AN ABSTRACT OF THE THESIS OF

Jennifer Wong for the degree of Master of Science in Medical Physics presented on October 22, 2015.

Title: Vernier Picket Fence Test: A Non-Imaging Method to Localize the Radiation Isocenter with Submillimeter Accuracy.

Abstract approved:

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Junan Zhang, Ph.D.

Vernier Picket Fence (VPF) offers a method to achieve submillimeter accuracy for aligning the QA phantom to the radiation isocenter without the use of x-ray imaging. VPF tests are read similarly to vernier calipers. The maximum detector signal determines the optimal matching between MLC defined dose strips and detector positions. A Gaussian function was used to fit signals from multiple detectors so that the optimal position can be solved iteratively. In order to evaluate the accuracy of the VPF test, the couch was shifted in a sequence of positions where VPF tests were performed to determine the couch positions in two dimensions on the Sun Nuclear MapCheck® (Melbourne, FL) device. The VPF was delivered at 0º gantry angle with 0º and 90º collimator angles to determine the lateral and longitudinal coordinates, respectively. Each position was also verified using ExacTrac® (Feldkirchen, Germany) to track the couch positions by infrared camera. To achieve three-dimensional capabilities, additional fields at 90º and 270º gantry angles were delivered on the Sun Nuclear ArcCheck® (Melbourne, FL) to determine the vertical direction, while accounting for the geometrical corrections of the diode distribution in the phantom. The radiation isocenter can be identified with up to 0.02 mm accuracy. The results from the VPF tests were compared with ExacTrac® to evaluate the accuracy with a difference of 0.3±0.055 mm laterally and 0.5±0.041 mm
longitudinally. Results from the ArcCheck® also verify that the VPF test can be applied in all three directions, with a resolution of 1 cm from the detector spacing. Overall, VPF tests can achieve submillimeter positioning accuracy for QA phantom setup in three-dimensions. The systematic difference found may be attributed to initial setup error. Standard deviations are small, suggesting that results from infrared tracking and VPF tests are highly reproducible.
Vernier Picket Fence Test: A Non-Imaging Method to Localize the Radiation Isocenter with Submillimeter Accuracy

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APPROVED:

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Head of the School of Nuclear Science and Engineering

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I understand that my thesis will become part of the permanent collection of Oregon State University libraries. My signature below authorizes release of my thesis to any reader upon request.

Jennifer Wong, Author
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1. Introduction

The AAPM’s Task Group 142 (TG-142) report establishes the quality assurance of medical accelerators. The AAPM TG-142 offers specific recommendations for machines performing radiosurgery treatments and intensity-modulated radiotherapy (IMRT), requiring different tests and tolerances for multileaf collimator (MLC) quality assurance. A quality assurance (QA) procedure should address treatment-planning systems, MLC mechanics, and patient treatment verification, all of which are an important part of the implementation of MLC for treatment delivery. The principle established for the AAPM TG-142 is that the dose delivery to the patient should be within ±5% of the prescribed dose. However, many components are involved in the process of delivering dose to a target volume in a patient and each must perform with an accuracy better than 5% to achieve the recommendation set forth by the task group (Klein, Hanley et al. 2009).

The goal of a QA program for linear accelerators is to assure that the machine characteristics do not deviate significantly from their baseline values. The importance of this is that these values are input into the treatment planning systems to characterize and model the treatment machine. Therefore, it has a direct effect on treatment planning calculations for the specific machine. The potential for dosimetric errors is consequential and could be clinically significant. The result could be suboptimal treatment of patients due to the deviations from the baseline values for many reasons. For example, unexpected changes in the mechanics can affect machine performance, which is why it is important to establish a proper QA program (Klein, Hanley et al. 2009).

For radiosurgery treatments, specifically Stereotactic Radiosurgery (SRS) and Stereotactic Body Radiotherapy (SBRT), and IMRT, more rigorous tolerances involve a more active QA program to achieve the required accuracy. Particularly in
IMRT, the leaves modulate as dose is delivered throughout the target volume, meaning that the dose delivery is sensitive to many factors such as the mechanics and output as mentioned above. Also, in the case of SRS and SBRT, where modern radiation treatment can delivery highly conformal radiation dose to small volumes very precisely, make the location of the tumor volume and positioning of the patient even more imperative, along with the machine characteristics.

QA includes the mechanical checks, such as leaf positioning and alignment, and dosimetric aspects, such as output reproducibility. QA for linear accelerators ensure that when treatment parameters are provided, the correct dose is delivered. For example, the coincidence of the collimator, gantry, and couch axes, determines the mechanical isocenter. The mechanical isocenter is recommended to be within 1 mm for stereotactic machines and within 2 mm for other machines of the radiation isocenter. The tests developed for the QA program should identify sources of error with the linear accelerator and a method for detecting mechanical problems. Also, dose must be delivered and verified to be accurate and reproducible (Klein, Hanley et al. 2009).

