Evaluation of complexity and deliverability of IMRT- treatment plans

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Abstract

Background: Intensity modulated beams are used in radiotherapy in order to achieve high absorbed dose to the tumor volume while sparing the surrounding normal tissue. The degree of amplitude and frequency fluctuations within the intensity modulated beams can be referred to as the complexity of the beams. High complexity is associated with increased demands on the multi leaf collimator. Thus, because of limitations in the treatment planning system; more complex beams have an increased probability of dosimetric failure in the quality assurance (QA). Beams that pass the QA are considered to be deliverable. The modulation complexity score (MCS) (1) and the Modulation Index (MI) (2) have previously been suggested as metrics of complexity.

The aim of this study was to interpret and adapt the MCS for intensity modulated beams associated with the sliding window technique. Further, the MCS, the MI as well as the number of Monitor Units (MUs), the MU-factor, the number of Control Points (CPs), the number of MU/CP, the average leaf pair opening and the maximum fluence within the beam versus deliverability were investigated for different delivery parameters. The final aim was to find one, or several, complexity parameters that separated intensity modulated beams that were deliverable from those who were not; for both clinical IMRT treatment plans and plans with controlled complexity.

Materials and Methods: All of the intensity modulated treatment plans investigated in this study were planed and delivered using the sliding window technique within the Varian environment. 15 clinical head and neck (H&N) and four clinical prostate cases were studied. Furthermore, five plans with controlled level of complexity were generated. The measurements of deliverability were carried out using an amorphous silicon electronic portal imaging device (EPID). In-house developed MatLab®-code was utilized for the calculations of the MCS and the MI.

Results and Discussion: The EPID measurements were evaluated using the gamma index as well as the dose difference. The commonly used passing criteria 3%/3mm for the gamma evaluation was found to be too insensitive for detection of differences in deliverability for the investigated beams. Therefore, the passing criteria 2%/1mm was used instead. All the chosen complexity parameters were investigated against the gamma maximum and the average gamma within the beam as well as the percentage area of gamma index lower then unity, area were dose difference were less than 2 and 3%. The difference between splitted and non-splitted beams was studied as well.

Conclusions: The MCS parameter was developed for intensity modulated beams associated with the sliding window technique. The MCS and the MI were calculated for all the beams within this study. For the investigated clinical plans; sensitivity and specificity were calculated and gave a high specificity for the deliverability versus the average leaf pair opening and the MCS. However, the sensitivity was low for all parameters.

The plans with controlled complexity were well separated in the MCS, the MI and the average leaf pair opening. However, the plans were only separated in deliverability for the maximum gamma parameter. This indicates that the EPID measurements are not quite suitable for this type of investigation. Future aspects will be to investigate the deliverability using other dosimetry techniques e.g. film.
Abbreviations

AAV  Aperture area variability
Area γ <1 [%]  Percentage of the beam area with a gamma value smaller than one
CN  Conformity number
CP  Control points
DTA  Distance-to-agreement
EPID  Electronic portal imaging device
H&N  Head and neck
IMRT  Intensity modulated radiation therapy
LMC  Leaf motion calculator
LSV  Leaf sequence variability
MCS  Modulation complexity score
MI  Modulation index
MLC  Multi leaf collimator
MU  Monitor units
NOT  Normal tissue objective
OAR  Organ at risk
PTV  Planning target volume
QA  Quality assurance
SD  Standard deviation
SIB  Simultaneous integrated boost
TPS  Treatment planning system
γ_{avg}  Average gamma
γ_{max}  Maximum value of gamma
The most common ways to deliver IMRT are with the step and shoot or the sliding window technique. Using the step and shoot technique; the beam is turned off while changing the shape of the multi leaf collimator (MLC) opening delivering one segment at the time. For the sliding window method the beam is on while the MLC moves in the specified pattern to achieve the desired fluence distribution.

By deciding the number of beams, their directions and define constraints for the doses to the PTVs and the OARs, the treatment planning system (TPS) creates an “optimal fluence map” through iterative reconstruction. Depending on the geometry of the PTVs and the OARs, the demands for conformity to the PTV and tolerance to the surrounding OAR the fluence maps can be more or less complex. By complexity is meant the degree of frequency fluctuations and the height of the amplitude in the fluence distribution of the beam. If the complexity is reduced, this implies that the quality of the treatment may be deteriorated by loss in the conformity or unfulfilled tolerance. But more complex plans put greater demands on the delivery system. The leaf motion calculator (LMC) creates the MLC positions and account for leaf transmission, leaf edge shape and motion limitations. Because of these physical and mechanical limitations more complex plans are harder to achieve and the MLC leaves cannot create the “optimal fluence map”. Therefore the LMC creates an “actual fluence map” which is as close to the “optimal fluence map” as possible (5). Theoretically the “actual fluence map” should be possible to deliver since the physically and mechanically limitations of the MLC are taken into account. However, because of limitations in the absorbed dose- and leaf motion calculations the delivered dose might still be different from the theoretical absorbed dose calculated in the TPS. The more complex the beam is, the larger the possibility is that the delivered absorbed dose differ from the desired one. Therefore, prior to each treatment, patient specific measurements are carried out to verify how precise the machines are able to deliver the actual fluence, and the subsequent absorbed dose.
There are many parameters that affect the deliverability of the treatment plan, i.e. the possibility to deliver an absorbed dose distribution that precisely represents the desired calculated absorbed dose from the treatment planning system. As mentioned above, a complex treatment plan with high frequency and amplitude fluctuations in the fluence distribution is harder to deliver. To achieve complex fluence patterns more narrow MLC openings is required. For small MLC openings (< 3 cm) a significant amount of the absorbed dose is received from scattered radiation from the leaves and transmission through and between the leaves (6). Further, an error in leaf positioning for small leaf openings can have a big impact on the beam width and thus, on the integrated dose deposited by that beam (7). For small beams the beam width are direct proportional to the dose, and in a plan with complex fluence distributions the minimum delivered intensity becomes higher (6),(7). An increased amplitude and increased number of valleys in the intensity pattern also leads to a larger number of monitor units (MU) i.e. a complex plan requires a large number of MUs (6).

A widely used method to measure the dose distributions from the separate IMRT treatment beams is by using the electronic portal imaging device (EPID). The “actual fluence map” is utilized for calculation of absorbed dose to the EPID; the calculated and the measured dose distribution can then be compared. The calculation of the predicted absorbed dose distribution to the EPID is associated with uncertainties that might increase with increased complexity. One method commonly used to evaluate the EPID measurements is the gamma concept. The gamma index, $\gamma$, is a combination of the dose-difference, which for each point tells the difference between the measured and the expected absorbed dose, and the distance-to-agreement (DTA), which is the distance between the measured absorbed dose and the nearest point that exhibits the same absorbed dose within a predefined tolerance. A $\gamma$-index smaller than unity indicates that the measured absorbed dose agrees with the calculated one within the passing criterions.

