GLAaS: An absolute dose calibration algorithm for an amorphous silicon portal imager. Applications to IMRT verifications

Giorgia Nicolini and Antonella Fogliata
Medical Physics Unit, Oncology Institute of Southern Switzerland, Bellinzona, Switzerland

Eugenio Vanetti and Alessandro Clivio
Medical Physics Unit, Oncology Institute of Southern Switzerland, Bellinzona, Switzerland and Medical Physics Specialisation School, University of Milan, Milan, Italy

Luca Cozzi
Medical Physics Unit, Oncology Institute of Southern Switzerland, Bellinzona, Switzerland

(Received 7 July 2005; revised 6 June 2006; accepted for publication 6 June 2006; published 21 July 2006)

A new calibration algorithm (GLAaS) to derive absolute dose maps from images acquired with the Varian PV-aS500 electronic portal imager (based on amorphous silicon detectors) has been developed incorporating the dependence of detector response on primary and transmitted radiation and on field size. Detector calibration and algorithm validation were performed at different depths (10.0, 3.8, 1.5, and 0.8 cm) in solid water to investigate various application possibilities. Calibration data were obtained against ion chamber measurements. Validation experiments were performed on intensity-modulated fields and comparison was carried out against calculated dose maps as well as against film measurements. Split fields were acquired independently and PV-aS500 images were summed offline with the new algorithm allowing complex fields to be verified in conditions most closely resembling clinical conditions. Excellent results were obtained for the 3.8, 1.5, and 0.8 depths on a set of 34 modulated fields including both split and nonsplit fields. Applying the gamma index analysis (with distance to agreement and dose thresholds set to 3 mm and 4%, respectively), only 2.3% of the field area showed $\gamma > 1$ at 1.5 cm depth (8.1%, 3.1%, 2.7% at 10.0, 3.8, and 0.8 and 2.5% with films at 10 cm depth). Tests were also performed to verify GLAaS at gantry angles different from 0°. No statistical differences were obtained for the comparison between split and nonsplit fields and between different gantry angles. Highly significant statistical differences were obtained when comparing independent samples of 240 fields verified either with GLAaS or with film. Fields verified with GLAaS presented a mean area with $\gamma > 1$ of 2.1±1.3% while for film this value was 3.9±3.4% ($p < 0.001$). Absolute dosimetry proved to be reliable with the PV-aS500 detector with the GLAaS algorithm. The minimal settings at depths of 1.5 or 3.8 cm would allow the use of the detector at any gantry angle without the need for any special fixation tool. © 2006 American Association of Physicists in Medicine. [DOI: 10.1118/1.2218314]

Key words: EPID dosimetry, portal dosimetry, IMRT verification, amorphous silicon

I. INTRODUCTION

Radiotherapy with intensity modulation (IMRT) implies the setup of adequate quality assurance (QA) programs to guarantee safe treatment of patients. In particular, pretreatment verification of the (treatment plan) dose calculation requires robust, reliable, and efficient tools in routine practice. In this context, the characteristics of some electronic portal imaging devices (EPIDs) have led to considerable interest in their use as two-dimensional (2D) dosimeters.

The flat-panel devices based on amorphous silicon (a-Si) technology are particularly interesting due to their high spatial resolution, large imaging area, stability, dynamic range, and real-time acquisition capabilities. Dosimetrically, the linear dose-response of a-Si panels is an additional factor of interest. Unfortunately, most of the panels measure dose indirectly due to the presence of phosphor screens and therefore performing accurate quantitative dosimetry is more complicated than simply applying linear calibrations. Using an experimental a-Si flat-panel detector, El Mohri et al. observed large discrepancies in relative dose response between ion chamber and EPID measurements for a 6 MV photon beam when the EPID was employed in its indirect configuration: ∼−7% inside the field boundaries and ∼+13% outside. These effects were explained by assuming a higher detector response to the low-energy scattered radiation. For the Varian a-Si detector, a field-size-dependent difference of ∼5% relative to ion chamber measurement (at $d_{\text{max}}$) was found by Greer and Popescu. When testing simple IMRT fields, the agreement between EPID and film was found to be within 5%. Grein et al. obtained accuracy of better than 1% using a field-size-dependent pixel-to-dose mapping, which included detector-source-distance and beam energy.