IMRT QA is important due to the many small field-segments shaped by the MLC, specifically leaf positioning accuracy, Monitor Unit (MU)-dose relationship, and advanced treatment planning techniques. In addition to machine QA, patient-specific QA becomes necessary since simple MU verification is difficult. Patient-specific QA, encompassed in QA procedures for IMRT, is the verification of the treatment plan from planning through delivery to ensure accurate dose distribution. Measurement-based QA refers to machine QA specific to each patient treatment plan, generally phantom-based. It uses the same fields and number of MUs as applied to the patient, but requires dose calculation with the CT data of the phantom used for the measurements. Various techniques for dosimetric verification include film, matrix
devices, and EPID for two-dimensional dose verification. Three-dimensional verification is readily achievable with three-dimensional capable phantoms as well (IAEA Nucleus).

Before each IMRT or Volumetric Modulated Arc Therapy (VMAT) course, QA devices are used to verify the radiation dose. At Oregon Heath & Science University (OHSU), patient-specific QA is performed on all IMRT and VMAT cases. Typically phantoms such as the MapCheck® for two-dimensional dose verification and the ArcCheck® for three-dimensional dose verification are used to perform these patient-specific QA measurements. However, when setting up the QA phantom, the question asked is: what is the accuracy of the setup itself?

QA results are subject to setup error. The goal here is to develop an easy method to verify QA setup within submillimeter accuracy.

2. Background

2.1. Vernier Scale

A vernier scale or a device known as a vernier caliper allows the user to measure more precisely than could be achieved with a single uniformly-divided straight measurement scale. It is a scale that indicates where the measurement lies between two marks on the main scale. The vernier scale is spaced at a constant fraction of the fixed scale. In a vernier caliper, the moving arm has a vernier scale spaced at nine tenths of the main scale on the fixed arm. If the two scales are placed together with the zero point aligned, the first mark on the vernier scale would be one tenth shorter than the main scale mark, the second would be two tenths shorter, and so on. The ninth mark or last mark would be misaligned by nine tenths. Only when a complete ten marks are counted is there alignment. This is because the tenth mark is ten tenths,
which is a whole main scale unit shorter. Therefore, it aligns with the ninth mark on the main scale. This technique helps the observer to read measurement with the precision of one tenth of the graduation length or with a precision of 0.1 mm, assuming the graduation is 1 mm (Wikipedia 2015, “Vernier scale”).

As mentioned before, a vernier caliper is read by looking for the best match between two marked lines (Figure 1). Because the spacing of the moving scale is 0.9 mm, a 0.1 mm offset will move the matched lines from one pair to the next pair.

![Figure 1: Vernier Caliper (Wikipedia 2015, “Vernier scale”)](image)
Therefore, if the vernier scale is moved by a small amount, one tenth of the fixed scale, the only pair of marked lines that align are the first pair. This is because it is originally misaligned by one tenth. If moved by two tenths, the second pair aligns, and so on. Only one pair of marked lines aligns for a measurement. Also, the aligned pair provides the value between the marks on the fixed scale. The way the vernier scale works is demonstrated in Figure 2 (Wikipedia 2015, “Vernier scale”).
Figure 2: Vernier Scale (Wikipedia 2015, “Vernier scale”)
Let $N$ indicate the number of divisions shown for the finer level of measure or the vernier scale or moving scale. For most vernier calipers, the magnification factor is set to:

$$N = 10$$

which allows the user to read measurements with 0.1 mm precision.

The moving scale is constructed so that when there are no points coincident with the start of the fixed scale, its graduations are at a slightly smaller spacing than those on the fixed scale. Therefore, none but the last graduation coincides with any graduations on the fixed scale. $N$ graduations of the moving scale cover:

$$N - 1$$

graduations of the fixed scale.

In general, the graduation length of the fixed arm is:

$$\frac{N - 1}{N}$$

of the graduation length of the fixed arm.

The main use of the vernier caliper is to measure the internal and the external widths of an object. The user reads the finer vernier scale, which measures between the smallest graduations on the fixed scale, as mentioned previously, providing much greater accuracy (Wikipedia 2015, “Vernier scale”).
2.2. Picket Fence Test

A Picket Fence Test is used to assess the positional accuracy of MLC leaves by matching segments and evaluating the interleaf transmission on films or EPID, but not a two-dimensional detector array. In the MLC picket fence test, a dose strip pattern is delivered onto films or EPID to verify the MLC leaf positions.

