On the clinically relevant detector resolution and error detection capability of COMPASS 3D plan verification

INTRODUCTION – WHAT IS COMPASS?
COMPASS is a system for clinically relevant 3D treatment verification and patient dose analysis. COMPASS reconstructs dose from measured fluence, compares the patient plan with measurements, and provides 3D dose deposition information inside the patient’s anatomy. Plan evaluation is achieved either by visual means (evaluating dose differences/gamma relative to TPS inside patient CT) or on a structure-by-structure statistical/quantitative basis via comparison of the TPS generated DVHs to that of COMPASS’s independently calculated DVHs.

EXECUTIVE SUMMARY

Radiotherapy-based cancer treatments are evolving rapidly. The machines that deliver these treatments are becoming more precise, comprehensive and flexible than ever. Along with these advances new and unknown uncertainties arise. Consequently, it is necessary that new and equally innovative pre-treatment QA methodologies be employed to adequately describe, predict, and mitigate any potential harm to the patient prior to plan delivery.

In light of a few recent and highly publicized treatment errors around the U.S., radiotherapy departments and their team members have focused and renewed their efforts into developing QA processes in which patient safety is the utmost concern. To achieve this, medical physicists and their fellow department teammates need to be working unison to identify, quantify, and prevent any potential mistreatments before they occur.

BACKGROUND

The traditional and most common methods for IMRT treatment QA are phantom-based and are two-dimensional in nature. While this methodology has and continues to be a useful way of performing pre-treatment plan QA, there have been recent publications that indicate the process can be improved in terms of dosimetric accuracy, quantification of anatomical impact of delivery errors, and increased relevance of QA information to others in the radiotherapy team besides medical physicists, e.g. radiation oncologists. While traditional phantom-calculated 2D based gamma maps provide a basic understanding of whether the linac is operating as planned, it provides no information regarding the end impact of small or large treatment errors in the patient [1]. Radiotherapy quality assurance is moving towards a patient-centric departmental approach and subsequently the QA tools of the future need to reflect these evolutions in turn.

INTRODUCTION TO COMPASS

Why is COMPASS different?
COMPASS differentiates itself from other QA systems in that it performs a full three-dimensional collapsed cone convolution/superposition dose reconstruction based on a dose engine developed in conjunction with RaySearch Laboratories AB. Each LINAC to be used with COMPASS is custom modeled in much the same fashion as a conventional TPS. The patient’s DICOM information from the TPS is imported into COMPASS. Afterwards,

patient specific measurements are collected and dose is computed inside the patient’s anatomy as opposed to that which is calculated inside a phantom by other QA systems.

COMPASS can also compute dose independently and function as an independent secondary TPS verification without the need for detector-based measurements. COMPASS employs a TPS-class dose engine in order to provide not only accurate but anatomically localized QA dose information.

COMPASS offers automatic plan verification with instant “fail” alerts for missed prescriptions and tolerances based on the clinic’s individual protocols. Because medical physicists and physicians can directly visualize and assess the clinical relevance of detected delivery errors in 3D patient anatomy per organ, (both in terms of image sets and DVH-based comparisons) potential treatment complications can be identified, quantified and avoided.

A comprehensive approval report for medical physicists and physicians can be generated. In short, COMPASS promotes joint departmental expertise and better patient outcomes.

**COMPASS WORKFLOW AND TECHNICAL INFORMATION**

**What is a dose engine and why does COMPASS use a CC C/S approach?**

A dose engine is an algorithm which can determine the three-dimensional dose distribution in the patient. This is a very demanding numerical task. As the power of planning computers is limited, various strategies have been used to simplify this task with the “pencil beam” approach being the most elementary. With increasingly more advanced computers being readily available, pencil beam can no more be considered a clinically valid “state-of-the-art” approach and should be used only for approximate dose computations rather than treatment planning. Various improvements of the pencil beam technique such as the Anisotropic Analytic Algorithm (AAA) are widely used. Another approach, which is employed in COMPASS (as well as in many other treatment planning systems), is the collapsed cone convolution/superposition algorithm [2, 3], which can be considered to deliver state-of-the-art clinical accuracy.

