl.*, 2014.	$CTR = \sum_{i=0}^{N_g-1}\sum_{j=0}^{N_g-1} \left\|GLCM_i - GLCM_j\right\|^2 \cdot GLCM_{i,j}$	Metric based on the GLCM that indicates a measure of the local variations in a fluence map.
Variance	Original VAR Park, *Radiat. Oncol. Lond. Engl.*, 2014.	$VAR = \sum_{i=0}^{N_g-1}\sum_{j=0}^{N_g-1} (GLCM_i - \overline{GLCM_i})^2 \cdot GLCM_{i,j} + \sum_{i=0}^{N_g-1}\sum_{j=0}^{N_g-1} (GLCM_j - \overline{GLCM_j})^2 \cdot GLCM_{i,j}$	Metric based on the GLCM that indicates a measure of the inhomogeneity of a fluence map.
Correlation	Original COR Park, *Radiat. Oncol. Lond. Engl.*, 2014.	$COR = \frac{\sum_{i=0}^{N_g-1}\sum_{j=0}^{N_g-1}(GLCM_i - \overline{GLCM_i}) \cdot \left(GLCM_j - \overline{GLCM_j}\right) \cdot GLCM_i}{\sigma_x \sigma_y}$	Metric based on the GLCM that indicates a measure of the linear dependency of gray levels in a fluence map.
Entropy	Original S Park, *Radiat. Oncol. Lond. Engl.*, 2014.	$S = -\sum_{i=0}^{N_g-1}\sum_{j=0}^{N_g-1} GLCM_{i,j} \cdot \log(GLCM_{i,j})$	Metrics based on the GLCM that indicates a measure of a randomness of a fluence map.

Table 1 : Review of IMRT/ VMAT plan Plan Complexity Metrics formulas calculated on beams fluence map.

Signification of the different variables that appears in metrics PCM (Note that for a IMRT plan and/or a VMAT plan is the sum of beams PCM included in the plan weighted by Monitor Units):

A_{Eq}: Equivalent square field or aperture ;

A_k: Aperture area for the k*th* CP

AAV_k: Aperture Area Variability for the k*th* CP (VMAT), segment (IMRT): Characterize the variation in segment area relative to the maximum aperture defined by all segments

AI_k : Aperture Irregularity calculated by considering the noncircularity of the aperture

α: Weighting factor for the acceleration: $\frac{1}{t_k}$

a_c: Aperture distance criteria for two opposite leaves

a_l: Aperture distance between two opposite leaves

CAM_k: Converted Aperture Metric for the for the k*th* CP

C_{leaf}: Centre of aperture distance between opposite leaves

C_{MLC}: Centre of the MLC axis (aligned with the beam axis)

c: Constant in the semivariogram function $\gamma(h)$ formula

D: Number of pairs of data points whose lag is h, for the Fractal Dimension calculation

F : Maximum fraction of the standard deviation of the sensitive parameter considered, which represents the upper born of integration of the spectrum

$FS(x_i)$: Fractal surface at the data point x_i

f : Fraction of the standard deviation of the sensitive parameter considered: $f = 0.001\,, 0.002\,, \ldots\ 2$

GA_k : Gantry Angle for the k*th* CP

$GLCM_{i,j}$: Gray Level Co-occurrence Matrix, that indicates the intensity relationships between pairs of pixels in the fluence map

$\overline{GLCM_i}$: Mean value of the pixels in the GLCM, in the i*th* direction

$\gamma(h)$: Semivariogram function used in spatial statistics that linked the Fractal Dimention (FD) to a profile of the fluence map

$g(A_{Eq})_k$: Conversion value of the equivalent square field, using conversion function $g(x)$, for the k*th* CP

$\overline{g(d_l)}_k$: Mean of all conversion values of the distances between MLC leaves in X and Y direction, using conversion function $g(x)$, for the k*th* CP

$g(x)$: Conversion function to obtain a nonlinear relation between distance between MLC leaves, and their contribution to the complexity of the aperture

h: Distance between two data point for the Fractal Dimension calculation

$I_{i,j}$: Matrix of the intensity fluence map with $n \,.\, m$ shape

ΔI_i : Absolute difference between intensity values of adjacent-bixel in the i*th* direction: $\Delta I_i = |I_i - I_{i+1}|$

K: Number of neighbouring CPs for a CP considered, which is an arbitrary value

LSV_k: Leaf Sequence Variability for the k*th* CP (VMAT), segment (IMRT): Characterize the variability of a field shape per segment or CP

$sLSV_k$: Sectored Leaf Sequence Variability for the k*th* CP (VMAT), segment (IMRT): Characterize the variability of a field shape by considering the leaves that cover the organ considered in the field, per segment or CP

λ: Weighting factor for lateral bixels, equal to 0.5 when a bixel have two lateral neighbours

MI_I : Modulation index sensitive to intensity fluence map, which is the integration of the spectrum $Z_I(f)$

MI_{MLCa} : Modulation index sensitive to MLC leaf acceleration changes for the k*th* CP, which is the sum of all MI_{MLCa_l}