Two-dimensional detector arrays are typically not used for picket fence tests because the spatial resolution is 5-10 millimeters, which is much coarser than the submillimeter spatial resolution of films or EPID. On the other hand, on board imaging (OBI) can achieve millimeter accuracy for patient setup. However, when used for QA phantom setup, its accuracy is even higher and only limited by the imaging resolution and system stability, typically on the order of submillimeters. The dose distribution of a two-dimensional detector array is mapped and can be seen in Figure 3.
Picket fence tests are useful for verifying relative leaf position and gap width accuracy by looking at the position of each individual MLC leaf relative to the alignment of the other leaves as the entire leaf bank moves together. The leaves from opposing banks form a small gap. Typically, narrow bands at specific intervals or abutting fields that form a uniform pattern at the junctions are used. A film is irradiated, and then the leaves are shifted. The same gap is formed by the MLC, and the film is again irradiated. This test pattern is automatically repeated across the field. This is done typically at the lowest energy available, usually 6 MV X-rays, without the use of any additional buildup at the isocenter. Leaf travel and positional deviations can be tracked through this method (LoSasso 2013).

The irradiated film or EPID image is then processed and evaluated for dose uniformity. The evaluation should confirm that the stripes have uniform width and the junctions are straight. The match lines and bands are sensitive to even a small
deviation of individual leaves, and any gaps or breaks in the pattern between the adjacent leaves can be detected by the naked eye, as seen below in Figure 4.

![image of picket fence test]

**Figure 4: Picket Fence Test (LoSasso 2013)**

Figure 4, seen above, is a film test to determine the relative leaf positioning. Intentional errors were introduced to demonstrate the error, which arises in the picket fence, from leaf positions given in the image on the right. The film image on the right has leaves intentionally shifted by −0.5 mm to +0.5 mm to demonstrate the method. The image on the left does not have errors in leaf positions for the picket fence (LoSasso 2003).
In order to demonstrate the effectiveness of the picket fence test, intentional errors were introduced to ensure that unknown errors could be identified in the figure above. For example, a picket fence with a 0.5 mm wider gap and 0.5 mm horizontal shift can be seen in Figure 5. The dark regions represent the gaps formed between opposing multileaf collimators. Whereas, the highlighted regions indicate leaves that deviate from the expected positions (Agnew, Agnew et al. 2014).

TG-142 recommends that the picket fence test be performed weekly. However, additional tests for multileaf collimators should be performed for IMRT and other specific treatment techniques.

2.3. Radiation Isocenter

The radiation isocenter is the point in space through which the central beam of radiation passes and intersects when the gantry, collimator, or couch is rotated during beam-on. The mechanical isocenter, on the other hand, should be the mechanical rotational center in which the optical beam is used to identify it (Wikipedia 2015, “Isocenter”).
The radiation and mechanical isocenters must coincide and also must agree with the isocenters defined from the lasers and optics. Typically the radiation isocenter is determined by using star shots. These star shot patterns involve irradiating slits with one set of jaws closed and with the second set opened to its maximum, creating a very narrow beam slits. The process is repeated with opposite jaws. The radiation isocenter is identified by irradiating film with multiple slits to achieve the star like pattern, as seen in Figure 6. If the film is placed in the path of the beam, so that the beam enters through the edge of the film, then a single straight line should be produced. The collimator, gantry, or couch is then rotated, and the field is delivered repeatedly. Performing this test for multiple angles for each of the collimator, gantry, or couch allows for the determination of error in positioning of the isocenter. The intersection of the film center defines the radiation isocenter. Typically the radiation isocenter is within 1 mm in all directions (KFJIRO 2013).

Figure 6: Star Shot Pattern (IAEA RPOP 2013)
This test is usually performed annually and can be time consuming compared to the developed method of the vernier picket fence test for detecting the radiation isocenter.

### 2.4. Vernier Picket Fence Test

Traditional QA setup is based on in-room lasers or gantry crosshairs. Unlike the traditional QA setup, the Vernier Picket Fence (VPF) helps align to the QA device directly with respect to the radiation center of the MLC leaves. The intent of this study was to develop a tool to align QA phantoms, which is achieved through the developed method of the VPF. This study is considered to be innovative because it is simple and can easily be implemented and delivered to QA phantoms for alignment purposes. The purpose of the VPF test is to identify the position of the QA phantom with respect to the radiation isocenter. The VPF test is a useful tool to identify the radiation isocenter, with potential applications including IMRT/VMAT QA setup, especially for small SRS fields, Winston-Lutz QA setup, to check crosshairs or lasers for the mechanical isocenter, and to check CBCT for the imaging isocenter, which are described more in detail below. Therefore, VPF offers a method to achieve submillimeter accuracy for aligning the QA phantom to the radiation isocenter without the guidance from in-room lasers or gantry crosshairs.

The motivation behind this research is attributed to many reasons as mentioned. Modern radiation treatment can deliver highly conformal radiation dose to small volumes very precisely. An example of this would be for Stereotactic Radiation Surgery (SRS). For a target that is 1-2 cm, accurate positioning of QA devices is absolutely necessary. Especially before each intensity-modulated radiotherapy (IMRT) or volumetric modulated arc therapy (VMAT) course, QA devices are used to verify radiation dose. The QA results are also subject to setup error. Therefore,
the goal here is to develop an easy method to verify setup within submillimeter accuracy.