Different TPS uses different methods that aim to reduce the complexity in the treatment plans. One way is to set constraints on a minimal leaf opening to minimize the influence from indirect radiation. Another way is to use different types of filtering (smoothing) to reduce large steps between neighboring fluencies. Mohan et al demonstrated that for a plan with filtered beams the delivered and the desired absorbed dose distribution conforms better than for a plan with unfiltered beams, it was also shown that for the plan with filtered beams both the parotid and cord sparing were improved (6). Giorgia et al presents in their study results that indicates that a sufficient smoothing gives a higher deliverability (8). By deliverability the agreement between the calculated and the delivered absorbed dose distribution is meant.

The Modulation Index (MI) is a metric for complexity that measures the modulation of the beam fluence (2). It takes into account the variation in adjacent pixel intensities that exceeds a certain fraction of the standard deviation of all pixels. The fact that MI takes the adjacent pixel variation into account makes it more useful than the standard deviation itself. In a previous study it was shown that the ratio between the mean dose in the OAR and the mean dose in the PTV increases as the MI increases (2). Large variations in the fluence indicate that the MLC-based delivery system is exposed to greater demands. Another study indicated that the quality of the delivery was shown by small changes in the MI (8). It was also claimed that
a MI under 19 ensures an accurately delivered absorbed dose distribution, within the Varian environment.

McNiven et al constructed and evaluated the Modulation Complexity Score (MCS), which is a metric that identifies dosimetrically robust beams for the step and shoot IMRT technique (1). The MCS defines the complexity of the total treatment plan by looking at the relative variability on leaf positions, the area of the beam opening and the numbers of MU. A MCS of unity defines an open rectangular beam with uniform fluence and decreases down to zero for more complex beams. In the study by McNiven et al the head & neck (H&N) treatment plans were found to be more complex than the breast and prostate plans.

There are many parameters that indicate that one plan is more or less complex than another for example the number of MU, width of MLC opening etc. However, there is an absence of a parameter that is verified, for our plans at Sahlgrenska University Hospital, to correlate with the deliverability, within the specific tolerance at the clinic.

The aim of this study was to interpret and adapt the MCS for intensity modulated beams associated with the sliding window technique. Further, the MCS, the MI as well as the number of Monitor Units (MUs), the MU-factor, the number of Control Points (CP), the number of MU/CP, the average leaf pair opening and the maximum fluence within the beam versus deliverability were investigated for different delivery parameters. The final aim was to find one, or several, complexity parameters that separated intensity modulated beams that were deliverable from those who were not; for both clinical IMRT treatment plans and plans with controlled complexity.

2. Materials and methods
All of the IMRT plans investigated in this study were planned and delivered with the sliding window technique created by the Varian treatment planning system Eclipse™, version 8.1; 8.6 and 8.9. The absorbed dose distributions were planned for and delivered with a CLINAC – 21iX linear accelerator and measured with an amorphous silicon EPID in the treatment room eight at the Sahlgrenska University Hospital. A mechanical limitation prevents the MLC leaves to go a distance larger than approximately 16 cm, beams that exceeded this limitation were split automatically within Eclipse™ into two smaller beams. An in-house developed software in the MatLab® (v.7.6.0.324 R2008a) environment was used for MCS and the MI calculations.

2.1 Plans

2.1.1 Clinical treatment plans
In this study, 15 completed clinical H&N treatment plans and four completed clinical prostate treatment plans were investigated. All of the investigated plans in this study were given with 2 Gy/fraction. Most of the H&N treatment plans had nine beam entries and most of the prostate treatment plans had seven beam entries. The beams were uniformly distributed in $2\pi$.

The H&N treatment plans that have been investigated were planned and measured between 2009-01-12 and 2010-05-18. The plans had a total of 204 beams all together, of which 158
beams were splitted beams. Ten of the plans were optimized for concave shaped PTV:s extending on both sides of the patients neck, whilst five of the plans were optimized on non concave shaped and more unilateral PTV:s.

The 4 prostate treatment plans that have been investigated were planed and measured between 2010-02-15 and 2011-01-11. The plans had a total of 31 beams all together, of which six beams were splitted beams.

2.1.2 Plans with controlled complexity

The clinical plans may be too similar to each other to see any difference in the complexity and the deliverability. Thus to get a wider distribution in complexity, five treatment plans with a controlled drift in complexity (C1-C4 and N) were generated in the scope of this study. The CT studies for two different H&N cancer patients were used, using one of the studies for C1-C3 and the other for C4 and N (Figure 1 a, b). The plans C1 –C3 were made as a serie were the first H&N plan (C1), only had one constraint; that the PTV should receive 68 Gy. The other two plans were optimized to give a maximum dose to medulla spinalis of less than 45 Gy (C2) and 15 Gy (C3), respectively. Hence, the complexity was expected to increase from plan C1 to plan C2 and from plan C2 to plan C3, respectively. The PTV had a non concave structure which increased the opportunities to achieve a non complex plan (Figure 1 a). The importance of the constraints and the degree of smoothing used in the optimization are described with different priority factors which are relatively connected (5). All of these plans had a smoothing priority of 50 and 30 for the X and the Y-parameter, respectively (50/30). These smoothing settings are commonly used at Sahlgrenska University Hospital. The Normal Tissue Objective (NTO) has been used with a priority of 150. For NTO, the distance from the target border was set to 1 cm, the start dose was 105 %, the end dose was 60 % and the fall-off was set to 0.05. These NTO settings have been used in all plans C1 – C4 and N. The minimum dose had a priority of 50 for all plans C1 – C4 and N. Two of the plans (C4 and N) were generated with clinically relevant absorbed dose constraints. Clinically relevant absorbed dose restrictions were defined for the parotid glands, the medulla spinalis and the larynx. Furthermore, the two plans had three different PTVs. These PTVs were optimized to achieve 68, 60 and 50 Gy, respectively, using the simultaneously integrated boost (SIB) technique. The SIB technique was believed to lead to more fluctuations in the fluence maps, due to the different absorbed dose levels. One of these plans was generated with the aim to be as non-complex as possible (N) and the other plan (C4) was made as complex as reasonably possible - having many constraints that were in conflict with each other. These two plans were optimized for the same absorbed dose levels. However, the priority setting for the PTVs and OARs were approximately duplicated for plan C4 compared with plan N. Furthermore the smoothing priority was set to zero for C4.