Various approaches have been investigated using the basic idea of modeling expected detector behavior using (semi-)empirical kernels and/or Monte Carlo (MC) simulations.
In the Varian environment, Van Esch et al. proposed an algorithm allowing the verification of fluence delivery for individual IMRT fields. Fluence distributions from the treatment planning system (TPS) are convolved with an empirically derived detector point-spread function (corrected by the collimator output factor measured with the EPID) to create in the TPS a predicted EPID image to be compared with the image measured by the a-Si EPID. With this approach highly satisfactory results were obtained but with the important limitation that all features/errors due to the fluence-to-dose conversion in the TPS are ignored, in other words, ignoring the impact of dose-calculation algorithms, the potential weak links in the IMRT chain. Similarly, Chang and Ling convolved the TPS fluence with an empirically derived Gaussian kernel to create predicted EPID images; 25 prostate IMRT fields were analyzed mostly on the basis of relative profiles. It was concluded that the Varian a-Si EPID was an effective tool for IMRT delivery verification. McCurdy et al. used MC simulation to calculate the dose-deposition kernels of the a-Si detector, and suggested incorporating also a “glare” kernel to improve measured versus predicted agreement, especially in the region outside the primary field. Siebers et al. by means of detailed descriptions of geometry in MC simulations, achieved very good agreement between measured and calculated data without the application of light spread or glare kernels: both the absolute beam output and the field shape were reproduced within 1%. Due to nonuniform backscatter, larger deviations were only observed in the direction from the central axis toward the gantry at distances from the detector center greater than 7.5 cm. Also, the effect of multileaf collimator (MLC) beam hardening (at 6 MV) on the a-Si was examined since the Gd2O2S:Tb phosphor layer was expected to have an energy-dependent response. Simulations of dynamically sweeping MLC gaps, used to produce uniform $10 \times 10 \text{ cm}^2$ fields, agreed with measurements to within 1% on average. Workentin et al. used a MC-computed dose kernel and an empirical glare kernel to deconvolve EPID images into 2D primary fluence maps that were further convolved with MC-computed water energy-deposition kernels in order to yield doses that could finally be compared to TPS dose calculations in water. The same group also imported the primary fluence as derived by a-Si measurements into the TPS in order to use it as a new input to recalculate 3D doses on the original patient CT, thus trying to close the loop left open by other workers.

Since IM beams consist in general of highly nonintuitive fluence distributions, and no mechanism currently exists to verify that any correctly delivered fluence yields the desired dose distribution, the key feature of IMRT pretreatment verification is a comparison of the (absolute) measured with the calculated dose distributions either on a “field by field” basis or on a “all fields at once” basis.

This article describes a new General Linear “calibration” Algorithm for the Varian a-Si PortalVision aS500 (PV-aS500), GLAaS, and reports the first results of a comparison of GLAaS with more conventional film dosimetry. GLAaS has been tested on IMRT fields realized with the sliding-window, dynamic multileaf-collimator (DMLC) technique. The innovative aspects of GLAaS can be summarized in a few key features: (i) it is an experimental method, based on simple direct calibration measurements where no specific kernel or special convolution operators are needed to operate; (ii) it allows one to compute absolute dose maps in (solid) water at any desired depth to verify IMRT fields including also the dose calculation algorithms used by planning systems and does not limit verification to fluence-based comparisons; (iii) it allows easy and robust verification of split fields (not available for example in some commercial applications); and (iv) it is robust with respect to gravity, allowing verification of individual IMRT fields at any gantry angle.

II. MATERIAL AND METHODS

A. Strategy

As part of a larger QA program, which includes the verification of the reproducibility and stability of the dynamic mode of MLC delivery in our institute, pretreatment verification of all IMRT plans is performed before treatment of patients for each individual modulated field. The aim of the verification is to compare absolute dose distributions calculated by the TPS with 2D absolute dose measurements at (or near to) the isocentre plane, at a given reference depth in a phantom of water-equivalent material using 2D detectors “inserted” in the phantom. With this procedure implemented, TPS dose maps and dosimetric data are respectively computed and measured under the same fixed conditions: measurement depth, SDD (source detector distance), gantry, and collimator angles. No (or minimal if unavoidable) air gap is intended to be present between the phantom and the detector and no “back-projections” of portal measurements into phantom (or patient) planes are included in our verification strategy. It is not an “in vivo” procedure; the goal is to identify potential errors either in the calculation or in the delivery process. The strategy and methods have been described by Cozzi et al. for film dosimetry; in the present report the use of a different detector (the EPID) and the development of a new algorithm are described.

B. The PV-aS500

The PV-aS500 used for this study is mounted on a Varian 6EX (6 MV) linear accelerator equipped with a multileaf collimator of 120 leaves (0.5 and 1.0 cm width). The detector consists of a 1 mm copper metal plate fixed to a high atomic number scintillation screen (134 mg/cm$^2$ gadolinium oxysulfide phosphor); optical photons are detected by an array of photodiodes ($512 \times 384$) on a 1.1 mm glass substrate and connected to a thin-film transistor (TFT) connected in turn to the read-out electronics. The resulting detection area is $40 \times 30 \text{ cm}^2$ with a resolution of 0.784 mm. TFT dimensions are $88 \times 11 \mu\text{m}^2$ and the maximum readout speed is 10 frames/second.
C. The measurement setup for pretreatment verification

Since pretreatment verification is performed in-phantom under fixed conditions as close as possible to the isocenter, experiments were performed with the detector positioned at SDD=105 cm (the minimum mechanically achievable). A slab phantom of water-equivalent material (PTW RW3) was placed in contact with the chassis (with the cover left on the EPID) of the portal imager in order to acquire images at a certain depth. Four different setups (called “configurations” in the following) at different depths were analyzed: 10, 3.8, 1.5, and 0.8 cm [these values include the intrinsic PV-aSS00 (water-equivalent) thickness of 0.8 cm²]. The slabs were positioned on top of the detector to achieve configuration depths of 3.8 and 1.5 cm. For the 10 cm depth configuration the gantry was set at 180°, as the weight of the slabs triggered the collision interlock if placed directly on top of the detector. Data at 10 cm depth were acquired to allow a direct comparison between the image acquisition time. Experimental data were acquired for

\[ D(Gy) = m \cdot R_{PV-aSS00} + q \]  

where \( D \) is the dose in Gy obtained from measurements with an ion-chamber or a PTW-Riga Diamond for smaller fields (both referred as IC in the figures). The fitting procedure was performed without any constraint.