A completely different approach can be achieved via “Monte Carlo” calculation, which, in principle, can deliver the highest accuracy of any dose engine. However, such accuracy has its downsides. Inherent in Monte Carlo computation is a direct relationship between calculation accuracy and computation time. In fact, in order to reduce the error by a factor of two, the computational time has to increase by a factor of four. Therefore, until recently, it was not possible to reach excellent clinical accuracy with reasonable computational times and affordable desktop computers. With the continuous improvement of computers and better exploitation of their features (GPU-based processing), it can be expected that Monte Carlo will eventually become the preferred approach for treatment planning.

Since it has been shown that a collapsed cone C/S approach to dose calculation produces the most accurate results (even for highly heterogeneous media) relative to all other algorithmic approaches when compared to Monte Carlo [4], it is clear that a CC C/S based dose engine offers the best computational accuracy to computation time ratio. This is why it was integrated into COMPASS in preference to other methodologies.

**Which patient plan information does COMPASS import?**

Dose computation in COMPASS requires TPS-exported patient DICOM information. The following files are required:

- RTPlan
- CT Images
- RTStruct
- RTDose

**How is the reference fluence derived from the DICOM patient plan in COMPASS?**

The patient plan is imported via the DICOM RTplan file. The whole plan is subdivided in a number of “control points”, where the system configuration is precisely defined (Figure 2). At the control points, the collimator (both MLC and jaws) opening and the number of MUs is given. Together with the knowledge of beam sources and collimator transmissions one can determine at this point the number and energy of photons which pass through a surface perpendicular to the beam – the energy fluence.

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From the Fluence, detector response and TERMA deposition in the patient is computed per segment, where a segment is the arc between two consecutive control points. The MU of the segment $i$ is given by the difference in accumulated MU between control point $i+1$ and control point $i$.

**How is comparative fluence computed and handled within COMPASS?**

**How is Fluence derived within COMPASS?**

- From the plan and using the commissioned beam model. The plan gives the number of Monitor Units (MUs) and the opening of the collimators (leaves and jaws). The commissioned beam model yields an individual (i.e. specific to both LINAC and collimator model as well to the individual machine) description of photon and electron sources. This information is sufficient for a fluence computation and, hence, computation of the dose distribution. This method allows COMPASS to perform an independent TPS-class dose computation without the need for measurements.

- Using the measured response from the detector, in this case, the ion chamber array “MatriXX” (IBA Dosimetry). The measured response from the detector array is deconvolved into measured fluence with a Monte Carlo generated ion chamber correction kernel along with other measurement-based corrections to be discussed later in this document. In this case, the deconvolved and corrected fluence is assumed to be the computed fluence that will eventually be fed into the dose engine for purposes of computing full three dimensional dose within the patient. This is the normal workflow for using COMPASS as a pre-treatment QA tool.

Is the fluence used for dose reconstruction in COMPASS directly measured?

No. In COMPASS, the reconstructed dose from measured fluence is referred to as indirectly measured. This is a consequence of how the ion chamber-based detector array (MatriXX) is designed to be used. The reason for this is due to an extended response function for ion chamber irradiation. The chamber, filled with a gas, gives an electrical signal when charge carriers (ions) are formed in the gas under the influence of ionizing radiation. The photons used in radiation therapy, however, undergo only few interactions in a low-density medium like air and, thus, will cause negligible ionization in a small detector volume.

Are there any fluence corrections or compensations for detector resolution employed in COMPASS?