MI_{MLCs} : Modulation index sensitive to MLC leaf speed changes for the k*th* CP, which is the sum of all MI_{MLCs_l}

MI_{MLCa_l} : Modulation index sensitive to the l*th* MLC leaf acceleration changes, which is the integration of the spectrum $Z_{MLCa_{k,l}}(f)$ (for one leaf only)

MI_{MLCs_l} : Modulation index sensitive to the l*th* MLC leaf speed changes, which is the integration of the spectrum $Z_{MLCs_{k,l}}(f)$ (for one leaf only)

$MLCa_{k,l}$: MLC leaf acceleration for the k*th* CP (for one leaf): $MLCa_{k,l} = \frac{|MLCs_{k,l} - MLCs_{k+1,l}|}{t_k}$

$MLCs_{k,l}$: MLC leaf speed for the k*th* CP (for one leaf): $MLCs_{k,l} = \frac{|L_k - L_{k+1}|}{t_k}$

MU: Total Monitor Units (MU) for all CPs

MU_k: Monitor Units for the k*th* CP

m : Number of bixel per column in the intensity fluence matrix (y direction)

$\max(p_{l,left\ bank})$: Maximum position of the the l*th* leaf of the left bank of the MLC

$\max(p_{l,right\ bank})$: Maximum position of the the l*th* leaf of the right bank of the MLC

N_{CP}: Total number of control point for a VMAT plan

N_g: Number of grey levels in the fluence map

N_I : Total number count of intensity adjacent-bixel changes that exceed a given fraction of the intensity standard deviation of the beam

N_{I_i} : Number count of intensity adjacent-bixel changes that exceed a given fraction of the intensity standard deviation of the beam in the i direction: $N_{I_i}(f; \Delta I_i > f\sigma_I)$

$N_{MLCs_{k,l}}$: Total number counts of MLC leaf speed changes for the k*th* CP, that exceeds a given fraction of the MLC leaf speed standard deviation (for one leaf only)

$N_{MLCa_{k,l}}$: Total number counts of MLC leaf acceleration changes for the k*th* CP, that exceeds a given fraction of the MLC leaf acceleration standard deviation (for one leaf only)

$N_{leaf,k}$: Number of MLC leaves not positioned under the jaws for the k*th* CP

$N_{leaf\ organ,k}$: Number of MLC leaves not positioned under the jaws, which cover the organ considered, for the k*th* CP

$N_{leaf}(c > a > 0)_k$: Number of MLC leaves with an aperture distance between opposing leaves from 0 to a aperture distance criteria c for the k*th* CP

$N_{leaf}(a > 0)_k$: Number of MLC open leaves for the k*th* CP

$N_{leaf}(a > C_{MLC})_k$: Number of MLC open leaves that crossed the centre for the k*th* CP

$N_{segment,plan}$: Total number count of segment in an particular IMRT plan (non planified with vendor recommendations)

$N_{segment,default\ plan}$: Total number count of segment in an default IMRT plan (planified with vendor recommendations)

n : Number of bixel per line in the intensity fluence matrix (x direction)

P_k: Aperture perimeter the k*th* CP

p_l: Position of the the l*th* leaf of the MLC for one bank

$p_{l,left\ bank}$: Position of the l*th* leaf of the left bank of the MLC

$p_{l,left\ bank,k}$: Position of the l*th* leaf of the left bank of the MLC, for the kth CP

$p_{l,k}$: Position of the l*th* leaf of the MLC for one bank, for the kth CP

$p_{l,right\ bank}$: Position of the l*th* leaf of the right bank of the MLC

$p_{l,right\ bank,k}$: Position of the l*th* leaf of the right bank of the MLC, for the kth CP

p_{max}: Maximum distance between leaf positions for a MLC bank: $pos_{max} = |\max(p_l) - \min(p_l)|$

R_{edge}: Region of 5mm from the MLC edge inside and outside the MLC opening

$R_{open\ area}$: Region of the MLC opening that is not taking into account by R_{edge}

σ_I: Standard deviation of intensity values of the beam

σ_i: Standard deviation of values of the beam, in the i*th* direction of the matrix

$\sigma_{MLCa_{k,l}}$: Standard deviation of the l*th* leaf acceleration of the MLC for all kth CPs

$\sigma_{MLCs_{k,l}}$: Standard deviation of the l*th* leaf speed of the MLC for all kth CP

SLP: Slope of the $\log(\gamma(h))$ versus $\log(h)$ plot

t_k: Time of the k*th* CP: $t_k = \begin{cases} \frac{Angle\ gantry\ interval\ between\ CP}{Maximum\ gantry\ speed} & for\ \Delta MU_k < Maximum\ Dose\ Rate * time\ per\ CP\ without\ slowing\ down\ gantry \\ \frac{\Delta MU_k}{10 * Maximum\ Dose\ rate} & for\ \Delta MU_k > Maximum\ Dose\ Rate * time\ per\ CP\ without\ slowing\ down\ gantry\ rot \end{cases}$