The PV-aSS00 signal (\( R_{PV-aSS00} \)) was defined as the average reading over a region of interest of 10×10 pixels (that corresponds roughly to the projected size of the ion chamber used for measurements) centered on the main axis and multiplied by the image acquisition time. Experimental data were acquired for

- square fields with 30, 25, 20, 15, 10, 5, 3, 2, and 1 cm side;
- rectangular fields, setting the main jaws to form square fields of 20, 15, and 10 cm side and closing down the opening in the X direction with the MLC to 15, 10, 8, 4, 3, 2, 1, and 0.5 cm;
- square “closed” fields of 20, 15, and 10 cm side (jaw settings), completely closed by the MLC to measure transmitted radiation.

For each field, the linearity of the response was investigated by delivering 5, 10, 20, 50, 100, and 200 MU.

An IMRT field can be considered a sequence of small subfields defined by a fixed setting of jaws and a variable MLC shape. Therefore an IMRT field changes its characteristics (size and energy spectrum) point by point with time. This means that for each subfield its size (and hence the output) changes. To account for these characteristics of IMRT fields, we introduced the concept of the equivalent window width field (EwwF) to define an effective field size. EwwF is defined according to the conventional Sterling equation\(^{15}\) as

\[ EwwF = 2 \cdot X \cdot Y / (X + Y) \]

For conventional static fields EwwF is calculated with \( X \) as the smallest distance between jaw settings and MLC coordinates and \( Y \) as defined by the jaw settings. For IMRT fields (static step and shoot), EwwF is defined for each segment \( s \), becoming

\[ EwwF_s = \text{EwwF calculated using, as } X, \text{ the mean of all apertures defined by opposing leaves within the } s \text{th segment and, as } Y, \text{ the distance corresponding to the open leaves (width of the leaves multiplied by the number of nonclosed leaves). In the Varian systems, an IMRT field with dynamic sliding window (DMLC) delivery is technically structured as a sequence of several (in theory up to 320) elementary segments with dose delivery occurring also during the movement of leaves between two consecutive segments. All necessary information (leaf position, weights) is stored in a MLC steering file accessible in ASCII or DICOM format. For the purposes of the present study, each elementary segment of a DMLC field is considered, to define EwwF_s in the same way as for the static cases.}

D. The PV-aSS00 image calibration settings

All images were acquired in the “IMRT” acquisition mode.\(^8\) To synchronize the image acquisition with the accelerator pulse and to guarantee a complete readout of all rows at each acquisition, the following selections were made: SyncMode=0, rows per PVSYNC=384. To assure maximal beam integration the following settings were chosen: synchronized delay=0, number of reset frames=0. Dose rate was always set to 300 MU/min, the same as used for clinical IMRT.

For each configuration, a new imager calibration (dark field and flood field) was performed.

E. The PV-aSS00 linear response

The response of the amorphous silicon detector was thoroughly investigated for various static beam conditions (in each configuration), focusing mainly on two aspects: the field size and the radiation type—primary (open beam) or transmitted (through a closed MLC). Radiation scattered from the linac head or inside the water phantom is not separately modeled in GLAaS and therefore it is included in both primary and transmitted components. A library of fit parameters (\( m \) and \( q \)) of the detector response-to-dose, assuming a linear relationship, was created from each set of experimental conditions, according to the equation:

\[ D(Gy) = m \cdot R_{PV-aSS00} + q \]
delivered dose. The fit parameters \( m \) and \( q \) were found to depend also on field size. Further investigations were carried out to determine some functional dependence of \( m \) and \( q \) on \( \text{EwwF} \) (or \( \text{EwwF}_i \)). This is aimed to develop an analytical procedure to routinely determine \( m \) and \( q \) for any field given the impossibility to cover all the possible configurations with a complete tabular library of prestored parameters. As a result, using as input data only the effective field size, derived from information stored in the MLC steering file, it will be possible to convert any PV-aS500 raw matrix into a dose matrix. In other words, a "configuration" procedure was developed to determine, from a relatively limited amount of measured data, a set of general parameters usable to convert EPID readings into doses for any field size (and shape). The procedure found and described in the following was based on empirical findings rather than on theoretical assumptions.