The QA phantom is typically aligned to the mechanical isocenter with the aid of crosshairs. The accuracy is typically within 0.1 to 0.5 mm for crosshair alignment. However, it is typically more than 0.2 mm. Other devices may accompany the alignment of the QA phantom, including ExacTrac®, On Board Imaging (OBI), Cone-Beam CT (CBCT), and the new method developed known as the Vernier Picket Fence (VPF) Test. The accuracy of aligning to the imaging isocenter with ExacTrac® is approximately 0.2 mm, and the use of OBI and CBCT to align to the imaging isocenter is about 0.2 mm for OBI and around 0.5 mm for CBCT as well. Therefore, when used for QA phantom setup, its accuracy is even higher and only limited by imaging resolution and system stability, typically on the order of submillimeter. A proposed alternative method, which does not use OBI or CBCT, but still can achieve submillimeter-positioning accuracy for QA phantom setup is presented here.

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<tr>
<th>Device</th>
<th>Accuracy</th>
<th>Aligned With?</th>
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<tr>
<td>Crosshair</td>
<td>0.1-0.5 mm</td>
<td>Mechanical Isocenter</td>
</tr>
<tr>
<td>ExacTrac</td>
<td>~0.2 mm</td>
<td>Imaging Isocenter</td>
</tr>
<tr>
<td>OBI/CBCT</td>
<td>~0.2 mm for OBI ~0.5 mm for CBCT</td>
<td>Imaging Isocenter</td>
</tr>
<tr>
<td>Vernier Picket Fence</td>
<td>&lt;0.02 mm</td>
<td>Radiation Isocenter</td>
</tr>
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Table 1: Imaging Techniques
From Table 1, the accuracy improves from crosshairs to the VPF, with an accuracy of 0.02 mm. This is due to the alignment with the radiation isocenter instead of the mechanical isocenter, which could be off slightly. The accuracy of ExacTrac® and OBI/CBCT setup is somewhere in between the two.

The method, known as the VPF test, that verifies QA setup within submillimeter accuracy has two advantages over OBI and CBCT setup. First, the phantom is directly aligned to the radiation isocenter, without subject to any residual error between the radiation and imaging isocenters. Secondly, when x-ray imaging is not available or not preferred, the QA phantom is usually setup based on lasers or gantry crosshairs, in which the accuracy is not as great. The VPF can align with the radiation isocenter with an accuracy of less than 0.02 mm as described in this study. There are a few advantages associated with this approach. First, not all QA devices have the two-dimensional array visible from the outside. While the vendor typically marks the phantom on the outside to facilitate the setup procedure, assembling variation can still bring uncertainties for those outside markers. Secondly, in-room lasers and gantry crosshairs are typically checked every month. They may be within the tolerance but any residual offset may affect the QA phantom setup. Thirdly, the VPF test can detect the relative offset between the QA device and the MLC leaves. If the deviation is big, a couch shift can be applied. When the offset is too small to correct by couch shift, it is still possible to correct in QA analysis to reduce setup uncertainty.

Remember that this is not a traditional picket fence test, so it is not a MLC test but for alignment QA purposes. By delivering 2-3 extra radiation fields, the user can identify the radiation isocenter and determine how accurate setup is to 0.02 mm with the VPF test.
The picket fence design was used to create the VPF so that the QA device can be positioned with the precision of one tenth of the detector spacing. In this study, slightly modified MLC picket fence tests are used and redesigned as a tool to verify the radiation isocenter for phantom setup for QA measurements, but not for MLC leaf QA. This is known as the VPF test.

The new method is called the VPF test because the dose pattern is designed by the principle of vernier calipers. The MLC dose fluence is created in a way to simulate vernier scales, which was described previously. In a vernier scale, the graduations in the sliding data scale have a slightly smaller spacing than the ones in the fixed data scale. Following the same principle, the spacing of the MLC picket fence is slightly smaller than the detector spacing. The moving arm has a vernier scale spaced at nine tenths of the main scale on the fixed arm, which helps the observer read measurements with a precision of one tenth of the graduation length.

Therefore, following the same principle, the spacing of the MLC picket fence is slightly smaller than the detector spacing. Mathematically, the VPF is given by:

\[
\text{Equation 1}
\]

\[
d_{\text{MLC}} = \frac{N - 1}{N} \cdot d_{\text{detector}}
\]

where \(d_{\text{MLC}}\) is the picket fence spacing, \(N\) is the number of dose strips, and \(d_{\text{detector}}\) is the detector spacing, which is slightly different from the picket fence spacing.
2.5. MapCheck®

The Sun Nuclear MapCheck® device used in this study contains 445 diode detectors unevenly distributed. In the center 10x10 cm² area, the detector spacing is 7.07 mm and 5 mm along the two-dimensional coordinates. In the surrounding area, the detector spacing is 14.14 mm and 10 mm along the two-dimensional coordinates. The MapCheck® device used in this study for measurement has a detector spacing of 5 mm. The detector spacings are 5 mm for both lateral and longitudinal directions. It follows from the design of the vernier scale that the picket fence should have a spacing slightly different than the detector spacing of 5 mm. The MLC sequences have $N - 1$ number of slits and use a 0.5 mm opening width (SNC 2015).