$U(A_k)$: Union area of all aperture area of a beam

$Z_I(f)$: Total spectrum of the number of adjacent-bixel changes that exceed a given fraction of the intensity standard deviation of the beam

$Z_{I_i}(f)$: Spectrum of the number of adjacent-bixel changes that exceed a given fraction of the intensity standard deviation of the beam, in the i direction

$Z_{MLCs_{k,l}}(f)$: Spectrum of the number of the MLC leaf speed changes for the k*th* CP, that exceeds a given fraction of the MLC leaf speed changes standard deviation for the k*th* CP (for one leaf only)

$Z_{MLCa_{k,l}}(f)$: Spectrum of the number of the MLC leaf acceleration changes for the k*th* CP, that exceeds a given fraction of the MLC leaf acceleration changes standard deviation for the k*th* CP (for one leaf only)

PCM	Type PCM Name Reference	Formula	Plan Complexity Sensivity (Influence factors)
Modulation Index	Adaptation MI_S Park *Phys. Med. Biol. 2014*	$MI_s = \sum_{l=1}^{N_{leaf}} MI_{MLCs_l}$ $MI_{MLCs_l} = \int_0^F Z_{MLCs_{k,l}}(f)\,df$ Where $Z_{MLCs_{k,l}} = \frac{1}{N_{CP}-1} N_{MLCs_{k,l}}(f; MLCs_{k,l} > f\sigma_{MLCs_{k,l}})$	MLC leaves speed between different control point (CP) (all leaves positions in each CP and the time of each CP).
	Adaptation MI_a Park *Phys. Med. Biol. 2015*	$MI_a = \sum_{l=1}^{N_{leaf}} MI_{MLCa_l}$ with $MI_{MLCa_l} = \int_0^F Z_{MLCa_{k,l}}(f)\,df$ Where $Z_{MLCa_{k,l}} = \frac{1}{N_{CP}-2} N_{MLCa_{k,l}}(f; MLCa_{k,l} > \alpha f \sigma_{MLCa_{k,l}})$	MLC leaves speed and acceleration (all leaves positions in each CP and the time of each CP weighted with the ponderation time factor).
	Adaptation MIt Park *Phys. Med. Biol. 2015*	$MI_t = \sum_{l=1}^{N_{leaf}} MI_{MLCt_n}$ Where $MI_{MLCa_l} = \int_0^k Z_{total}(f)\,df$	MI evaluating the speed of MLC, acceleration of MLC, gantry rotation acceleration and DR variation comprehensive

		K=0.2,0.5,1,2 Where $$Z_{total}(f) = (\frac{1}{N_{CP}-2})\sum_{i=1}^{N_{CP}}\{N_i(f; MLC\ speed_i > f\sigma MLC_{speed}).W_{GA,i+1}W_{MU,i+1}\}$$	
	Adaptation MI_{SPORT} Li & Xing, *Med. Phys*. 2013.	$$MI_{SPORT} = \sum_{k=1}^{-K:K}\left[\sum_{l=1}^{N_{leaf}}(\lvert p_{l,left\ bank,k} - p_{l,left\ bank,k+1}\rvert + \lvert p_{l,right\ bank,k} - p_{l,right\ bank,k+1}\rvert)\right]\cdot\left\lvert\frac{MU_k - MU_{k+1}}{GA_k - GA_{k+1}}\right\rvert$$	Sensitive to the level of intensity modulation of a CP, by considering the leaves positions of the MLC, MU and Gantry Angle (GA) at the CP considered and for the -K*th* and K*th* CPs neighboring the CP considered.
Delivery Complexity	Original DC Anker, *J. Appl. Clin. Med. Phys*, 2010	$$DC = \frac{MU \cdot N_{segment,plan}}{MU \cdot N_{segment,default\ plan}}$$	FF-IMRT: Sensitive to the Monitor Units (MU) and to the total number of segments of an IMRT plan.
Index of Modulation	Original M Younge, *Med. Phys* 2012	$$M = \frac{1}{MU}\sum_{k=1}^{N_{CP}} MU_k \cdot \frac{P_k}{A_k}$$	Sensitive to field aperture per CP, by considering the ratio between the MLC aperture perimeter and the area weighted by Monitor Units (MU) per CP.