To avoid the uncertainties related to splitted beams the controlled plans consisted only non splitted beams. The plans C1-C3 was planned for 2 Gy per fraction as was the case for C4 and N planed for the 68 Gy target.
2.1.2.1 Differently smoothed plans

Plans with different settings on the smoothing parameters were made to see how the smoothing parameter in Eclipse™ affected the complexity and the conformity. One H&N plan was made to accomplish the constraints of 50 Gy to the PTV and less than 20 Gy to the medulla spinalis. The priority of the constraints on the PTV and the OAR was set to ≤ 100 and the smoothing was set to 50/30. This plan was then reconstructed with all the constraints fixed but with different smoothing settings. The smoothing was modified as follows: 0/0, 30/50, 100/100, 200/200 and 500/500 in the x/y direction.

2.2 Complexity parameters

From each beam in the plans, including splitted beams, parameters that could give information of the complexity were collected from Eclipse™. The selected parameters are parameters that in earlier studies been described as complex measures or are complex according to the explanation below (6), (7), (9) and (10). The investigated parameters from Eclipse™ were:

- **MU** (**M**onitor **U**nits): The total number of MUs is a measure of the machine output from a linear accelerator. A small beam opening requires more MUs to achieve the same dose as compared to a large beam opening (7), a larger number of MUs is also associated with more transmitted radiation between the leafs (10). Therefore a low number of MUs was expected to correlate with a low complexity (6).

- **MU-factor**: The MU-factor is a factor that is used for calculating the number of MUs and depends on the maximum leaf velocity (cm/s), the dose rate (MU/min) the field maximum in MU and the fluence variation (11). More irregular fluences give a higher MU-factor i.e. a more complex beam. Hence, a low MU-factor is desired (9). It is not clear how the MU-factor works for splitted beams (11 s. 241).

- **CP** (**C**ontrol **P**oints): During treatment delivery the position of the MLC-leaves are verified in a number of CP. In these CPs the machine checks that the correct number of MU has been delivered. A beam with a low number of CPs was expected to be less complex because it is more similar to an open beam.
• **MU/CP**: A low quota between the numbers of MUs per CP was believed to put higher demands on the MLC-leaves to move faster between the CPs. A high value on the MU/CP is therefore expected to correlate with less complex beams.

• **Average leaf pair opening**: Large leaf pair openings is associated with less indirect radiation and therefore a large value of the average leaf pair opening should correlate with a beam with low complexity \( (6)(7) \).

• **Maximum fluence**: A fluence distribution with many high tops and deep valleys of values is associated with high complexity \( (6) \). These high amplitude fluctuations might be more likely to be found in a beam with a high maximum value of the fluence than in a beam with a low maximum value of the fluence. A beam with a low maximum fluence is therefore believed to be less complex.

The calculated parameters collected from the literature were:

• **MI** (Modulation Index): The modulation of the beam fluence, a low MI value is associated with a beam with low complexity \( (2),(8) \).

• **MCS** (Modulation Complexity Score): Take into account the relative variability on leaf positions, the area of the beam opening and the numbers of MU \( (1) \). A high value of the MCS is associated with a beam with low complexity. The MCS was originally designed for the step and shoot technique but was in this study modified to suit the sliding window technique.

**Modulation Index**

MI was calculated according to Webb \( (2) \) using the actual fluence distributions. The mean intensity, \( \langle I \rangle \), and the standard deviation, \( \sigma \), were calculated for the whole beam. Only the fluences with values larger than one were included in the calculation of the MI. The number of intensity changes between adjacent intensities that exceeded a certain fraction, \( f \), of the standard deviation, \( \sigma \), in the beam was given by:

\[
N_x: \Delta x = |I_{i,j} - I_{i+1,j}| > f\sigma \\
N_y: \Delta y = |I_{i,j} - I_{i,j+1}| > f\sigma \\
N_{xy}: \Delta xy = |I_{i,j} - I_{i+1,j+1}| > f\sigma \\
N_{yx}: \Delta yx = |I_{i,j} - I_{i+1,j-1}| > f\sigma
\]

\( Z_x(f) \) is a histogram showing the number of adjacent intensity changes that exceeds the fraction, \( f_0 \), in the x direction. Similar histograms are given in the y direction as well as for the both of the diagonals, xy and yx. According to previous studies, \( f \) was defined from zero to two with an interval of 0.01 \( (2),(8) \). The \( \Delta xy \) and \( \Delta yx \) compares the intensities on the two diagonals.

\[
Z_x(f) = \frac{1}{C_x} N_x(f; \Delta x > f\sigma) \\
Z_y(f) = \frac{1}{C_y} N_y(f; \Delta y > f\sigma) \\
Z_{xy}(f) = \frac{1}{C_{xy}} N_{xy}(f; \Delta xy > f\sigma)
\]
\[ Z_{yx}(f) = \frac{1}{C_{yx}} N_{yx}(f; \Delta yx > f\sigma) \]

C is the total number of comparisons that has been carried out between adjacent intensities in the different directions (eq. 1). The total \( Z(f) \) is given by:

\[ Z(f) = \frac{[Z_x(f) + Z_y(f) + Z_{xy}(f) + Z_{yx}(f)]}{4} \]

Further the MI gives a single numerical metric of the modulation:

\[ MI(F) = \int_0^F Z(f)df \]

Within the scope of this study, different values of \( F \) were tested in order to evaluate which value that best separated plans with controlled complexity.

**Modulation Complexity Score**

The original MCS was described for the step and shoot technique (1). Within this study the MCS was developed to be used for plans with sliding window technique. The calculations are based on the MLC plan exported from the Eclipse™. The leaf sequence variability (LSV) parameter defines the distance between adjacent MLC leaf positions for each control point (CP). The variation between the adjacent leaves is related to the maximum possible change in the CP, defined by the distance between the leftmost leaf and the rightmost leaf in each leaf bank (eq.5 and Figure 2).