A MATLAB® (Natick, MA) script was used to set the slits at the equation of the picket fence spacing:
Equation 2

\[ d_{MLC} = \frac{N - 1}{N} \times d_{detector} \times i \]

multiplied by \( i \), where \( i \) is given below:

Equation 3

\[ i = -\frac{N-1}{2}, -\frac{N-1}{2} + 1, ..., \frac{N-1}{2} - 1, \frac{N-1}{2} \]

For convenience, \( N \) is typically chosen to be 10 or any multiplier of 10.

\[ N = 20 \]

was chosen for this study. The resolution limit will therefore be:

\[ \frac{5}{20} = 0.25 \, mm \]

As a result, the MLC picket fence has a spacing of 4.75 mm. There are a total of:

\[ 2N - 1 \]

number of slits, which are located at 0, ±4.75 mm, ±9.5 mm, and on. Using a larger \( N \) can improve the measurement precision. However, it also limits spacing within the detector, specifically in one dimension. Therefore too large of a spacing will leave the picket fence impractical to use. The precision is also subject to signal-noise-ratio of the measurement. One way to increase signal-noise-ratio is to increase MU’s or the MLC strip opening. One object of the study was to optimize the parameters of the picket fence test for individual QA devices, including the number of dose strips, MU for each strip, and the MLC opening.

In QA setup, the highest signal measured by the detectors is identified.
Figure 8: Maximum Detector Signal
The QA setup position is determined by looking for the highest detector signal. Maximum detector signal changes based on detector position. The QA setup position is determined by looking for the maximum detector signal determined by the relative position between the MapCheck® device and the VPF. The resolution is determined by the width difference between two scales. According to Figure 8, the slit size is 5.25 mm and the detector spacing is 5 mm, which gives a resolution of 0.25 mm. As can be seen in the figure, the maximum detector signal changes based on the detector position. The maximum signal may be defined by a different detector in the sequence. This is indicated by a shift in the detector signal. At 0.25 mm the detector response drifts form one detector to the next.

3. Materials and Methods

The development of the VPF test is given by the method below. The VPF test requires multiple processes in order to confirm the validity of the test, including an independent check of the VPF test through the use of ExacTrac’s optical tracking system. The following sections are divided into the different procedures performed to establish the VPF test. This includes determining the optimal VPF attributes for each QA device and measuring the VPF on the devices.

In this study, two popular QA devices are used to check the performance of the VPF test, including the MapCheck® and ArcCheck® by Sun Nuclear. The two QA devices have different design in terms of the detector distribution. The MapCheck® device is described in Section 2.5.

3.1. Materials

The following resources and tools were used to complete the development and examination of the VPF test:
• MATLAB®
• Linear accelerator, specifically the Novalis Tx™ (Feldkirchen, Germany) with a 6 MV photon beam was used in this study, located at OHSU in Portland
• MapCheck®
• ArcCheck®
• Sun Nuclear software
• Excel with the solver plugin
• ExacTrac® optical tracking system
• ExacTrac® software

3.2. Defining Parameters

The picket fence sequence was generated using a MATLAB® script. A DICOM file coded in MATLAB® was designed for the VPF to accommodate the MapCheck® QA phantom. Collimator jaws form a square field of 24x40 cm opening. The x-jaws are set at -12 cm and +12 cm positions so that MLC leaves can travel inside the range, without any over traveling limitations. MLC leaves form a sequence of slit openings, given in Equation 5. Different parameters were tested to define the most optimal
settings to deliver the VPF onto the MapCheck® device. These parameters included gap size or slit width, magnification factor, and depth. For each VPF test, the device was setup based on the makers on the device. Initial VPF tests were performed with different combinations of these parameters. The gap size or slit width was delivered at 0.1 cm and 0.05 cm, and the best gap size was determined to be 0.05 cm, which is used through this study. Also, the magnification factor was tested at 10, 20, and 40. The most ideal magnification factor was found to be at 20. Lastly, the VPF was delivered at a depth of 1 cm and 5 cm, where 1 cm gave better results. Therefore, a set of parameters, specifically a gap size of 0.05 cm, magnification factor of 20, and 1 cm depth, were used consistently throughout this study, given the results of these findings.

3.3. Offset Test

The first test performed was an offset test to verify the hypothesis that the measurements should be shifted by a known amount of 5 mm, given a magnification factor of 20 and an offset of 0.25 mm. The offset was adjusted in the DICOM file prior to delivery of the fields. The fields were created and delivered on the MapCheck® device individually at different offsets including 0 mm, 0.25 mm, 0.5 mm, and 0.75 mm to verify the measurement curve does indeed shift by the known amount predicted. The data was collected using the Sun Nuclear software.