Modulation Complexity Score	Original MCS McNiven, *Med. Phys.*, 2010	$$MCS = \sum_{k=1}^{N_{segment}} AAV_k \cdot LSV_k \cdot \frac{MU_k}{MU}$$ Where $$AAV_k = \left(\frac{\sum_{l=1}^{N_{leaf}} \left(p_{l,left\ bank} - p_{l,right\ bank} \right)}{\sum_{l=1}^{N_{leaf}} \left(\max(p_{l,left\ bank}) - \max(p_{l,right\ bank}) \right)} \right)_k$$ $$LSV_k = \left(\frac{\sum_{l=1}^{N_{leaf}} [p_{max} - (p_l - p_{l+1})]}{N_{leaf} . p_{max}} \right)_{left\ bank,k} . \left(\frac{\sum_{l=1}^{N_{leaf}} [p_{max} - (p_l - p_{l+1})]}{N_{leaf} . p_{max}} \right)_{right\ bank,k}$$	Sensitive to the aperture area variability (AAV) and the leaf sequence variability (LSV) per segment for an IMRT beam.
	Adapted MCSv Masi, *Med. Phys.*, 2013.	$$MCS_V = \sum_{k=1}^{N_{CP}} \left(\frac{AAV_k + AAV_{k+1}}{2} \cdot \frac{LSV_k + LSV_{k+1}}{2} \right) * \frac{MU_k}{MU}$$ Where $$AAV_k = \left(\frac{\sum_{l=1}^{N_{leaf}} \left(p_{l,left\ bank} - p_{l,right\ bank} \right)}{\sum_{l=1}^{N_{leaf}} \left(\max(p_{l,left\ bank}) - \max(p_{l,right\ bank}) \right)} \right)_k$$ $$LSV_k = \left(\frac{\sum_{l=1}^{N_{leaf}} [p_{max} - (p_l - p_{l+1})]}{(N_{leaf} - 1) . p_{max}} \right)_{left\ bank,k} . \left(\frac{\sum_{l=1}^{N_{leaf}} [p_{max} - (p_l - p_{l+1})]}{(N_{leaf} - 1) . p_{max}} \right)_{right\ bank,k}$$	VMAT. Sensitive to the aperture area variability (AAV) and the leaf sequence variability (LSV) per CP.
Modulation Complexity Score	Adapted oMCS Sumida, *J. Radiat. Res.*, 2017.	$$oMCS = \sum_{k=1}^{N_{segment}} AAV_k \cdot sLSV_k \cdot \frac{MU_k}{MU}$$ Where $$sLSV_k = \left(\frac{\sum_{l=1}^{N_{leaf\ organ}} [p_{max} - (p_l - p_{l+1})]}{(N_{leaf} - 1) . p_{max}} \right)_{left\ bank,k} . \left(\frac{\sum_{l=1}^{N_{leaf\ organ}} [p_{max} - (p_l - p_{l+1})]}{(N_{leaf} - 1) . p_{max}} \right)_{right\ bank,k}$$	Sensitive to the aperture area variability (AAV) and to the sectored leaf sequence variability (sLSV), which considers a specific organ located in the field, per segment for an IMRT beam.
Mean Field	Original	$$MFA = \sum_{k=1}^{N_{CP}} A_k \cdot \frac{MU_k}{MU}$$	Sensitive to field aperture per CP, by

Area	MFA Crowe, *Australas. Phys. Eng. Sci. Med.*, 2014		considering only the MLC aperture area weighted by the Monitor Units (MU) per CPs.
Converted Aperture Metric	Original CAM Götstedt, *Med. Phys.*, 2015	$CAM = \overline{CAM_k}$ Where $CAM_k = 1 - \overline{g(d_l)}_k \cdot g(A_{Eq})_k$ $g(x) = 1 - e^{-x}$	Sensitive to the field aperture per CP, by considering distance between the MLC leaves in both X and Y directions. Note that the CAM of a beam is the mean value of all CAM scores calculated for each CP.
Edge Area Metric	Original EAM Götstedt, *Med. Phys.*, 2015	$EAM = \overline{EAM_k}$ Where $EAM_k = \frac{R_{edge}}{R_{edge} + R_{open\ area}}$	Sensitive to the relative amount of edge region for the MLC aperture. Note that the EAM of a beam is the mean value of all EAM scores calculated for each CP.
Circumference / area	Original C/A Götstedt, *Med. Phys.*, 2015	$C/A = \sum_{k=1}^{N_{CP}} \frac{P_k}{A_k}$	Sensitive to the field aperture per CP, by considering the ratio between the MLC aperture perimeter (or circonference) and the area.
Small	Original	$SAS = \sum_{k=1}^{N_{CP}} \frac{N_{leaf}(a_c > a_l > 0)_k}{N_{leaf}(a_l > 0)_k} \cdot \frac{MU_k}{MU}$	Sensitive to the aperture per CP by

Aperture Score	SAS Crowe, *Australas. Phys. Eng. Sci. Med.*, 2014		considering the distance between opposite leaves under a certain criteria.
Mean Asymmetry Distance	Original MAD Crowe, *Australas. Phys. Eng. Sci. Med.*, 2014	$MAD = \sum_{k=1}^{N_{CP}} \left(\sum_{l=1}^{N_{leaf}} \lvert \overline{C_{leaf} - C_{MLC}} \rvert \right) \cdot \frac{MU_k}{MU}$	Sensitive to the aperture per CP by considering the average of the distance between the centre of the aperture distance between opposite leaf pairs and the MLC central axis.
Closed Leaf Score	Original CLS Crowe, *Australas. Phys. Eng. Sci. Med.*, 2014	$CLS = \sum_{k=1}^{N_{CP}} \frac{N_{leaf}(a_l > 0)_k}{N_{leaf,k}} \cdot \frac{MU_k}{MU}$	Sensitive to the aperture per CP by considering the closed leaves.
Cross-Axis Score	Original CAS Crowe, *Australas. Phys. Eng. Sci. Med.*,	$CAS = \sum_{k=1}^{N_{CP}} \frac{N_{leaf}(a_l > C_{MLC})_k}{N_{leaf}(a_l > 0)_k} \cdot \frac{MU_k}{MU}$	Sensitive to the aperture per CP by considering the leaves that cross the MLC central axis.