Figure 2: An example of the MLC-leafs positions in one CP. The green leafs represents the maximum position in each leaf bank and the red leafs shows the minimum position in each leaf bank. The maximum possible opening is given by the two red leafs.
The LSV includes all the moving MLC leaves, \( N \), inside the jaws, with one exception for leaves that moves but never have a leaf pair opening larger than 0.06 cm (closed leaf pairs). This phenomenon has been noticed in some beams but is assumed not to contribute to the complexity. The machine that is used in this study is set to have a minimum leaf opening of 0.05 cm for leaves that moves. Hence, leaf pair openings smaller than 0.06 cm was in this study not considered to contribute to the complexity. It has also been noticed that some leaves moves outside the jaws but never enter the collimator opening (yellow line, Figure 2), these leaves are not included in the MCS. Other leaves that are positioned outside the collimator, but in later CPs are moving inside the field, will be set to have the same value as the jaw border until they move inside the field. Immobile leaves that are placed between moving leaves are excluded because they affects the MCS differently depending on where in the field the leaf pair openings are positioned (Figure 3).

\[
\text{pos}_{\text{max}} = \langle \max(\text{pos}_{n \in N}) - \min(\text{pos}_{n \in N}) \rangle_{\text{leaf bank}}
\]

\[
\text{LSV}_{CP} = \left( \frac{\sum_{n=1}^{N-1} (\text{pos}_{\text{max}} - |\text{pos}_n - \text{pos}_{n+1}|)}{(N - 1) \times \text{pos}_{\text{max}}} \right)_{\text{Left bank}}
\times \left( \frac{\sum_{n=1}^{N-1} (\text{pos}_{\text{max}} - |\text{pos}_n - \text{pos}_{n+1}|)}{(N - 1) \times \text{pos}_{\text{max}}} \right)_{\text{Right bank}}
\]

The aperture area variability (AAV) was defined as the area of each leaf pair opening normalized to the maximum possible area in each CP (Figure 2).
The total number of MUs is delivered between the first and last CP within the beam. Therefore the MCS_{beam} is given by the product of the mean value between each successive LSV_{CP} and the mean value for each successive AAV_{CP}, weighted by the relative MU delivered between two successive CPs in the beam.

\[
AAV_{CP} = \frac{\sum_{n=1}^{N} (pos_n)_left \text{bank} - (pos_n)_right \text{bank}}{N \times ((max(pos_n))_left \text{bank} \in CP - (max(pos_n))_right \text{bank} \in CP)}
\]

Where \( I \) is the total number of CP in the beam. The sum of all the MCS_{beam} weighted by the relative MU of each beam in the plan gives the total MCS for the plan.

\[
MCS_{beam} = \sum_{i=1}^{I} \left( \frac{LSV_{CP_i} + LSV_{CP_{i+1}}}{2} \right) \times \left( \frac{AAV_{CP_i} + AAV_{CP_{i+1}}}{2} \right) \times \frac{MU_{i+1}}{MU_{beam}}
\]

Where \( J \) is the total number of beams in the plan.

### 2.3 Delivered dose distributions

The 2D dose distribution for each beam has been calculated in Eclipse™ and measured with an EPID. Prior to evaluation the calculated and measured dose distributions were aligned to match each other and normalized within an adjustment of no more than three percent of the total absorbed dose. This is done because the position of the EPID is not completely accurate.

A common clinical combination of criteria’s is is 3% dose difference and 3 mm DTA (3%/3mm) (12). There is no general consensus of clinical action levels for the gamma evaluation. However, a previous study by Howell et al (13) suggested three parameters, the maximum value of gamma, \( \gamma_{max} \), the average gamma, \( \gamma_{avg} \), and the percentage of the beam area with a gamma value greater than 1.0 (area \( \gamma > 1 \)). These values have in this study been used as deliverability parameters together with the dose difference.

The gamma values, \( \gamma_{max} \), \( \gamma_{avg} \) and area \( \gamma < 1 \) [%] values were collected for different pass criterions, the global dose difference criteria was used. The area dose of differences less than 2 and 3 % was also collected from the EPID evaluation. The percentage area with gamma values smaller than 1.0 (area \( \gamma < 1 \)) was used to be more consistent.

All complexity parameters were analyzed against the measures of deliverability in order to evaluate if there was any correlation.
2.4 Conformity Number
The quality of the clinical treatment plans was evaluated by calculating the Conformity number (CN) for each plan (eq. 10), (14).

\[ CN = \frac{TV_{RI}}{TV} \times \frac{TV_{RI}}{V_{RI}} \]

Where TV\(_{RI}\) is the target volume covered by the 95 % isodose, TV is the target volume and V\(_{RI}\) is the total volume covered by the 95 % isodose. A 95 % isodose that precisely covers the TV and spare the rest of the body gives the CN = 1.

Selected measurements of the complexity were analyzed against CN to investigate possible correlation.

2.5 Sensitivity and specificity
For the complexity parameters that showed a visual correlation against the deliverability the sensitivity and specificity was calculated. These parameters identify the ability for the complexity parameter to distinguish beams that were deliverable from those who were not (eq. 11). A high sensitivity (100%) in this case means that all beams with a complexity below the threshold (i.e. high complexity) are non deliverable. A high specificity (100 %) in this case means that all beams with a complexity exceeding the threshold (i.e. low complexity) are deliverable. If the sensitivity is low this means that beams with a complexity below the threshold can be deliverable and a low specificity means that even beams with a complexity exceeding the threshold can be non deliverable (15).

Figure 4: The different squares are defined by the thresholds for complexity and deliverability. The complexity decreases along the x-axis and the deliverability increases along the y-axis

\begin{array}{ccc}
\text{Sensitivity: } & A & \frac{A}{A+C} \\
\text{Specificity: } & D & \frac{D}{B+D} \\
\end{array}

If a threshold that gives both a high sensitivity and a high specificity is found, this could result in a reduction in the number of control measurements. The sensitivity and specificity was only calculated for the area \( \gamma < 1 \) [%], a commonly used measure in the clinic.
3. Results and discussion

A commonly used passing criterion for γ evaluations of absorbed dose distributions is 3%/3 mm (12),(16). The 3%/3mm passing criteria and tighter criteria of 2%/1mm were investigated in this study. The tighter passing criteria gave a more apparent separation in the deliverability parameters of the treatment plans, which also been seen in a previous study (1). Therefore, only the results of the 2%/1mm passing criteria were included in this report.

3.1 Clinical treatment plans

Compared with the H&N treatment beams the prostate treatment beams tended to have a higher deliverability for the investigated deliverability parameters and had a smaller standard deviation (SD) (Table 1). Further the non-splitted H&N treatment beams tended to be more deliverable than the splitted beams (Table 2).

Table 1: Statistical analysis of the results of the EPID measurements for 204 H&N treatment beams and 31 treatment prostate beams. The gamma analyses were carried out using the 2%/1mm criteria.