1. Primary radiation

From measurements for primary radiation described in the previous paragraph, different sets of \( m \) and \( q \) parameters (here \( m_{pr} \) and \( q_{pr} \) refer to primary radiation) were obtained from Eq. (1) for different values of \( \text{EwwF} \). From measurements, it was also possible to compute output factors (OF) for the PV-aS500. As a first step in the creation of the analytical “configuration” procedure, measured OF were fit against \( \text{EwwF} \) according to

\[
\text{OF}(\text{EwwF}) = [c + d \ln(\text{EwwF})]^{-1}. \tag{2}
\]

Then the set of angular coefficients \( m_{pr} \) determined for Eq. (1) were used as new input data to fit against corresponding measured OF according to

\[
m_{pr}(\text{OF}) = a^* \text{OF} + b. \tag{3}
\]

As a consequence, it was possible to relate measured \( m_{pr} \) to \( \text{EwwF} \) by means of four independent parameters \( a, b, c, d \) incorporating in their determination detector response [Eq. (2)] and conversion to dose [Eqs. (1)–(3)].

The four empirical “configuration” parameters \( a, b, c, d \), allow, for any given field size \( \text{EwwF} \) and without the need of huge tabular data, computation of the needed angular coefficient \( m_{pr}(\text{EwwF}) \) or \( m_{pr}(\text{EwwF}_i) \) to be used to convert EPID readings into dose.

The intercept \( q_{pr} \) was well approximated by the average \( q \) of all fields acquired for “primary radiation,” and therefore it was assumed to be constant for all field sizes.

It is clear that each measurement depth has its own set of parameters.

2. Transmitted radiation

Measurements of radiation transmitted through the MLC were collected for both IC and PV-aS500 with the MLC completely closed and for several field sizes defined by the jaw settings (as \( \text{EwwF} \)) as described in Sec. II E. As for primary radiation, sets of \( m \) and \( q \) parameters [Eq. (1)] were obtained (here \( m_{tr} \) and \( q_{tr} \) refer to transmitted radiation) for different \( \text{EwwF} \) values. In this case a single parameter was empirically found to be sufficient to link the angular coefficients of transmitted and primary radiation for any field size (jaw settings) with a simple proportionality rule:

\[
m_{tr} = k m_{pr}. \tag{4}
\]

The \( k \) parameter was obviously determined for each measurement. As for primary radiation, the knowledge of this parameter allows determination of the angular coefficient \( m_{tr} \) needed to convert EPID readings into dose for a specific setting.

The \( q_{tr} \) coefficient for transmitted radiation was well approximated by the average value over the available data, in the same way as \( q_{pr} \).

G. The dose matrix calculation: the GLAaS algorithm

In this section the GLAaS algorithm, which is the conversion of the raw PV-aS500 image acquired for an IMRT field into a dose matrix, is described. It is based on the following assumptions:

(i) The dose \( d_i \) to the \( i \)th pixel of the detector is attributed in part to the primary beam \( (d_{pr,i}) \) and in part to the transmitted radiation under the MLC \( (d_{tr,i}) \):

\[
d_i = d_{pr,i} + d_{tr,i}. \tag{5}
\]

(ii) A DMLC field can be described as a sequence of \( N \) elementary “segments” \( s \) with different shapes and (normalized) weights \( w_s \). Weights and geometric information (leaf positions over time) are extracted from the DMLC steering data.

(iii) For each \( s \)th segment, pixels in the raw PV-aS500 image are assumed to contribute to primary dose if positioned inside the CIAO, while pixels belonging to its geometrical complement are assumed to contribute to transmitted radiation. [CIAO is the fraction of open field within the shape defined by the MLC. In a DMLC the total CIAO is given from the first (last) position of left (right) MLC leaves. In a “segment” \( s \) the CIAO is given by the instantaneous position of MLC leaves.] The coordinate systems of EPID and of the IMRT field are matched to allow this procedure.

(iv) For the \( i \)th pixel, the fraction of the PV-aS500 signal due to primary radiation and attributed to an \( s \)th segment \( (r_{is}) \) is assumed to be a fraction of the total signal read in that pixel \( (R_{PV-aS500,i}) \) according to \( r_{is} = w_s^* R_{PV-aS500,i} \) if the pixel belongs to that CIAO, \( r_{is}=0 \) if the pixel is outside CIAO.

(v) An equivalent window width field \( \text{EwwF}_i \) is associated with each \( s \)th segment. \( \text{EwwF}_i \) is calculated as discussed above.

Analytically, the first term in Eq. (5) can be replaced by

\[
d_{pr,i} = \sum_{s=1}^{N} m_{pr,s}(\text{EwwF}_s) r_{is} + q_{pr,s}, \tag{6}
\]

where \( m_{pr,s}(\text{EwwF}_s) \) and \( q_{pr,s} \) are the parameters of the linear...
dose expression for primary radiation for the $i$th segment. The parameter values are determined as described above, as a function of $EwWF_i$. The description above is valid for both step and shoot (with a small number of segments) as well as for dynamic sliding window (described as a high number of segments).

The sum, extended to all segments in the DMLC field, gives the dose component attributed to primary radiation in the $i$th pixel. The matrix of the primary dose for the whole field is given by the envelope of contributions, pixel by pixel, of all segments.

Then, the matrix obtained by subtracting the readings attributed to primary dose from the total raw image is then entirely attributed to the transmitted radiation, and the corresponding dose can be expressed as

$$d_{ir} = m_{ir} \left( R_{PV-aS500,i} - \sum_{j=1}^{N} r_{ij} \right) + q_{ir}$$

for the $i$th pixel, where $m_{ir}$ and $q_{ir}$ are the parameters of the linear dose expression for transmitted radiation and are obtained as previously described.