	2014		
Plan Average Beam Area (PA)	Original PA Du, *Med. Phys.*, 2014.	$$PA = \frac{\sum_{k=1}^{beam} BA_i . MU_i}{MU_p}$$ Where $$BA_i = \frac{\sum_{j=1}^{segment} MU_{ij} AA_{ij}}{MU_i}$$ Where $AA_{ij} = \sum_{k=1}^{Nleafpair} t_k . (2_{ijk} - 1_{ijk})$	Sensitive to field aperture per CP, by considering only the MLC aperture area weighted by Monitor Units (MU) per CP.
Plan Average Beam Irregularity (PI)	Original PI Du, *Med. Phys.*, 2014.	$$PI = \frac{\sum_{k=1}^{beam} BI_i . MU_i}{MU_p}$$ where $$BI_i = \frac{\sum_{j=1}^{segment} MU_{ij} AI_{ij}}{MU_i}$$ Where $AI_{ij} = \frac{AP^2{}_{ij}}{4\pi AA_{ij}}$	Sensitive to the field aperture irregularity per CP, by considering the no-circularity of the aperture area.
Plan Averaged Beam Modulation (PM)	Original PM Du, *Med. Phys.*, 2014.	$$PM = 1 - \frac{\sum_{k=1}^{beam} BM_i . MU_i}{MU_p}$$ where $$BM_i = \frac{\sum_{j=1}^{segment} MU_{ij} AA_{ij}}{MU_i . U(AA_{ij})}$$ U(AAij) is the union area of all apertures of beam i.	Sensitive to the field aperture area per CP by considering the union area of all aperture areas of a beam.

Plan Normalized MU (PMU)	Original PMU Du, *Med. Phys.*, 2014.	$PMU = \frac{MU_p . 2Gy}{d}$ With d the prescribed dose per fraction (Gy)	
MLC leaf velocity	Original MLC_{velo} Agnew, *J. Appl. Clin. Med. Phys.*, 2014.	$MLC_{velo} = \frac{p_{l,k} - p_{l,k+1}}{t_k}$	Sensitive to the mechanical delivery inaccuracies of the MLC at each CP, by considering the ratio between the distance travelled by an active MLC leaf between two consecutive CPs and the time between two consecutive CPs.
Average Leaf Pair Opening (ALPO)	Original ALPO Zygmanski, *Med. Phys.*, 2001.	$ALPO = \frac{\sum_{k=1}^{N_{CP}} \sum_{l=1}^{N_{leaf}} \left\lvert p_{l,right\ bank} - p_{l,left\ bank} \right\rvert_k \cdot MU_k}{\sum_{k=1}^{N_{CP}} \sum_{l=1}^{N_{leaf}} MU_k \quad (for\ a_l \neq 0)}$	Sensitive to MLC gap error by considering the ratio between the sum of the aperture area and the sum of the fractional MU during which a leaf pair is open.

Table 2: Review of IMRT/ VMAT plan Plan Complexity Metrics formulas based on Degrees Of Freedom variation

Signification of the different variables that appears in metrics equations (Note that the metric for a IMRT plan and/or a VMAT plan is the sum of the metric of all beams included in the plan weighted by Monitor Units) .:

A_{Eq}: Equivalent square field or aperture ;

A_k: Aperture area for the k*th* CP

AAV_k: Aperture Area Variability for the k*th* CP (VMAT), segment (IMRT): Characterize the variation in segment area relative to the maximum aperture defined by all segments

AI_k : Aperture Irregularity calculated by considering the noncircularity of the aperture

α: Weighting factor for the acceleration: $\frac{1}{t_k}$

a_c: Aperture distance criteria for two opposite leaves

a_l: Aperture distance between two opposite leaves

CAM_k: Converted Aperture Metric for the for the k*th* CP

C_{leaf}: Centre of aperture distance between opposite leaves

C_{MLC}: Centre of the MLC axis (aligned with the beam axis)

c: Constant in the semivariogram function $\gamma(h)$ formula

D: Number of pairs of data points whose lag is h, for the Fractal Dimension calculation

F : Maximum fraction of the standard deviation of the sensitive parameter considered, which represents the upper born of integration of the spectrum

$FS(x_i)$: Fractal surface at the data point x_i

f : Fraction of the standard deviation of the sensitive parameter considered: $f = 0.001\,, 0.002\,, \ldots\ 2$

GA_k : Gantry Angle for the k*th* CP

$GLCM_{i,j}$: Gray Level Co-occurrence Matrix, that indicates the intensity relationships between pairs of pixels in the fluence map

$\overline{GLCM_i}$: Mean value of the pixels in the GLCM, in the i*th* direction

$\gamma(h)$: Semivariogram function used in spatial statistics that linked the Fractal Dimention (FD) to a profile of the fluence map