3.4. MLC Offset Test

In addition, a MLC offset test was applied to the VPF and performed. The VPF was measured using the QA device from the previous test, and the offset was calculated based on the measurement and compare to the applied offset. A sequence of VPF fields were delivered with different MLC offsets for every 0.05 mm step size. Once
again, these fields were created in DICOM format in MATLAB® and delivered onto the MapCheck® device. After offsetting the MLC, the offsets were measured by detection of the VPF. The same process of collecting data with the Sun Nuclear software was performed as before. The error was determined by taking the difference in the measured offset compared to the known applied offset given to the VPF. It was calculated using Excel, once again where the data was transferred for analysis. This determined how accurately the algorithm could detect the offset.

3.5. VPF Test

It follows from design of the vernier scale that the picket fence should have a spacing, $t$, slightly different than the detector spacing $s$. Mathematically:

Equation 4

$$ t = \frac{N + 1}{N} \times s $$

where $N$ is the number of dose strips. For reading convenience, $N$ is typically chosen to be any multiplier of 10, specifically in this study 20, as defined in a previous test.

The VPF test works in the following way. The picket fence has a sequence of dose profiles, which can be modeled as:

$$ \sum_i D(x - (i \times t)) $$

where $D(x)$ is the dose profile of each MLC opening slit centering at zero. The dose profiles were measured by a sequence of detectors. If the two-dimensional array is misaligned by an offset distance of $d$, the response of the $j$’th detector can be modeled as:

$$ f(x - (j \times s) - d) $$
As a result, the $j$'th detector has a signal of:

$$\sum_i D(x - (i \ast t)) \otimes f(x - (j \ast s) - d)$$

because both $D(x)$ and $f(x)$ have peak values at $x = 0$. The signal is maximized when:

$$|i \ast t - j \ast s - d|$$

is minimized. This is achieved for:

$$-0.5 \ast \frac{s}{N} < d < 0.5 \ast \frac{s}{N}$$

with $i = j = 0$. This is achieved for:

$$0.5 \ast \frac{s}{N} < d < 1.5 \ast \frac{s}{N}$$

with $i = j = 1$ and so on. Therefore the observer can estimate $d$ to be:

$$j \ast \frac{s}{N}$$

if the $j$'th detector is the one with the highest signal and the estimated precision is:

$$0.5 \ast \frac{s}{N}$$

Using a larger $N$ can improve measurement precision. However, it also limits $d$ within:

$$\frac{s}{N} \ast \# \text{ of the detector in one dimension}$$

VPF tests are read analogous to a vernier caliper by seeking the maximum detector signal to determine the optimal matching between MLC defined dose strips and detector positions, specifically rows or columns of the MapCheck® device, as
described in Section 2.4. VPF tests can be read by visually finding the maximum detector signal. The resolution is determined by the width difference between the two scales, for MapCheck® that is:

\[ 5.25 \text{ mm} - 5 \text{ mm} = 0.25 \text{ mm} \]

However, a better approach is to utilize all relevant detector signals, fit them into a curve, and then determine the peak position. Visual inspection can easily complete this task except for the case where two adjacent rows or columns have similar signal, which call for a tiebreak. To solve this dilemma, all nearby detector signals are taken, fit into a curve, and then the position of the peak value is determined. The position of the peak value can be between two adjacent rows or columns so that no further tiebreak is needed. Curve-fitting requires more computation than visual inspection, but it also makes the VPF test less sensitive to measurement noise. A Gaussian function, with a non-zero background, works reasonably well for the VPF test on Mapcheck®. Therefore, a Gaussian function with a positive background is chosen. Mathematically:

\[ A \times e^{-\frac{(x-d_{\text{detector}}-x)^2}{\text{var}}} + d \]

is used to fit the detector measurements, where \( A, x, \text{var}, \) and \( d \) are four parameters that need to be optimized. The optimization was performed using the Solver plugin available in the Excel software. The Gaussian function was used to fit signals from multiple detectors so that the optimal position can be solved iteratively.

To determine couch positions in three dimensions, the VPF sequence was delivered three times utilizing the DICOM file coded in MATLAB® again. The VPF was delivered onto the MapCheck® device at 0º gantry angle with 0º and 90º collimator angles to determine the lateral and longitudinal coordinates, respectively. The
MapCheck® device was manually setup and then automatically positioned by the ExacTrac® orthogonal x-ray imaging. After that, the couch was shifted into a series of lateral and longitudinal positions. Each position was also verified using ExacTrac® to track the couch positions by infrared camera. As the VPF was delivered, the optical tracking offset was also read from the ExacTrac® software. This required visual inspection of the high and low deviations of the optical tracking readings, which the average value was then taken. Results from the VPF test were compared using Excel with ExacTrac®’s optical tracking system to evaluate the accuracy. To achieve three-dimensional capabilities, additional fields at 90° or 270° gantry angles were delivered on the ArcCheck® to determine the vertical direction, while accounting for the geometrical corrections of the diode distribution in the phantom.