The final dose matrix is the sum, pixel by pixel, of the two components, primary and transmitted: it is a 2D matrix of absolute dose, measured at a specific depth in water-equivalent material.

These maps are then directly comparable to corresponding maps exported from the TPS.

As a particular case, when DMLC fields exceed geometrical limits of the MLC hardware in the X direction, they are split in two (or more) fields partially overlapping. This feature was included in GLAaS and, whenever necessary, two or more dose matrices derived from PV-aS500 images can be summed off-line, allowing the comparison between calculation and delivery for the entire dynamic field.

Detector and linac stability over time was accounted for by acquiring at every measurement session a static 10 x 10 cm$^2$ open field with a fixed number of monitor units (50 MU) which is then compared against a reference image. A global correction factor was thus applied to the raw PV-aS500 images to correct detector inter-fraction instability or linac output fluctuations (smaller than 1% in our experience). The same static image was used also to correct for geometric offsets between isocenter and detector center due to mechanical inaccuracy of the PV-aS500 supporting arm (r-arm); this is relevant when verifications are performed at different gantry angles. A 10 x 10 cm$^2$ image must be acquired at each gantry position.

H. Testing GLAaS with IMRT fields

To test the GLAaS algorithm for pretreatment IMRT dosimetric verification, a pool of 34 IMRT clinical fields (16 from breast and 18 from head-and-neck cases) were acquired for all the four setup configurations (depths). IMRT plans were optimized and dose calculations performed using the Varian Eclipse TPS with Pencil Beam algorithm, release 7.2.35. In Eclipse verification dose maps can be generated in any desired phantom, at any desired depth, for any desired plane (axial, coronal, or sagittal) and for any desired gantry angle by means of built-in tools and exported as relative or absolute dose matrices in DICOM-RT files. Full dose calculation is performed to generate these matrices with an assigned spatial resolution (compatible with dose-calculation algorithm limitations). In Eclipse, verification plans in a phantom can be created for “field by field” or for “all fields combined” verification strategies.

To cross validate the reliability of GLAaS, the standard institutional pretreatment verification with films at 10 cm depth in solid water was performed for the 34 clinical fields, as described by Cozzi et al.\textsuperscript{14} In this case, a dedicated phantom developed in-house allowing the use of Kodak Xomat-V films without the protection envelope was used. Films were calibrated in terms of absolute dose at every verification session using a calibration film irradiated with 11 known dose levels (from 0.03 to 0.8 Gy). Films were then digitized with a CCD scanner (Vidar-VXR) at 12-bit pixel resolution.

A second validation test was performed by comparing results of QA procedures for the first 240 clinical fields verified with GLAaS against another group of 240 fields previously verified with films as described above, and pooled from our database of QA verifications to be similar (in terms of fluence patterns) to the GLAaS ones.

For the 240 clinical fields, a further comparison was performed between the subgroup of 110 split fields and the subgroup of 130 non-split fields.

Finally, a subgroup of 25 fields was verified at multiple gantry angles ($0^\circ$, $90^\circ$, and $270^\circ$) to test the performance of GLAaS under different geometrical conditions.

For all 240 clinical cases GLAaS was used with the configuration at 1.5 cm depth, the one finally chosen for clinical application.

I. Evaluation tools

Computed and measured dose images were analyzed through our own software based on the PV-WAVE v6.21 (Visual Numerics, Inc.) scripting language using DICOM (RT) as the input standard for computed or measured images.

Measurements (dose matrices derived with GLAaS) were compared with TPS dose maps and differences were evaluated by means of (i) absolute dose profiles along directions parallel to the $x$ and $y$ axes to assess qualitative agreement and (ii) the gamma index ($\gamma$) as described by Low et al.\textsuperscript{16,17} for quantitative evaluations (readers are referred to the original publication for details).

For the gamma method, distance to agreement (DTA) and dose difference ($\Delta D$) acceptance criteria were set to 3 mm and to 4% of the maximum significant measured dose per field. This was defined as the maximum dose value in the...
Histogram of measured doses in the field after cutting the highest 5% dose tail in the histogram itself. This definition was introduced to avoid bias in the analysis due to the presence of unexpectedly high spikes in the measured data (due to faulty pixels in the detector or to extremely narrow and high dose peaks). The conceptual description of this definition is shown in Fig. 1 for three thresholds. The difference between absolute maximum in a field and the significant maximum here defined was tested on a sample of 30 IMRT fields and was found to be $-9.6 \% \pm 3.7$ for 2% cut, $-11.4 \% \pm 4.1$ for 3%, and $-14.0 \% \pm 4.8$ for 5%. The cutoff value of 5% was retained. The application of the maximum significant dose instead of the conventional conservative acceptance criteria as shown in Fig. 1 (right side) where the acceptance area under the curve is smaller if the new definition is used instead of the conventional one.

Assessment of the quantitative agreement between calculation and measurement was performed in terms of the percentage of field area with $1.0 < \gamma < 1.5$ or $\gamma > 1.5$ and $p$ tests were performed between PV-aS500 and film data as well as between data from PV-aS500 at 0.8, 3.8, and 10 cm depth and data from PV-aS500 at 1.5 cm depth, chosen as reference for the EPID measurements.