The fact that photons can be detected at all within a given ion chamber cavity is due to their much stronger interaction with the dense material of the chamber walls. Those interactions (photoelectric effect, Compton Effect and pair-production) will produce electrons. These electrons are strongly ionizing and will create a response signal (current) in the chamber volume which can then be related to dose. It is such that the area of a pixel in an ion chamber array (MatriXX) is much bigger than the air volume contained within the pixel chamber itself. Figure 3 shows the response function for a pixel being irradiated in the MatriXX. This irradiation is for a 6 MV photon beam (where photons of various energies up to 6 MeV are present). Figure 4 illustrates the response function for various mono-energetic beams.
In addition to the response broadening mentioned above, there is also a need to consider the physical resolution limitations of the ion chamber hardware itself. The ion chamber-to-chamber distance for the MatriXX is 7.62 mm (chamber diameter of 4.5 mm) at the measurement plane (762 mm SDD), however, the desired resolution for direct comparison to TPS plans is in the order of 2 mm. In order to overcome this limitation, COMPASS employs the above (Figure 3) Monte Carlo derived response function which describes an individual MatriXX ion chamber’s response to a given photon energy and build up condition in high resolution to transform measured coarse chamber response with a resolution of 7.62 mm into a response with resolution in the order of 2 mm (or whatever required). This is possible, since, the low resolution measurement itself provides the amplitude (total integrated chamber response) for the response function distribution. Since it is known (via high-resolution Monte Carlo modeling) what the response function should look like, all that is required is to know the amplitude of relative response in order to turn a coarse pixel-by-pixel distribution into a better description of the response fall-off inside each individual chamber, i.e. a higher resolution than is nominally possible with the hardware.

How is fluence obtained from measured detector response?
Previously it was discussed how COMPASS is able to achieve measurement resolution that is better than nominally possible with the current detector hardware, however, it is important to discuss another important aspect of how COMPASS utilizes a measurement-based correction method in order to achieve the highest accuracy in dose reconstruction.

In order to collect measurements, the MatriXX needs to be positioned normal to the beam’s central axis via the use of a gantry fixture and a holder (76.2 cm or 100 cm options). The primary purpose of using the holder is two-fold. The first is that the holder mounting allows the MatriXX to be normal to the beam at all times during beam delivery (no-angular dependence) and two: it increases the total measurement area available of the detector. The MatriXX itself has a nominal available measurement area of 24 x 24 cm². When that is projected to the SDD of 76.2 cm, a field size of up to 32 x 32 cm² is possible.

It should be recalled that COMPASS predicts a response in the MatriXX measurement plane prior to measurement based on the input plan fluence, beam model and the high resolution Monte Carlo-derived detector response model. That process allows COMPASS to increase the resolution of the measurements within each measurement pixel; however, the prediction may not be entirely accurate in terms of pixel-by-pixel actual response. This is due to small errors in the delivery of the plan stemming from discrepancies such as MLC positioning or timing. In general, the combination of the aforementioned models (both beam and detector) performs quite well in the previous scenario; however, there will always be very slight differences (on the order of a few percent) that need to be accounted for. The way COMPASS handles this is to correct the aforementioned predicted response via applying the difference (measured-prediction) back into the prediction. In essence, what COMPASS is doing is performing a measurement-based correction methodology. COMPASS is not changing the measurements to fit anything; rather it is fixing its own prediction based on what it sees in the actual delivery.

In order to better understand the process of measurement based corrections to the response that COMPASS employs, the following examples will be presented.
Figures 5 (a)-(d) provide an example of the predicted (Figure 5a), measured (Figure 5b), Response Difference (Figure 5c), and Corrected Response (Figure 5d) for one segment. A considerable overall deviation in the measured response (Figure 5b) relative to the nominal predicted value (Figure 5a) is immediately visible in red (Figure 5c). As a result, COMPASS then applies a correction factor (ACORR) to the nominal prediction factor, which then minimizes the residual differences, between predicted and measured responses. The remaining discrepancies in response can be seen in Figure 5d.

The scaling correction A corr (which corresponds to the wrong effective Monitor Units in the segment being delivered) can be simply applied to the nominal predicted fluence and that provides the first fluence correction. The remaining part of the response difference cannot be converted directly to a difference in fluence. Since there is a broad response function for the ion chambers, a small photon beam impinging on the center of a chamber would also produce a strong signal in this chamber; however, there would be a small signal in the neighboring pixels as well. Therefore, a fluence derived directly from this signal would be too broad for this narrow beam as it would “smear out” the original signal also would result in a loss of information.