<table>
<thead>
<tr>
<th>Mean value ±SD</th>
<th>H&amp;N</th>
<th>Prostate</th>
</tr>
</thead>
<tbody>
<tr>
<td>γ max</td>
<td>4.10 ± 1.62</td>
<td>3.00 ± 1.07</td>
</tr>
<tr>
<td>γ avg</td>
<td>0.44 ± 0.08</td>
<td>0.38 ± 0.06</td>
</tr>
<tr>
<td>area γ &lt; 1 [%]</td>
<td>92.9 ± 5.49</td>
<td>95.8 ± 2.25</td>
</tr>
<tr>
<td>Area dose diff &lt; 2 % [%]</td>
<td>85.8 ± 5.92</td>
<td>88.1 ± 3.76</td>
</tr>
<tr>
<td>Area dose diff &lt; 3 % [%]</td>
<td>93.2 ± 3.65</td>
<td>94.3 ± 1.74</td>
</tr>
</tbody>
</table>

Table 2: Statistical analysis of the results of the EPID measurements for 158 splitted beams and 46 non-splitted H&N treatment beams. The gamma analyses were carried out using the 2%/1mm criteria.

<table>
<thead>
<tr>
<th>Mean value ±SD</th>
<th>Splitted beams</th>
<th>Non-splitted beams</th>
</tr>
</thead>
<tbody>
<tr>
<td>γ max</td>
<td>4.24 ± 1.57</td>
<td>3.64 ± 1.69</td>
</tr>
<tr>
<td>γ avg</td>
<td>0.44 ± 0.08</td>
<td>0.43 ± 0.09</td>
</tr>
<tr>
<td>area γ &lt; 1 [%]</td>
<td>92.5 ± 5.60</td>
<td>94.4 ± 4.85</td>
</tr>
<tr>
<td>Area dose diff &lt; 2 % [%]</td>
<td>85.2 ± 6.27</td>
<td>87.8 ± 3.95</td>
</tr>
<tr>
<td>Area dose diff &lt; 3 % [%]</td>
<td>92.8 ± 3.91</td>
<td>94.4 ± 2.18</td>
</tr>
</tbody>
</table>
The total numbers of MUs for 15 H&N treatment plans were plotted against the different deliverability parameters (Figure 5). Visually, there was a slight correlation with the total number of MUs and all of the measures of deliverability. However, to get a statistically significant correlation more data is needed. The four prostate plans which have been investigated in this study were too few to give even a tendency of correlation.

![Figure 5: The different deliverability parameters versus total number of MUs for 15 H&N treatment plans. The complexity decreases along the x-axis and the deliverability increases along the y-axis. Visually a slight correlation was observed for all investigated deliverability parameters and total number of MUs.](image)

The number of MUs per beam has also been investigated against the different parameters of deliverability. However, no correlation was found for neither the H&N nor the prostate treatment beams (not showed). The prostate beams tended to have a higher number of MUs than the H&N beams (Table 3). The geometry of the prostate treatments and the H&N treatments are different. The PTV:s are situated deeper into the patient for prostate treatments as compared to the H&N treatments and therefore results in a higher number of MUs. The number of beam entries is usually larger for the H&N treatment plans than for the...
prostate treatment plans which also affect the number of MUs distributed between the beams. The H&N plans also often have a large amount of splitted beams resulting in an even smaller number of MUs per beam (Table 4). Degree of complexity for plans with different amount of beams can therefore not be compared by the numbers of MUs. The non-splitted beams were however more similar to the prostate beams in the number of MUs (Table 3 and Table 4). Further, the non-splitted beams were found to be more deliverable than the splitted beams (Table 2).

For the MU-factor no correlation was found with any of the deliverability measures for the clinical treatment beams (not showed). However, it is not clear how the MU-factor is affected by the splitted beams (11 s. 241), and hence no conclusions can be drawn. Further the lack of correlation can be the fact that only eight of these clinical treatment beams had values on the MU-factors higher than 2.5. The 2.5 value of the MU-factor has been evaluated and used as an upper limit for deliver treatment plans at another clinic (9). A broader range of the MU-factor value for the treatment plans in this study might have given a different result.

<table>
<thead>
<tr>
<th>Mean value</th>
<th>H&amp;N</th>
<th>Prostate</th>
</tr>
</thead>
<tbody>
<tr>
<td># MU</td>
<td>84 ± 25</td>
<td>105 ± 29</td>
</tr>
<tr>
<td>MU-factor</td>
<td>1.65 ± 0.48</td>
<td>1.61 ± 0.44</td>
</tr>
<tr>
<td># CP</td>
<td>126 ± 30</td>
<td>124 ± 32</td>
</tr>
<tr>
<td>#MU/CP</td>
<td>0.671 ± 0.133</td>
<td>0.854 ±0.169</td>
</tr>
<tr>
<td>Average leaf pair opening [cm]</td>
<td>1.54 ± 0.49</td>
<td>2.54 ± 0.85</td>
</tr>
<tr>
<td>Maximum fluence [CU]</td>
<td>0.156 ±0.048</td>
<td>0.231±0.058</td>
</tr>
<tr>
<td>MI</td>
<td>13.09 ±2.73</td>
<td>13.23 ±1.99</td>
</tr>
<tr>
<td>MCS</td>
<td>0.21 ± 0.07</td>
<td>0.272 ±0.074</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Mean value</th>
<th>Splitted beams</th>
<th>Non- splitted beams</th>
</tr>
</thead>
<tbody>
<tr>
<td># MU</td>
<td>78 ±21.5</td>
<td>106 ± 32.3</td>
</tr>
<tr>
<td>MU-factor</td>
<td>1.56 ± 0.47</td>
<td>1.94 ± 0.43</td>
</tr>
<tr>
<td># CP</td>
<td>120 ± 30</td>
<td>147 ± 20</td>
</tr>
<tr>
<td>#MU/CP</td>
<td>0.654 ± 0.116</td>
<td>0.732 ±0.116</td>
</tr>
<tr>
<td>Average leaf pair opening [cm]</td>
<td>1.45 ± 0.45</td>
<td>1.87 ± 0.49</td>
</tr>
<tr>
<td>Maximum fluence [CU]</td>
<td>0.146 ±0.044</td>
<td>0.192 ± 0.043</td>
</tr>
<tr>
<td>MI</td>
<td>12.47 ± 2.47</td>
<td>15.20 ± 2.51</td>
</tr>
<tr>
<td>MCS</td>
<td>0.20 ± 0.068</td>
<td>0.23 ± 0.075</td>
</tr>
</tbody>
</table>

The default value of a maximum of 166 CP per beam is used for the TPS. In this range of the number of CP no correlation between the numbers of CP and the deliverability was found (not showed) and no significant difference was verified between the H&N and the prostate treatment beams (Table 3). The number of CP between the splitted and non-splitted beams
tended to be different which may depend on the fact that the splitted beams most often are smaller and therefore need less CPs to achieve the desired fluence.

For the number of MU/CP no correlation was found for the $\gamma_{\text{max}}$ nor the $\gamma_{\text{avg}}$ (Figure 6 a, b). However, the deliverability tends to be higher with a larger number of MU/CP for the rest of the deliverability parameters investigated (Figure 6 c, d, e).