$g(A_{Eq})_k$: Conversion value of the equivalent square field, using conversion function $g(x)$, for the k*th* CP

$\overline{g(d_l)}_k$: Mean of all conversion values of the distances between MLC leaves in X and Y direction, using conversion function $g(x)$, for the k*th* CP

$g(x)$: Conversion function to obtain a nonlinear relation between distance between MLC leaves, and their contribution to the complexity of the aperture

h: Distance between two data point for the Fractal Dimension calculation

$I_{i,j}$: Matrix of the intensity fluence map with $n \,.\, m$ shape

ΔI_i : Absolute difference between intensity values of adjacent-bixel in the i*th* direction: $\Delta I_i = |I_i - I_{i+1}|$

K: Number of neighbouring CPs for a CP considered, which is an arbitrary value

LSV_k: Leaf Sequence Variability for the k*th* CP (VMAT), segment (IMRT): Characterize the variability of a field shape per segment or CP

$sLSV_k$: Sectored Leaf Sequence Variability for the k*th* CP (VMAT), segment (IMRT): Characterize the variability of a field shape by considering the leaves that cover the organ considered in the field, per segment or CP

λ: Weighting factor for lateral bixels, equal to 0.5 when a bixel have two lateral neighbours

MI_I : Modulation index sensitive to intensity fluence map, which is the integration of the spectrum $Z_I(f)$

MI_{MLCa} : Modulation index sensitive to MLC leaf acceleration changes for the k*th* CP, which is the sum of all MI_{MLCa_l}

MI_{MLCs} : Modulation index sensitive to MLC leaf speed changes for the k*th* CP, which is the sum of all MI_{MLCs_l}

MI_{MLCa_l} : Modulation index sensitive to the l*th* MLC leaf acceleration changes, which is the integration of the spectrum $Z_{MLCa_{k,l}}(f)$ (for one leaf only)

MI_{MLCs_l} : Modulation index sensitive to the l*th* MLC leaf speed changes, which is the integration of the spectrum $Z_{MLCs_{k,l}}(f)$ (for one leaf only)

$MLCa_{k,l}$: MLC leaf acceleration for the k*th* CP (for one leaf): $MLCa_{k,l} = \frac{|MLCs_{k,l} - MLCs_{k+1,l}|}{t_k}$

$MLCs_{k,l}$: MLC leaf speed for the k*th* CP (for one leaf): $MLCs_{k,l} = \frac{|L_k - L_{k+1}|}{t_k}$

MU: Total Monitor Units (MU) for all CPs

MU_k: Monitor Units for the k*th* CP

m : Number of bixel per column in the intensity fluence matrix (y direction)

$\max(p_{l,left\ bank})$: Maximum position of the the l*th* leaf of the left bank of the MLC

$\max(p_{l,right\ bank})$: Maximum position of the the l*th* leaf of the right bank of the MLC

N_{CP}: Total number of control point for a VMAT plan

N_g: Number of grey levels in the fluence map

N_I : Total number count of intensity adjacent-bixel changes that exceed a given fraction of the intensity standard deviation of the beam

N_{I_i} : Number count of intensity adjacent-bixel changes that exceed a given fraction of the intensity standard deviation of the beam in the i direction: $N_{I_i}(f; \Delta I_i > f\sigma_I)$

$N_{MLCs_{k,l}}$: Total number counts of MLC leaf speed changes for the k*th* CP, that exceeds a given fraction of the MLC leaf speed standard deviation (for one leaf only)

$N_{MLCa_{k,l}}$: Total number counts of MLC leaf acceleration changes for the k*th* CP, that exceeds a given fraction of the MLC leaf acceleration standard deviation (for one leaf only)

$N_{leaf,k}$: Number of MLC leaves not positioned under the jaws for the k*th* CP

$N_{leaf\ organ,k}$: Number of MLC leaves not positioned under the jaws, which cover the organ considered, for the k*th* CP

$N_{leaf}(c > a > 0)_k$: Number of MLC leaves with an aperture distance between opposing leaves from 0 to a aperture distance criteria c for the k*th* CP

$N_{leaf}(a > 0)_k$: Number of MLC open leaves for the k*th* CP

$N_{leaf}(a > C_{MLC})_k$: Number of MLC open leaves that crossed the centre for the k*th* CP

$N_{segment,plan}$: Total number count of segment in an particular IMRT plan (non planified with vendor recommendations)

$N_{segment,default\ plan}$: Total number count of segment in an default IMRT plan (planified with vendor recommendations)

n : Number of bixel per line in the intensity fluence matrix (x direction)

P_k: Aperture perimeter the k*th* CP

p_l: Position of the the l*th* leaf of the MLC for one bank

$p_{l,left\ bank}$: Position of the l*th* leaf of the left bank of the MLC

$p_{l,left\ bank,k}$: Position of the l*th* leaf of the left bank of the MLC, for the kth CP