Figures 6(a)-(d) below describe how this process occurs. Figure 6(a) shows the fluence for a narrow beam, figure 6(b) shows the shape of the ion chamber array signal (the response) produced by this signal. Since the fluence is what needs to be characterized (at least with the resolution of the chamber array) a correction kernel such as in Figure 6(c) suppresses the neighbor channel signals. This creates negative contributions in the neighboring chambers. The result of this operation is shown in Figure 6(d), namely, a single pixel signal, which is broader than the original input (because of chamber resolution limitations) but has sharp edges that are not as diffuse as the original response signal (Figure 6b).

\[ \Psi (\text{fluence}) \]
\[ (a) \]
\[ R (\text{detector response}) \]
\[ (b) \]

\[ (c) \]

\[ (d) \]

**Figure 6:** An elementary fluence in one element of the fluence grid (a) gives a response in the detector according to the detector response function \( f \) (b). The fluence correction kernel \( k \) is the theoretical fluence (c) that produces a signal in exactly one single ionization chamber (d). In practice, the correction kernel amplitude (c) is proportional to the difference in signal between the predicted and measured response. Note the negative contributions in the fluence correction kernel that are required to cancel out responses in neighboring ionization chambers. [5]

Workflow of fluence determination in COMPASS

The NOMINAL fluence is determined from the DICOM RT plan file and the COMPASS beam model (resolution 2 mm). From this fluence, the PREDICTED response is calculated with a resolution of 10 mm via convolution with the detector response function. This PREDICTED response is compared to the MEASURED response. The response difference is split in 2 components. The first is a scaling correction (Acorr), which can be applied directly to the NOMINAL fluence to derive the WEIGHTED fluence (resolution 2 mm). The other component, the remaining RESIDUAL response, is then converted to the RESIDUAL fluence with a deconvolution kernel (resolution 10 mm) and is then added to the WEIGHTED fluence. The result is the DELIVERED fluence.

How accurate is plan verification with COMPASS?
The precision of the fluence reconstruction process in COMPASS depends on the type of deviation from the nominal fluence as categorized below:

- Pure deviation of the fluence in a segment, i.e. “the wrong number of MUs”. This is perfectly reconstructed via the aforementioned Acorr factor.

- Deviations representing low spatial frequencies, such as symmetry and flatness errors. These are also perfectly reconstructed.

- For higher spatial frequencies (strong deviations of the fluence over small distances) there are limitations to the reconstruction capabilities of COMPASS. These limitations, their relative magnitude and their clinical relevance are discussed in the following section.

If provided with a given step-signal input (an infinitesimal sharp jump in fluence), COMPASS will reconstruct a somewhat “smeared-out” fluence due to the limited resolution of the MatriXX ion chamber array as in Figure 8 below.

Figure 8: A sharp-step fluence input signal and derived fluence correction/reconstruction in COMPASS.
In actual delivery there will never be such a sharp change. The collimators used in radiation therapy, though being constructed of thick blocks of dense tungsten alloy, cannot completely attenuate the high energy radiation from the LINAC. Therefore, there will always be a diffuse border of fields delimited by jaws and MLCs, also known as the penumbra.

A close approximation to the sharp field edge of Figure 8 could be achieved by a rectangular field. Figure 9 and Figure 10 describe how COMPASS reconstructs such a field edge when its location differs from the nominal position [5] and illustrate the deviation of the reconstructed profile from the ideal slope, leading to “overshoot” and “undershoot” sections of the profile.

In clinical terms, it is more important to be able to determine the position of a given leaf or, more appropriately, where the penumbra has reached the value of 50% of fluence. What can be seen in Figure 9 is the fact that the area of undershoot and overshoot regions is roughly equivalent. Therefore, both effects compensate each other and this reduces the uncertainty in 50% fluence level (leaf edge) determination. When considering Figure 10, the accuracy of field edge determination is approximately 1 to 2 mm (+/-).

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**Figure 9:** Planned, delivered and reconstructed dose profiles in the case of an intentionally introduced 5 mm error in the field edge position (relative to the planned position). The reconstructed dose is a typical dose that can be obtained with the COMPASS system in the case of an error in leaf positioning. The SDD is 762 mm. [5]

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**Figure 10:** Dose reconstruction for a 5 mm field edge position error as a function of the location of the field edge. The dose blurring at the edge of the field is responsible for errors in the position of the 50% dose. Every point represents one location of the field edge, with 1 mm shift between two adjacent locations. The SDD is 762 mm. [5]
While quantifying the system’s absolute uncertainty in determining the 50% fluence field edge is useful, it is more clinically relevant to assess the ability of the system to perform QA of delivered plans and then to provide results in accordance with more traditional methods of plan evaluation, specifically, the well-established gamma test methodology. One such comparison and verification is provided above in Figure 11 [5] wherein, gamma values are plotted as a function of introduced leaf error for both a given reference field and for the same field reconstructed in COMPASS. One set of curves describes the correlation between gamma values and the magnitude of error for a 3%/3 mm gamma criteria and the other set for 5%/5 mm.