Figure 6: The different deliverability parameters versus total number of MU/CP for 204 beams from 15 H&N treatment plans and 31 beams from four prostate treatment plans. The complexity decreases along the x-axis and the deliverability increases along the y-axis. Visually there is a small correlation between the MU/CP for the area $\gamma < 1$, dose diff $< 2 \%$ and $< 3 \%$.

It was found that all the investigated delivery parameters gave a high deliverability for a large average leaf pair opening (Figure 7). The non-splitted treatment beams tended to have larger average leaf pair openings than the splitted beams. However, the prostate treatment beams had the highest mean average leaf pair opening (Figure 7, Table 3 and Table 4).
Figure 7: The different deliverability parameters versus average leaf pair opening for 204 beams from 15 H&N treatment plans and 31 beams from four prostate treatment plans. The complexity decreases along the x-axis and the deliverability increases along the y-axis. An average leaf pair opening just over 2 cm tends to have a high deliverability according to all the deliverability parameters investigated. The black lines in c indicate the values used for calculating the sensitivity and specificity (Table 5).

The PTV typically lays shallower in the H&N region compared with in the prostate region. Even though the absorbed dose/fraction is the same the PTV that are placed deeper inside the body result in a higher entrance dose i.e. a higher fluence. Hence, the result from the maximum fluence for the H&N and the prostate beams cannot be compared with each other (Table 3). The splitted beams tended to have a lower maximum fluence and be less deliverable than the non-splitted beams (Figure 8). A high maximum fluence tends to give a better deliverability according to area $\gamma < 1$, area dose diff < 2 and 3 % (Figure 8 c, d, e), which is the opposite to what was expected. However, high fluences have already been considered as a measure of complexity at the clinic, consequently the highest fluences have already been sorted out and an eventual tendency can therefore have been missed. Another explanation is that the dose difference in the gamma index evaluation has been calculated relatively a global reference dose. A high maximum fluence might correlate with a high
reference dose which relatively accepts larger dose differences in low dose areas and results in lower gamma values. Furthermore, the EPID measurements might be more unsure for lower fluences.

Figure 8: The different deliverability parameters versus the maximum fluence for the 204 beams from 15 H&N treatment plans and 31 beams from four prostate treatment plans. The complexity decreases along the x-axis and the deliverability increases along the y-axis.

The separate H&N beams gave no correlation between the MI value and the different parameters of deliverability (Figure 9), nor did the H&N plans (not showed). There was no significant separation between the H&N and prostate beams, however the non-splitted and splitted beams tended to be separated (Table 3 and Table 4). Visually, the prostate beams tended to have a small correlation with all the delivery parameters except for $\gamma_{\text{max}}$, however this correlation was not statistically proven (Figure 9).

The F factor used for calculating MI (eq. 4) was set to the value two (see section 3.2).
Figure 9: The different deliverability parameters versus MI for the 204 beams from 15 H&N treatment plans and 31 beams from four prostate treatment plans. The complexity decreases along the x-axis and the deliverability increases along the y-axis. The prostate beams visually tend to correlate with all the delivery parameters except for the $\gamma_{\text{max}}$. However for the H&N beams no correlation was observed.

For the MCS beam no significant separation was found between the splitted and non splitted beams (Table 4). With a good will some correlation was visually observed for all the deliverability parameters (Figure 10).
Figure 10: The different deliverability parameters versus MCS for 204 beams from 15 H&N treatment plans and 31 beams from four prostate treatment plans. The complexity decreases along the x-axis and the deliverability increases along the y-axis. Visually, all the deliverability parameters correlate with the MCS. The black lines in c indicate the values used for calculating the sensitivity and specificity (Table 5).

3.1.1 Sensitivity and specificity

For clinical treatment plans at Sahlgrenska University Hospital, the pass rate for an acceptable deliverability is a percentage area with gamma values smaller than one over 97% with a criterion of 3%/3mm. For the tighter criteria 2%/1mm used in this study a pass rate of 90% for area $\gamma < 1 \%$ has been used as an example of an acceptable limit according our results, this limit has also been used in a previous study (Figure 6c, Figure 7c and Figure 10c), (1).

The average leaf pair opening and MCS are the complexity parameters that visually showed the best correlation against the different delivery parameters and were therefore examined further by calculating the sensitivity and specificity.
The thresholds for the average leaf pair opening (≥2.16 cm) and the MCS (>0.315) gave both a specificity of 100%. However, the sensitivity was only 19% and 17% respectively (Figure 7 c, Figure 10 c and Table 5).

### Table 5: Calculated the sensitivity and specificity for different complexity parameters.

<table>
<thead>
<tr>
<th>% difference and DTA criteria</th>
<th>Percentage pass rate criteria</th>
<th>Complexity parameter</th>
<th>Threshold value</th>
<th>Sensitivity [%]</th>
<th>Specificity [%]</th>
</tr>
</thead>
<tbody>
<tr>
<td>2 % / 1mm</td>
<td>90 %</td>
<td>Average leaf pair opening [cm]</td>
<td>≥2.16</td>
<td>19</td>
<td>100</td>
</tr>
<tr>
<td></td>
<td></td>
<td>MCS&lt;sub&gt;beam&lt;/sub&gt;</td>
<td>&gt;0.315</td>
<td>17</td>
<td>100</td>
</tr>
</tbody>
</table>

This result says beams that have an average leaf pair opening equal or larger than 2.15 cm or has a MCS value over 0.315 are deliverable according to the pass rate of delivery used in this example. However, because of the low sensitivity beams that do not exceed the threshold cannot be dismissed. The thresholds for the complexity parameters that were used were set according to all the investigated clinical treatment beams in this study. However if the threshold had been set for the splitted and non-splitted beams separately or for the H&N and prostate beams separately the result would have been different. If the specificity would have been under 100%, it would not say anything about how far from the threshold the non complex or non delivered beams would be.

### 3.2 Plans with controlled complexity

In the evaluation of the total number of MUs per plan for the controlled plans with known difference in complexity the plans were shown to be separated in the expected order (Figure 11). Visually there was a tendency to correlation between the delivery parameters and the MU<sub>tot</sub>. However, the γ<sub>max</sub> was the only delivery parameter that had a linear correlation ($R^2=0.97$) in the expected direction. The second best correlation was observed for the area dose difference < 2 % ($R^2=0.71$). However, the difference in deliverability was very small and the correlation was in the opposite direction of expectation. Overall, the difference in deliverability between the beams in the plans with controlled complexity seems to be too small to show the expected trends, except for the γ<sub>max</sub> (Figure 11 and Table 6). However, it is important to be aware that the amount of plans was too small to draw any statistical conclusions.
Figure 11: The different deliverability parameters versus the total number of MUs for the plans with controlled complexity. The complexity decreases along the x-axis and the deliverability increases along the y-axis.