3.6. Couch Hysteresis

In order to evaluate the accuracy of the VPF test, the couch was shifted in a sequence of positions to characterize couch hysteresis. VPF tests were performed to determine the couch positions in two dimensions on the MapCheck® device and the vertical direction on the ArcCheck® device. To evaluate the accuracy of the VPF test, the couch was moved to a sequence of positions in 1 mm increments, and VPF tests were delivered to determine couch positions. The couch was shifted in one direction and back in the other to the original starting position to characterize couch hysteresis. Couch hysteresis is dependent on the path the couch travels before moving to position. This can be due to motor issues and such.

4. Results and Discussion

4.1. Defining Parameters

A set of optimal parameters was defined by delivering VPF tests to achieve the best output for the MapCheck®, specifically with a 5 mm detector spacing. Table 2 gives
the parameters set forth in this study, along with the offset distances. Specifically, a slit width of 0.5 mm, magnification factor of 20, and 1 cm depth was used. Also, a standard of 30 MU’s is irradiated per slit for the developed VPF test.

<table>
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<th>Distance</th>
<th>0.125</th>
<th>0.25</th>
<th>0.5</th>
<th>1</th>
<th>1.5</th>
<th>2</th>
<th>2.5</th>
<th>3</th>
<th>3.5</th>
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<th>4.5</th>
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<th>6</th>
<th>6.5</th>
<th>7</th>
<th>7.5</th>
</tr>
</thead>
<tbody>
<tr>
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<td>0.3</td>
<td>0.9</td>
<td>1.5</td>
<td>3.1</td>
<td>6.3</td>
<td>11.1</td>
<td>18.9</td>
<td>27.6</td>
<td>37.3</td>
<td>48.0</td>
<td>58.7</td>
<td>69.4</td>
<td>80.1</td>
<td>90.8</td>
<td>101.5</td>
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<td>0.5</td>
<td>1</td>
<td>1.5</td>
<td>2</td>
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<td>6.5</td>
<td>7</td>
<td>7.5</td>
</tr>
</tbody>
</table>

Table 2: VPF Parameters

4.2. Offset Test

The measurement data tables were imported, or easily copied and pasted, from the Sun Nuclear software and into Excel. Figure 10 is an example of the data collected from a VPF test and transferred to Excel for analysis.

![Figure 10: VPF Data](image)

The VPF test can detect the relative offset between the QA device and the MLC leaves. The QA setup position is determined by looking for the maximum detector signal from the relative position between MapCheck® and the VPF as mentioned before. The maximum detector signal changes based on the detector position and
may be defined by a different detector in the sequence, indicated by a shift in the
detector signal, as seen in Figure 11.

![Figure 11: Offset Test Results](image)

The average detector reading for the center detector row was taken for each distance
or position at every 0.5 cm, from -3 cm to 3 cm, for each offset measurement
including 0 mm, 0.25 mm, 0.5 mm, and 0.75 mm. The average absolute dose
measurements per position were plotted for each offset in Figure 11. The test
confirms the hypothesis that the measurement curve shifts by 5 mm, the predicted
shift, given a magnification factor of 20 and an offset of 0.25 mm.

As mentioned before, one object of this study was to optimize the parameters of the
picket fence test for individual QA devices, including the number of dose strips.
Through this process, it was discovered that a 0.25 mm offset moves the
measurement curve by 5 mm, which can be seen in the graph above. This is why a magnification factor of 20 was chosen.

4.3. MLC Offset Test

Sequences of VPF fields were delivered with different MLC offsets in Figure 12. The offset is measured by the VPF after offsetting the MLC for every 0.05 mm step size. The offsets detected by the VPF tests are given in Figure 12 along with the error in the measurement. This determined and confirmed that the VPF could detect the offset accurately.

![Figure 12: MLC Offset Test Results](image)

This shows that the VPF can be accurate up to 0.02 mm, meaning that the radiation isocenter can be identified with up to 0.02 mm accuracy. This can be seen in the graph of Figure 12 where the blue line represents the offset detected by the VPF and the red curve is the error in the measurement times 10.
**4.4. Lateral Direction VPF Test**

The results from the VPF tests were compared with ExacTrac® to evaluate the accuracy. On average, the two methods could detect couch hysteresis up to 0.3 mm. Also, the VPF agreed with the optical tracking by 0.055 mm. The two methods have a difference most likely due to initial setup error. It seemed that ExacTrac® had difficulty aligning to MapCheck® with reference DRR’s. However, the standard deviation of the difference is very small, suggesting that VPF could achieve submillimeter accuracy. This can be seen in Figure 13, that the couch was shifted in one direction and back as the shifts were measured. This figure gives the lateral shift of the VPF test and the ExacTrac® infrared tracking. The applied shift is the x-axis, and the detected shift is the y-axis. The red data curve represents the shift calculated for the VPF test, and the blue data curve represents the average shift given by the optical tracking. The arrows show the direction of shifts. This indicates couch hysteresis. Couch hysteresis is dependent on the path the couch travels before moving to position. This can be due to motor issues and such, as mentioned before. Though couch hysteresis is interesting, more importantly, the two curves match each other. This is the main purpose of cross validation, that the VPF agrees with the optical tracking.
The results from the VPF test could detect couch hysteresis up to 0.3 mm and agreed with the optical tracking system by 0.055 mm for the lateral direction, as shown in Figure 13.