$p_{l,k}$: Position of the l*th* leaf of the MLC for one bank, for the kth CP

$p_{l,right\ bank}$: Position of the l*th* leaf of the right bank of the MLC

$p_{l,right\ bank,k}$: Position of the l*th* leaf of the right bank of the MLC, for the kth CP

p_{max}: Maximum distance between leaf positions for a MLC bank: $pos_{max} = |\max(p_l) - \min(p_l)|$

R_{edge}: Region of 5mm from the MLC edge inside and outside the MLC opening

$R_{open\ area}$: Region of the MLC opening that is not taking into account by R_{edge}

σ_I: Standard deviation of intensity values of the beam

σ_i: Standard deviation of values of the beam, in the i*th* direction of the matrix

$\sigma_{MLCa_{k,l}}$: Standard deviation of the l*th* leaf acceleration of the MLC for all kth CPs

$\sigma_{MLCs_{k,l}}$: Standard deviation of the l*th* leaf speed of the MLC for all kth CP

SLP: Slope of the $\log(\gamma(h))$ versus $\log(h)$ plot

t_k: Time of the k*th* CP: $t_k = \begin{cases} \frac{Angle\ gantry\ interval\ between\ CP}{Maximum\ gantry\ speed} & for\ \Delta MU_k < Maximum\ Dose\ Rate * time\ per\ CP\ without\ slowing\ down\ gantry \\ \frac{\Delta MU_k}{10 * Maximum\ Dose\ rate} & for\ \Delta MU_k > Maximum\ Dose\ Rate * time\ per\ CP\ without\ slowing\ down\ gantry\ rot \end{cases}$

$U(A_k)$: Union area of all aperture area of a beam

$Z_I(f)$: Total spectrum of the number of adjacent-bixel changes that exceed a given fraction of the intensity standard deviation of the beam

$Z_{I_i}(f)$: Spectrum of the number of adjacent-bixel changes that exceed a given fraction of the intensity standard deviation of the beam, in the i direction

$Z_{MLCs_{k,l}}(f)$: Spectrum of the number of the MLC leaf speed changes for the k*th* CP, that exceeds a given fraction of the MLC leaf speed changes standard deviation for the k*th* CP (for one leaf only)

$Z_{MLCa_{k,l}}(f)$: Spectrum of the number of the MLC leaf acceleration changes for the k*th* CP, that exceeds a given fraction of the MLC leaf acceleration changes standard deviation for the k*th* CP (for one leaf only)

<table>
<tr><th>PCM Name
Reference</th><th>Results Reference
Technical environnement (Delivering mode and Linac ; TPS ; optimization and calculation dose algorithm, measurement device)</th><th>Localizations,
Patient Number,
Type of test</th><th>PCM-PTQA link results</th></tr>
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Park Phys. Med. Biol. 2015</td><td rowspan="3">Park Phys. Med. Biol. 2014
● VMAT Varian Trilogy with MLC Millenium + TrueBeam STx; MLC HD; PRO3 v10, AAAv10, Elipse; calc grid 2.5mm;
NB : MIs (f=1) Webb formalism</td><td rowspan="4">● Prostate + Head and Neck
● N=40 (20each)
● Spearman’s rho</td><td><table><tr><td></td><td>2%/2mm</td><td>2%/1mm</td><td>1%/2mm</td></tr><tr><td>Rs (p value)</td><td>-0.637 (< 0.001)</td><td>-0.471 (0.002)</td><td>-0.657 (< 0.001)</td></tr></table></td></tr>
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Park Phys. Med. Biol. 2015</td><td><table><tr><td></td><td>2%/2mm</td><td>2%/1mm</td><td>1%/2mm</td></tr><tr><td>Rs (p value)</td><td>-0.663 (< 0.001)</td><td>-0.561 (< 0.001)</td><td>-0.669 (< 0.001)</td></tr></table></td></tr>
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Park Phys. Med. Biol. 2015</td><td><table><tr><td></td><td>2%/2mm</td><td>2%/1mm</td><td>1%/2mm</td></tr><tr><td>Rs (p value)</td><td>-0.667 (<0.001)</td><td>-0.552 (<0.001)</td><td>-0.669 (< 0.001)</td></tr></table></td></tr>
<tr><td>MI_{SPORT}
Li & Xing, Med. Phys. 2013.</td><td>Park Phys. Med. Biol. 2014
VMAT, Varian Trilogy with MLC Millenium and TrueBeam STx MapCHECK2
NB : MIs (f=1) Webb formalism
MLC HD; PRO3 v10, AAAv10, Elipse; calc grid 2.5mm</td><td><table><tr><td></td><td>2%/2mm</td><td>2%/1mm</td><td>1%/2mm</td></tr><tr><td>Rs (p value)</td><td>-0.455 (0.003)</td><td>-0.49 (0.001)</td><td>-0.502 (0.001)</td></tr></table></td></tr>
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<tr>
<td>MI

Crowe, Australas. Phys. Eng. Sci. Med., 2014</td>
<td>Crowe, Australas. Phys. Eng. Sci. Med., 2014

FF-IMRT, TPS Brainlab, MapCHECK2</td>
<td>● Prostate

● N=122 beams

● F-value linear relationship test (p-value)</td>
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<tr><td>F (p-value)</td><td>11.397 (0.001)</td></tr>
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<tr>
<td>MCS