Table 6: Statistical analysis of the EPID measurements for the beams from the controlled plans. The gamma analysis were carried out using the 2%/1mm criteria.

<table>
<thead>
<tr>
<th>Mean value ± 1 SD</th>
<th>C1</th>
<th>C2</th>
<th>C3</th>
<th>C4</th>
<th>N</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\gamma_{\text{max}}$</td>
<td>2.33 ± 0.12</td>
<td>2.92 ± 0.78</td>
<td>4.10 ± 1.05</td>
<td>6.00 ± 1.80</td>
<td>3.92 ± 1.49</td>
</tr>
<tr>
<td>$\gamma_{\text{avg}}$</td>
<td>0.45 ± 0.02</td>
<td>0.42 ± 0.06</td>
<td>0.41 ± 0.06</td>
<td>0.41 ± 0.07</td>
<td>0.40 ± 0.06</td>
</tr>
<tr>
<td>area $\gamma &lt; 1%$</td>
<td>92.9 ± 1.0</td>
<td>94.2 ± 2.72</td>
<td>94.7 ± 2.16</td>
<td>95.5 ± 1.90</td>
<td>95.7 ± 2.68</td>
</tr>
<tr>
<td>Area dose diff &lt; 2%</td>
<td>85.7 ± 1.5</td>
<td>86.2 ± 3.8</td>
<td>88.0 ± 2.9</td>
<td>89.1 ± 2.8</td>
<td>88.6 ± 3.22</td>
</tr>
<tr>
<td>Area dose diff &lt; 3%</td>
<td>92.9 ± 0.97</td>
<td>92.9 ± 2.3</td>
<td>93.7 ± 1.4</td>
<td>94.2 ± 1.7</td>
<td>94.4 ± 1.82</td>
</tr>
</tbody>
</table>

The fact that the most complex plan (C4) tended to be more deliverable than the least complex plan (C1) was not expected. One speculation about this is that dose profiles with many tight peaks make it easier to find a dose level that match the criterions closer in distance than in regular dose profiles. A constructed example is visualized in (Figure 12). This is not something that was noticed for the treatment beams that have been investigated in
this study. However, it is something that could happen if the dose profiles are not evaluated carefully. It is therefore important to know the weaknesses of the gamma evaluation and carefully look at the profiles when using it in the clinic.

![Figure 12: Calculated (orange) and measured (green) absorbed dose profiles, percentage absorbed dose versus distance. The white lines represent a distance of 3 mm and clarify which parts of the calculated profile that are associated with the measured profile. These profiles have not been properly aligned. This results in that the measured absorbed dose peak approves both a large part of the right peak that it is supposed to represent as well as parts of the left peak that the delivery system failed to reconstruct. This makes the gamma evaluation falsely better than is actually is.](image)

In low dose areas the transmission between and through the MLC leaves appears more than in the high dose areas, which makes it harder to fit the dose profiles from the EPID measurement with the calculated ones.

The plans with controlled difference in complexity had a larger complexity range than all of the non-split H&N treatment beams and had more complex beams than the splitted H&N treatment beams for most of the complexity parameters. Despite this expansion in complexity there was no significant difference in none of the deliverability parameters (Table 6). This indicated that the results from EPID measurements were not sufficient to use as a measure of deliverability for this type of study.

The doubtful parameter $\gamma_{\text{max}}$, that only represents the difference in a single small area defined by the DTA criteria in the gamma evaluation, was the only delivery parameter correlating in the expected way. Hence, $\gamma_{\text{max}}$ was chosen when presenting how the different complexity parameters separated the plans with controlled complexity (Figure 13). The average leaf pair opening separates all of the controlled plans while the number of CP and the MU-factor were not able to separate any of the plans. The total numbers of MU and the maximum fluence were able to separate some of the plans (Figure 13). The range of the beam distribution for the more complex plans was seen to be larger than for the less complex plans for these two parameters (Figure 13). The number of MU/CP was also able to separate some of the beams. However the beams from the least complex plans had the lowest number of MU/CP and the beams from more complex plans had higher number of
MU/CP. This is the opposite from what was expected and noticed for the clinical treatment plans (Figure 6). This indicates that the numbers of MU/CP are not a reliable parameter.

Only nine of the beams had a MU-factor higher than 2.5, of which only one beam had a value over 3. Hence, there were still too few high values to observe any potential correlation between the MU-factor and the deliverability that is expected for high values on the MU-factor (9). Neither is the range of CP sufficient to give any correlation with the deliverability. The default value for the maximum number of CP was used when generating these plans. Thus the range in numbers of CP was no larger than for the clinical plans. The rest of the parameters tend to correlate with the $\gamma_{max}$ (Figure 13).

<table>
<thead>
<tr>
<th>$\gamma_{max}$ (2% / 1 mm)</th>
<th>$\gamma_{max}$ (2% / 1 mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>MU</td>
<td>MU-faktor</td>
</tr>
<tr>
<td>CP</td>
<td>MU/CP</td>
</tr>
<tr>
<td>Average leaf pair opening [cm]</td>
<td>Maximal fluence</td>
</tr>
</tbody>
</table>

Figure 13: The Maximum gamma value versus different complexity parameters from Eclipse™. The complexity decreases along the x-axis and the deliverability increases along the y-axis.

To determine which value of F to be used in the evaluation of MI, the $Z(f)$ was plotted against the fraction, f for two plans (eq. 4). The least complex (C1) and the most complex, (C4) controlled plans were used for this purpose. The MI value for the plans is found by integrating $Z(f)$, i.e. the area under the graph (eq. 4), (Figure 14). The largest differences in
MI were fund when both the plans had saturated. The more complex plan saturated later than the less complex plan. However, both plans were saturated at $f$ equal to two (Figure 14). Therefore, the value of $F$ was set to two in the MI calculations.

![Figure 14: The histogram of $f$, for two plans with controlled complexity. At $f = 2$ both were well saturated.](image)

For the clinical plans the MI factor did not correlate with any of the delivery parameters. However the controlled plans proved that MI was able separate plans with known difference in complexity (Figure 15). MI had a linear correlation with $\gamma_{\text{max}}$ ($R^2 = 0.6$).

![Figure 15: The maximum gamma value versus MI(2). MI was able to separate the controlled plans in the expected order. The complexity decreases along the x-axis and the deliverability increases along the y-axis.](image)

The MCS were able to separate all plans with known difference in complexity and had a visual, but not significant, correlation against the maximum gamma (Figure 16).
Figure 16: The maximum gamma versus the MCS. The MCS was able to separate the controlled plans with known complexity in the expected order. The complexity decreases along the x-axis and the deliverability increase along the y-axis.