As a criterion of our quality assurance procedures, any IMRT field is considered as failing pretreatment verification and further investigations shall be performed on it if, after gamma analysis, the percentage of field area with $\gamma > 1$ (%FA) exceeds 10%. Further actions would require a second verification and, eventually, modifications in the optimization of the fluence.

III. RESULTS
A. PV-aS500 Dosimetric properties and the GLAaS parameters

The linear response of the detector to primary and transmitted radiation was assessed for a large number of square and rectangular fields. In Fig. 2 (first row), as an example, the results obtained for a $10 \times 10$ cm$^2$ square field are reported. Data are shown for all four experimental configurations. Linearity was excellent for all conditions tested with regression coefficients $\approx 1.000$. The detector signal and the standard deviation $\sigma_{\text{ROI}}$ of the readings was such that $\sigma_{\text{ROI}}/\text{average}_{\text{ROI}} < 1\%$ for primary radiation and $<10\%$ for transmitted radiation.

The second and third rows of Fig. 2 show, for the four depths separately, the detector linear response to primary radiation for square fields of different sizes from 3 x 3 to 30 x 30 cm$^2$. Similar results were obtained for rectangular fields and for transmitted radiation. Of note is the strong decrease in the dependence of detector sensitivity on field size as the depth of measurement is decreased. Without additional build-up material the variation is almost negligible.

To assess the importance of using the correct effective field size $E_{\text{wwF}}$ to determine the calibration coefficients, $m$ and $q$, let us consider square fields (defined by the jaws) of 20, 15, and 10 cm, reduced to narrow windows of 2 cm in the X direction by the application of a MLC aperture. The percentage error made if the signal is converted into dose using the data for the field size defined by the jaws instead of the corresponding $E_{\text{wwF}}$ increases with depth and with jaw settings. At 1.5 cm depth it ranges from $-1\%$ to $-3\%$, at 3.8 cm depth from $-3\%$ to $-8\%$ and at 10 cm depth from $-5\%$ to $-13\%$.

To appraise the error made when attributing the calibration data of primary radiation to measurements performed in transmission conditions we report (e.g., using $m_{\mu}$ instead of $m_{\nu}$), as an example, calculations performed for a field $10 \times 10$ cm$^2$ completely defined by the MLC (with the jaws retracted). Depending on depth, the percentage dose error in a field region hypothetically irradiated at 0.5 Gy (a “high fluence” region of a normal IMRT field) would range between 1% and 2%. For a field region irradiated at 0.05 Gy (a “low fluence” region to shield an organ at risk such as the spinal cord in the head and neck region) the error would range between 4% and 13%. In the latter case the dosimetric error can be severe and could compromise quantitative evaluations in a quality assurance procedure.
FIG. 2. Dosimetric characterization of PV-aS500. In the first row: linear response to primary or transmitted radiation for a representative case (10 × 10 cm$^2$) and for the different experimental conditions (measurement depths). In the second and third rows: the linear response to primary radiation for the four setups and for different field sizes from 3×3 to 30×30 cm$^2$. Note the maximum (minimum) spread of data at 10 cm (0.8 cm) depth.
It is important to note that the wrong determination for calibration coefficients (due to wrong field-size selection) would lead to an underestimation of the dose measured with PV-aS500. Errors induced by the wrong choice of primary or transmitted parameters would lead to a dose overestimation. If simultaneously present, the two effects would not necessarily compensate each other.

Figure 3 shows the OF measured with the PV-aS500 and the fit according to Eq. 2 (solid lines) as a function of EwwF. The dashed lines shown in the figures represent the corresponding OF measured with an ion chamber in the same conditions and substantiate the difference in the behavior of PV-aS500. The discrepancy is greater at larger depths (and negligible at depths in the build-up region).

Figure 4 shows a summary of the data used to determine, from EwwF, the angular coefficients $m_{pr,s}$. Figure 4(a) shows the OF dependence on EwwF for all depths [Eq. (2)]; Fig. 4(b) shows the experimental data fit according to Eq. (3) for the angular coefficients as function of OF.

The values of parameters $a$ and $b$ [Eq. (3)], of $c$ and $d$ [Eq. (2)], of $q_{pr}$ and $q_{tr}$ [Eqs. (6) and (7)], the angular coefficients $m_{tr}$, and the regression coefficients of the fit are all shown in Table I.

B. GLaS validation tests with IMRT fields

Figure 5 shows the qualitative results of the dosimetric validation of GLaS. The first column presents dose maps derived from the measured data after application of the GLaS algorithm. The second column shows the map of $\gamma$ index evaluation (pixels shown in white correspond to $\gamma < 1$). The third and fourth columns show the dose profiles along the lines shown in the previous columns for the computed (Eclipse) and measured dose maps. Data are shown for 1.5 cm depth. In the first two cases (head and neck) %FA is 0.8% and 0.5%, respectively, in the third case (breast) 1.3%. In Fig. 6, a summary of the comparison with more conventional film dosimetry is presented for all the 34 fields used to
validate the GLAaS algorithm. Data are reported as scatter plots with, in \( x \), the %FA from GLAaS and, in \( y \), the same quantity derived from film measurements. As can be seen the best correlation is achieved at 3.8 or 1.5 cm depth. Also the 0.8 cm data correlate well with films but the values cannot be interpreted as “dose.”