McNiven, Med. Phys., 2010</td>
<td>● Götstedt, Med. Phys., 2015

● FF-IMRT and VMAT; Varian Clinac iX; Eclipse; AAA; calc grid 2.5mm; Varian EPID aSi 1000 and Gafchromic™ EBT3 film</td>
<td>● Various MLC openings

● N=30

● Pearson’s correlation between dose difference and PCM value</td>
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<tr><td></td><td>EPID</td><td>EBT3</td><td>EPID</td><td>EBT3</td></tr>
<tr><td>r</td><td>0.44</td><td>0.46</td><td>0.59</td><td>0.67</td></tr>
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<tr>
<td rowspan="2">MCSv</td>
<td>● Masi, Med. Phys., 2013.

● VMAT, Elekta Synergy 1cm MLC; ONCENTRA; Masterplan v4.1 ; PencilBeam algorithm ; DELTA 4</td>
<td>● 142 plans different plans

● Pearson’s r correlation</td>
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<td>●Park Phys. Med. Biol. 2015

●VMAT, Varian Trilogy with MLC Millenium and TrueBeam STx MapCHECK2; NB : MIs (f=1) Webb formalism; MLC HD; PRO3 v10, AAAv10, Elipse; calc grid 2.5mm</td>
<td>● Prostate + Head and Neck

● N=40 (20each)

● Spearman’s rho</td>
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<tr><td>Rs (p value)</td><td>0.186 (0.251)</td><td>0.365 (0.021)</td><td>0.157 (0.334)</td></tr>
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<td>Agnew, J. Appl. Clin. Med. Phys., 2014.
Eclipse PRO v10, AAAv10, calc grid 0.25cm, Octavius 4D</td>
<td>VMAT
10H&N, 10 prostate, 10 pelvis
Pearson’s correlation</td>
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<td>LTMCS
Masi, Med. Phys., 2013</td>
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NB : MIs (f=1) Webb formalism
MLC HD; PRO3 v10, AAAv10, Elipse; calc grid 2.5mm</td>
<td>● 142 plans different plans
● Pearson’s r correlation</td>
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<td>oMCS
Sumida, J. Radiat. Res., 2017.</td>
<td>FF-IMRT, Siemens ONCOR; TPS XiO; calc grid 2mm;
MapCHECK2</td>
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● N=16
● Spearman’s rho</td>
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<td>MFA
Crowe, Australas. Phys. Eng. Sci. Med., 2014</td>
<td>FF-IMRT, TPS Brainlab, MapCHECK2</td>
<td>● Prostate
● N=122 beams
● F-value linear relationship test (p-value)</td>
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<td>CAM</td>
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● FF-IMRT and VMAT; Varian Clinac iX; Elipse; AAA; calc grid 2.5mm; Varian EPID aSi 1000 and Gafchromic™ EBT3 film</td>
<td>● Various MLC openings
● N=30
● Pearson’s correlation between dose difference and PCM value</td>
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<tr><td></td><td colspan="2">3% dd</td><td colspan="2">5% dd</td></tr>
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● FF-IMRT and VMAT; Varian Clinac iX; Eclipse; AAA; calc grid 2.5mm; Varian EPID aSi 1000 and Gafchromic™ EBT3 film</td>
<td>● Various MLC openings
● N=30
● Pearson’s correlation between dose difference and PCM value</td>
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Götstedt, Med. Phys., 2015</td>
<td>Götstedt, Med. Phys., 2015
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<td>● Various MLC openings
● N=30
● Pearson’s correlation</td>
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<td>SAS_{5mm}
Crowe, Australas. Phys. Eng. Sci. Med., 2014</td>
<td rowspan="4">Crowe, Australas. Phys. Eng. Sci. Med., 2014
FF-IMRT, TPS Brainlab, MapCHECK2</td>
<td rowspan="4">● Prostate
● N=122 beams
● F-value linear relationship test (p-value)</td>
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<tr><td></td><td>2%/2mm</td></tr>
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<td>MAD
Crowe, Australas. Phys. Eng. Sci. Med., 2014</td>
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Crowe, Australas. Phys. Eng. Sci. Med., 2014</td>
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PA Du, *Med. Phys.*, 2014.	Du, *Med. Phys.*, 2014. FF-IMRT/VMAT, Phillips Pinnacle, Ion Chamber Wellhoffer CC04	• Prostate; H&N; Spine • N=65 FF-IMRT + 26VMAT (prostate only) • two-sided Wilcoxon rank sum test (p-value)	Dd<3% R (p-value): -0.38 (0.0009)
PI Du, *Med. Phys.*, 2014.			3mm/5% R (p-value): -0.04 (0.51)
PM Du, *Med. Phys.*, 2014.			3mm/5% R (p-value): 0.21 (0.005)
PMU Du, *Med. Phys.*, 2014.			3mm/5% R (p-value): 0.22 (0.004)

Table 3: Main results about correlation tests between Pre-Treatment Quality Assurance score and Plan Complexity Metrics