The histogram, Figure 14, shows the absolute differences for the lateral shifts. This is less than 0.25 mm, the resolution limit for visual inspection. This confirms not only the accuracy of the VPF in the lateral direction, but the agreement with the ExacTrac® optical tracking system.
4.5. Longitudinal Direction VPF Test

The same method was also applied to determine the shift in the longitudinal direction. Similarly, couch hysteresis for the longitudinal direction is up to 0.5 mm, which is even larger than the lateral direction. The VPF agrees with optical tracking within 0.041 mm. Once again, it can be seen that the couch was shifted in one direction and back, indicating couch hysteresis, shown in Figure 15. This figure shows the longitudinal shift of the VPF test and the ExacTrac® infrared tracking. The applied shift is the x-axis, and the detected shift is the y-axis again. The red data curve represents the shift calculated for the VPF test, and the blue data curve represents the average shift given by the optical tracking, similar to the lateral direction shifts in Figure 13. The direction of shifts indicates couch hysteresis. The shifts for the VPF test and infrared tracking and how they overlap very well can be seen once again. This shows that the two curves overlaying each, meaning that the VPF agrees with the optical tracking.
The couch hysteresis for the longitudinal direction is up to 0.5 mm, and the VPF agreed with the optical tracking system within 0.041 mm, as seen in Figure 15. This is also less than the resolution limit of 0.25 mm for visual inspection. The absolute differences are even smaller for the longitudinal shifts than the lateral shifts given in Figure 16. This also confirms the accuracy of the shifts and the agreement of the VPF and ExacTrac® optical tracking system in the longitudinal direction.
4.6. Vertical Direction VPF Test

The VPF was delivered to the ArcCheck® device to verify that the test does indeed work in the vertical direction as well. The vertical direction was determined by delivering a field at a 270° or 90° gantry angle and 90° collimator angle on the ArcCheck® device. In order to do so, geometrical corrections of the diode distribution in the phantom had to be made. This was done by editing the VPF DICOM file in MATLAB® to account for the spiraling distributions of detectors, each at 1 cm apart, in the ArcCheck® device. After doing so, the field was delivered and a dose distribution and profile were obtained through the Sun Nuclear software, which can be seen in Figure 17 and Figure 18, respectively.
The dose distribution and profile for a 270° gantry angle and 90° collimator angle define the VPF in the vertical direction in the figures above.
Results from the ArcCheck® device verify that the VPF test can be applied in the vertical direction as well, meaning that the VPF can be applied in all three directions, with a resolution of up to 1 cm for this QA phantom.

5. Conclusion

Overall, VPF tests can achieve submillimeter positioning accuracy for QA phantoms, specifically the MapCheck® and ArcCheck® QA phantoms, setup in three-dimensions to identify the radiation isocenter. The systematic difference found may be attributed to initial setup error. Standard deviations are small, suggesting that results from the VPF tests and infrared tracking of the ExacTrac® system are highly reproducible.

The MLC offset test shows that VPF tests can be accurate up to 0.02 mm, meaning the radiation isocenter can be identified with up to 0.02 mm accuracy, from error in the MLC offset. Cross validation with ExacTrac® shows that the VPF agrees with optical tracking within 0.05 mm.

The results from the VPF tests were compared with ExacTrac® to evaluate the accuracy with a difference of 0.3±0.055 mm laterally and 0.5±0.041 mm longitudinally. Results from the ArcCheck® for the vertical direction also verify that the VPF test can be applied in all three directions, with a resolution up to 1 cm. This allows for a three-dimensional correction to be applied.

The potential applications of the VPF test are most limited to physics QA because a minimum of a two-dimensional detector array is needed. VPF is a useful tool to identify the radiation isocenter. The results of this study demonstrate that the VPF test could have potential applications for IMRT/VMAT patient QA setup and measurement, especially for small fields in SRS, which are 1-2 cm in size. Also, for
other purposes such as Winston-Lutz QA setup for defining the radiation isocenter. Lastly, it can be used to check the coincidence of the radiation, mechanical, and imaging isocenters. The VPF test is useful in checking the crosshair or laser for the mechanical isocenter and checking the CBCT for the imaging isocenter. Therefore, VPF tests could be useful to assist physicists in QA phantom setup within submillimeter accuracy for a variety of tasks.

Future work could involve applying and verifying the VPF test to other QA phantoms. Also, implementing a procedure for the VPF test to make the test more systematic could be beneficial to the applications in the clinic.
6. Bibliography