Table II reports a summary of the tests performed showing that there is no statistical difference between film and GLAaS at 0.8 and 1.5 cm while the statistical difference is limited (\( p=0.07 \)) at 3.8 cm; of note is that GLAaS data at 3.8 cm are statistically different (\( p<0.01 \)) from data at 1.5 cm, which are globally the best.

Figure 7 shows the results of the comparison between the first 240 clinical fields verified with GLAaS and a sample of 240 equivalent (in terms of fluence patterns) fields verified with film dosimetry. The histograms of %FA are qualitatively different with a much shorter tail for GLAaS and average %FA equal to 2.1±1.3% for GLAaS and 3.9±3.4% for film; \( p<0.001 \) from a \( t \) test for independent samples, indicating an highly significant statistical difference between the two groups. Figure 7 reports also the comparison of the distributions of %FA for the 110 split and 130 nonsplit fields measured with GLAaS, showing that no statistical difference is present (\( p=0.97 \)), i.e., GLAaS implementation allows a robust off-line integration of independent PV-aS500 images (split fields must be acquired on different images). Finally, Fig. 8 shows the results obtained from the analysis of the 25 fields verified at different gantry angles. In this case the observed %FA values were: 1.2±0.9, 1.3±1.3, and 1.4±2.0 for 0°, 90°, and 270°, respectively. Using paired \( t \) tests, no significant differences were observed [\( p=0.60 \) (0.54, 0.81) for data at 90° vs. 0° (270° vs. 0° and 90° vs. 270°, respectively)]. The scatter plot shows a very good correlation between the different gantry angles.

### IV. DISCUSSION AND CONCLUSIONS

A new algorithm (GLAaS) has been developed to convert raw data acquired with the Varian Portal Vision PV-aS500 into absolute dose maps. GLAaS was conceived for IMRT pretreatment verification. Results from characterizations and from validation tests performed on fields delivered with the sliding window technique have been given. GLAaS was based on the proven assumption that the a-Si detector has a linear response to dose, which in turn depends on two main factors: whether the radiation is primary or transmitted and

### TABLE I. Equation parameters.

<table>
<thead>
<tr>
<th>Equation/Parameters and fitting correlation</th>
<th>Depth (cm)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>10</td>
</tr>
<tr>
<td>Eq. (3): ( m_{pr}(OF)=aOF+b )</td>
<td>( a \times 10^{-6} )</td>
</tr>
<tr>
<td>( b \times 10^{-5} )</td>
<td>1.939</td>
</tr>
<tr>
<td>( r^2 )</td>
<td>0.996</td>
</tr>
<tr>
<td>Eq. (2): ( OF(\text{EwwF})=[c+d\ln(\text{EwwF})]^{-1} )</td>
<td>( c )</td>
</tr>
<tr>
<td>( d )</td>
<td>-0.231</td>
</tr>
<tr>
<td>( r^2 )</td>
<td>0.983</td>
</tr>
<tr>
<td>Eq. (6): ( d_{pr,s}=\Sigma_{N_{pr,s}}^{N} m_{pr,s}(\text{EwwF}) \Sigma_{N_{pr,s}}^{N} r_{pr,s}+q_{pr,s} )</td>
<td>(×10^-3)</td>
</tr>
<tr>
<td>Eq. (7): ( d_{pr}=m_{pr}(\text{PV-aS500}) \Sigma_{N_{pr}}^{N} r_{pr}+q_{pr} )</td>
<td>(×10^-4)</td>
</tr>
<tr>
<td>Eq. (4): ( m_{pr}=km_{pr,\text{aS500}} )</td>
<td>k</td>
</tr>
</tbody>
</table>

\( r^2 \) is the square of the correction coefficient from the linear fit.
field size (including MLC aperture). Detector-response modeling in terms of both these factors was realized without convolutions, application of kernels, or MC simulations and, in principle, GLAaS could be generalized to other applications besides IMRT verification.

In our institution, the GLAaS algorithm has been used for routine pretreatment IMRT verification since the start of 2005 with a high degree of satisfaction by all the professionals involved. To the authors' knowledge GLAaS is the first application in routine practice of in-phantom absolute dosimetry using PV-aS500 measurements under the conditions described in this paper. Other methods, as summarized in the Introduction, have involved different strategies, such as measuring exit doses (Grein et al.\textsuperscript{5}) or measuring fluences (van Esch et al.\textsuperscript{6}) or even more complex strategies (Warketin et al.\textsuperscript{9}). One potential weak point of the present study is the absence of a comparison of GLAaS against other published algorithms for use with the PV-aS500. This is a task which intrinsically cannot be achieved because of the different strategies used (and also because of different noncommercial phantoms, different geometrical settings, and the need for specific MC simulations which are obviously not easily accessible). Therefore the only real comparison pertinent to the study was to test GLAaS against film dosimetry as we have done and reported in this paper.