It can be inferred from Figure 11 that COMPASS, though slightly overestimating the gamma values, provides results that are very well correlated to the reference values. This is true for both the 3%/3 mm and 5%/5 mm gamma criterion. Of particular note is COMPASS’s reaction in terms of mean gamma to errors as small as 1 mm. At this point it becomes obvious that ERROR DETECTABILITY is a more relevant metric in assessing the quality of plan delivery QA as opposed to HARDWARE RESOLUTION. In short, COMPASS is able to detect errors with greater confidence than would be assumed by judging system performance primarily on hardware resolution.

**What is error detectability like for more realistic clinical IMRT fields?**

In order to evaluate COMPASS’s detection sensitivity for errors typically encountered in IMRT fields, the position of 5 leaves in an IMRT field were purposely changed in 1 mm increments ranging from 1 mm to 10 mm in order to simulate errors in the delivery [5]. Film dosimetry (with extremely high spatial resolution) was used as a reference in this case. Figure 12 illustrates the effect of a 5 mm leaf displacement on an H&N IMRT field.

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**Figure 11:** Mean gamma evaluation of edge positioning errors reconstructed by the COMPASS system, for several sizes of the introduced error. Every point represents the average over ten successive locations of the field edge. The SDD is 762 mm. [5]

**Figure 12:** Dose difference (% relative to the prescribed dose) of a beam (12 segments) in the H&N plan, for five leaves with 5 mm introduced errors. COMPASS dose difference agreed with the film but shows more blurring. A film to film registration error of the order of 0.5 mm introduced dose differences in the high gradient regions (field edges). The SDD is 1000 mm.

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It can be seen that there is a very good agreement between the reference film and COMPASS, however, there is some blurring present in the COMPASS evaluation due to aforementioned effects introduced via the measurement reconstruction process.

As mentioned previously, the blurring of the introduced errors due to COMPASS’s resolution limitations are not the whole story and should not be entirely indicative of the system’s ability to accurately detect errors. A better analysis of the clinical relevance pertaining to the COMPASS QA process can again be evaluated by comparing the average values of gamma and the number of points displaying a gamma value in excess of 1 for COMPASS and that of film as in Figure 13 above [5].

When considering Figure 13, it can be concluded that:

- Film and COMPASS results are in excellent agreement for the mean gamma value for introduced errors from 1 to 10 mm.
- There is very good agreement in the number of points with gamma > 1.
- The point where there is an onset of points displaying gamma > 1 is at an introduced error of 3 mm. This is exactly where it should be expected when using gamma evaluation criterion of 3%/3 mm.

**SUMMARY**

COMPASS is a system for the verification of highly conformal treatments (3D-CRT, IMRT and rotational treatments) that renders the results as 3D dose distributions in patient anatomy, giving the possibility to evaluate the clinical relevance of dose discrepancies for each region of interest.

The COMPASS system can be used as a stand-alone software tool for a pure dose re-computation from the plan, or can be driven by measured and time-resolved fluence from the MatriXX detector array.

COMPASS delivers a clinically relevant measurement resolution.

Comparisons with traditional high-resolution verification tools (film) show that COMPASS achieves excellent error detectability and gamma analysis outcome for leaf errors down to 1 mm. Due to the set-up of the detector, COMPASS is not angular dependent and offers an increased total measurement area.

COMPASS promotes a more collaborative patient QA workflow. We at IBA believe that joint expertise leads to better patient outcomes.

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**Figure 13:** Mean gamma and number of points above gamma 1 (3%/3 mm) of several errors in five leaf pairs of the H&N case. The SDD is 762 mm. [5]

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COMPASS software is developed in cooperation with RaySearch Laboratories AB.

MatriXX was designed and built in cooperation with Torino University and INFN.

Technical data is subject to change without prior notice.