MCS is based on the average leaf pair opening and the two parameters do correlate (Figure 17 a). However, the MCS do also take the MLC position into account. Both MCS and the average leaf pair opening are able to distinguish the deliverable beams of the clinical treatment plans with the specificity 100 %. The fact that immobile leaves that are placed between moving leaves were excluded in the calculations of MCS might lead to that some of the true complexity may be lost since the areas appear to be related. Further, the fact that opening areas that are separated by the MLC-leaves have not been treated specially can also be a source to loss of true complexity in the MCS (Figure 3). However, it has been adopted that the LSV includes this phenomena.

Both the MI and the MCS metrics were able to separate plans with known difference in complexity (Figure 17 b).

Figure 17: The average leaf pair opening versus MCS (a) and the MI(2) versus MCS (b). The complexity decreases along the x and the y-axis. The MCS are based on the average leaf pair opening and the two parameters do correlate. MCS and MI do correlate, as well. However MCS separates the plans more than MI.

3.3 Smoothed plans

High priorities on the smoothing parameters in Eclipse™ makes the fluences appear more regular. However, a smooth fluence distribution can be delivered by a very complex MLC pattern. The plan with the smoothing priorities 500/500 got very complex according to the MCS because of very small leaf pair openings and the plan actually failed to achieve a PTV dose higher than 5 Gy. Some of the beams for this plan had average leaf pair openings smaller than 0.06 cm and therefore the MCS could not be calculated for each of these
beams. These results indicates that the smoothing parameter in Eclipse™ affects the fluence and do not work against the MLC (Figure 18).

Figure 18: The smoothing priorities versus the MI(2) (a) and the smoothing priorities versus the MCS plan (b). The complexity decreases along the x-axis, and the smoothing priority increase along the y-axis. MI indicates that the 500/500 plan has a low complexity while the MCS indicates that the 500/500 plan has a high complexity. This indicates that the smoothing parameter in Eclipse™ only affects the fluence and do not work against the MLC.

3.4 Conformity Number

It is well known that more complex fluence distributions are needed to give a better dose conformity to the PTVs, especially for a PTV that has a concave shape around the OARs. The clinical plans with a low complexity tended to have a higher CN than the plans with high complexity. However, there was no significant difference between plans with double-side and unilateral PTVs (Figure 19). Small distances between the structures as well as a large amount of structures taken into account, means that the demands on the optimization system become greater and makes it harder to achieve tight dose conformity to the PTV. Some geometrical situations require complex plans more than other and making a complex plan less complex does not necessarily mean that the dose distribution gets more conform (Figure 20). The fact that it is the H&N plans that have the worst coverage can be explained by the fact that sparing of the medulla spinalis and sometimes also the parotid glands have higher priority than covering of the PTV. The PTV might overlap the OAR to be spared. This is a decision that the physician makes when accepting the treatment plans. However, the calculation of CN does not take into account such a decision.
Figure 20: The CN versus the MI(2) and the CN versus MLC_{plan} (b). The complexity decreases along the x-axis and the CN increases along the y-axis. A more complex plan can achieve a more conform plan according to the CN. The 500/500 plan was excluded from this graph because it did not achieve the required dose to the PTV.

4. Conclusion

The MCS parameter was developed for the sliding window technique and was visually able to separate plans with controlled difference in complexity. MI was applied and was also visually able to separate the plans with controlled complexity. The other investigated metrics of complexity that were visually able to separate the controlled plans were the average leaf pair opening that separated all of the controlled plans. Further, the total numbers of MU, the MU/CP and the maximum fluence were visually able to separate some of the controlled plans. For the MU-factor and the number of CP no separation was observed.

Visually there was a tendency of correlation for the total number of MUs, the average leaf pair opening and for MCS versus the different delivery parameters for the clinical treatment plans. The sensitivity and specificity were calculated for the average leaf pair opening and the MCS. All of these parameters distinguished deliverable beams with high specificity; however the sensitivity was low for all of them.

The plans with known difference in complexity had a wider range among the complexity parameters. However, they were not distinctly separated by the delivery parameters, except for the maximum gamma parameter. This indicates that the EPID measurements are not perfectly suitable for this type of investigations.

Too high priorities on the smoothing parameter gave a small gain in smoothing according to the MI, whilst the complexity of the MLC pattern increased according to the MCS. This proves that the MLC only affects the fluence, but do not affect the dynamic MLC that generates the MLC-pattern for the sliding window technique.

As expected it was observed that the prostate treatments plans tended to be more deliverable than the H&N treatment plans.

4.1 Future aspects

Some of the complexity metrics in this study were able to distinguish some beams that were deliverable from those who were not. Today it might not be any gain of time if only a few beams per plan were proved by calculation to be deliverable. However, further development of the external radiotherapy has led and will lead to more advanced delivery techniques that will require patient specific measurements. The increased use of these technologies will
contribute to an increased number of dosimetric measurements. A metric that even if it just distinguish a few beams per plan would then be time saving because of the larger amount of plans that has to be dosimetrically verified and controlled.

RapidArc is one of the newer techniques that requires patient specific dosimetric measurements and would benefit from a metric that provides information about the deliverability of the plans in advance. In a study by Kallehauge et al the MCS metric gave the best correlation to deliverability for dose distributions from prostate treatment plans, however improvements of the MCS by adding a dynamic term before use was suggested (17).

A further development of the MCS could be to find out a way to weight areas that are separated by the MLC leaf and areas that seem to be related because the immobile leaves are excluded (section 3,2). It would also be interesting to find out if the range for the average leaf pair opening affects the deliverability of the beam.

The EPID measures together with the gamma evaluation were not able to separate the plans with known difference in the complexity. This is believed to depend on uncertainties in the dose calculation to the EPID and in the gamma evaluation. Therefore it is proposed that other dosimetric methods for the deliverability should be tested e.g. film, diode and ionization chamber matrixes.

Since the average leaf pair opening was one of the parameters that were able to distinguish dosimetrically robust beams, the distribution of the leaf openings within the different beams could be of interest for further studies.

**Acknowledgements**

I first would like to thank my supervisors Anna Bäck and Anna Karlsson Hauer for all the time, effort and support they have given me during this work. Also a big thank you to Mattias Berglund for all valuable points of view about the MI and the MCS parameters, and particularly for the interpretation of the developed calculations into software code in Matlab®. And to Fredrik Nordström for helping me find the fluences in the jungle of the data within the DICOM-files.

Thanks to the rest of the department who took the time to answer my questions and made me feel welcome at the department.
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