The experiments to validate our new algorithm were highly satisfactory. Agreement between TPS calculations and measurements was excellent and the comparison against films demonstrated the robustness of the GLAaS under different experimental conditions. This consistency was proved also by a comparison of two larger samples of "similar" fields measured with both GLAaS and films which showed, in addition, that GLAaS distributions have a shorter ‘tail’ than film-derived measurements. By allowing off-line summation of different images, GLAaS adequately manages the dosimetry of split fields with no statistical difference in the results from a comparison of two groups of split and nonsplit fields.

Since phantom-based pretreatment verification of IMRT fields is performed under fixed geometrical conditions, including the distance between phantom and detector, there is no need to investigate the sensitivity of the PV-aS500 with
varying SDD. Nevertheless, some experiments were performed at SDD=120 and 140 cm to verify the main assumptions (linearity, OF versus field size dependency, etc.). The final decision about SDD was justified also for the following reason: at SDDs much larger than 100 cm, the maximum size of fields that can be verified with PV-aS500 decreases significantly for geometrical reasons [with SDD=105 the maximum size in y allowed is 30 cm, with SDD=140 this is reduced to 22 cm]. In general, given the linearity of its dose response, the system could be used at any SDD with

![Diagram](image)

**Fig. 6.** Quantitative assessment of GLAaS performance for the 34 IMRT fields for which GLAaS and film dosimetry were performed at all the different depths. Data are shown as scatter plots of the percentage of field area %FA with γ > 1 for GLAaS (in x) versus the same quantity calculated for film dosimetry (in y). Note the good correlation for 3.8 and 1.5 depths (no data beyond the acceptance threshold of 10%) and the poorer agreement for 10 cm (showing, however, an improvement in results with GLAaS compared to films).

<table>
<thead>
<tr>
<th>TABLE II. Summary of γ index evaluation on the 34 fields in the main validation experiment.</th>
</tr>
</thead>
<tbody>
<tr>
<td>%FA 1.0&lt;γ&lt;1.5</td>
</tr>
<tr>
<td>GLAaS@10 cm</td>
</tr>
<tr>
<td>GLAaS@3.8 cm</td>
</tr>
<tr>
<td>GLAaS@1.5 cm</td>
</tr>
<tr>
<td>GLAaS@0.8 cm</td>
</tr>
<tr>
<td>FILM</td>
</tr>
</tbody>
</table>
obviously different parameters, but the core of the GLAaS algorithm will not change. Moreover, SDD=105 cm is the distance closest to isocenter, i.e., to the setup used to compute dose distributions for patients.

The results at depths of 3.8 and 1.5 cm were highly comparable and preferable to those at 10 cm. The configuration that utilizes a 0.8 cm depth is invalid, since it is too shallow for actual dose measurements. It is not recommended to use this easiest configuration even if the results are promising.

In routine practice, either the 3.8 or the 1.5 cm configurations could be used interchangeably at low energies (all experiments presented here refer to a beam quality of 6 MV). The 3.8 cm depth could be preferable since it is well beyond $d_{\text{max}}$. In contrast, the 1.5 cm configuration requires the use of only 0.7 cm of additional material in front of the detector. This thin, light layer can be easily positioned either on top of the PV-aS500 cassette or underneath the cover (with minor modifications of the collision interlock). In practice GLAaS allows the use of PV-aS500 as a robust 2D absolute dosimeter at any gantry angle to test possible MLC problems due to gravity. The results reported (measured at 1.5 cm depth) confirm this.

The application of GLAaS to measurements with the a-Si panel also plays a major role in the general area of pretreatment verification of IMRT. As shown in the Introduction, several studies have been published, based on the convolution/deconvolution of computed/measured data with the detector response function; these “measured” fluences can be compared with the TPS values. The limitation of such approaches is that fluences are among the strongest elements of the IMRT chain. Ideal fluences from the TPS are mathematical objects and the conversion between ideal and actual fluences includes little more than the geometrical limitations of MLC movements. Therefore fluence distributions are, generally speaking, correctly delivered by linacs (the Varian MLC has a spatial resolution during movement of 0.1 mm).

The weak link in the IMRT chain is instead the dose calculation algorithm used in the TPS. The accuracy of pencil-beam or 3D-convolution algorithms depends upon a number of factors (e.g., spatial resolution of the calculation grid, calculation point position with respect to MLC leaf position, proper modeling of head and phantom scatter and of transmission through the MLC). These limitations become “visible” only when performing absolute dosimetry in 2D. GLAaS will allow this in routine practice.

A final comment concerns logistical aspects. Film dosimetry requires intensive allocation of time and resources. GLAaS dosimetry with a PV-aS500 requires by contrast a minimal investment of time. There is no need for external hardware such as phantoms, scanners, or developers and the GLAaS procedure can be carried out without difficulty by properly trained dosimetrists. The off-line analysis can be
performed in a separate room outside the clinical area. Data preparation, acquisition, and analysis takes ~15–20 min per patient.

ACKNOWLEDGMENT

Professor Alan Nahum (Clatterbridge, UK) is sincerely acknowledged for his careful editorial reading of our manuscript and for fruitful discussions about its content.

Electronic mail: lucozzi@iosi.ch


