Dosimetric Characteristic of Digital CCD Video Camera for Radiation Therapy

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Patient dose verification is one of the most important parts in quality assurance of the treatment delivery for radiation therapy. The dose distributions may be meaningfully improved by modulating two dimensional intensity profile of the individual high energy radiation beams. In this study, a new method is presented for the pre-treatment dosimetric verification of these two dimensional distributions of beam intensity by means of a charge coupled device video camera-based fluoroscopic device (henceforth called as CCD-VCFD) as a radiation detecter with a custom-made software for dose calculation from fluorescence signals. This system of dosimeter (CCD-VCFD) could reproduce three dimensional (3D) relative dose distribution from the digitized fluoroscopic signals for small ($1.0\times1.0\,cm^2$ square, $\phi\,1.0\,cm$ circular) and large ($30\times30\,cm^2$) field sizes used in intensity modulated radiation therapy (IMRT). For the small beam sizes of photon and electron, the calculations are performed in absolute beam fluence profiles which are usually used for calculation of the patient dose distribution. The good linearity with respect to the absorbed dose, independence of dose rate, and three dimensional profiles of small beams using the CCD-VCFD were demonstrated by relative measurements in high energy photon (15 MV) and electron (9 MeV) beams. These measurements of beam profiles with CCD-VCFD show good agreement with those with other dosimeters such as utramicro-cylindrical (UC) ionization chamber and radiographic film. The study of the radiation dosimetric technique using CCD-VCFD may provide a fast and accurate pre-treatment verification tool for the small beam used in stereotactic radiosurgery (SRS) and can be used for verification of dose distribution from dynamic multi-leaf collimation system (DMLC).

Key words: CCD, scintillator, small field, sterotetic radiosurgery

INTRODUCTION

Radiation beams of 4.0 cm or less in diameter are customarily used in SRS to deliver a single large dose fraction to a small target volume with steep dose gradients around periphery.[1] Such small fields do not provide the full lateral electronic equilibrium. Measurement of the dosimetric characteristics of those radiation beams requires the use of small-volume detectors in order to achieve high spatial resolution and to minimize the negative effect on the measurement due to the lack of lateral electronic equilibrium. Air-filled small-volume ionization chamber, film dosimeter, silicon diode and diamond detector are most often used for the measurement of relative dose distributions in radiotherapy. From the fact that lateral electronic disequilibrium and steep dose gradients are typical characteristics of small SRS beams,[2] commercialized ionization chambers, because of their large sensitive volumes, are not suitable for dosimeters used in SRS. The thermoluminescence dosimeter (TLD) is popular because of its small size, the ease of use on the patient, and the lack of good alternative technique. But the utilization of TLD for clinical dose evaluation shows several limitations. For example, advanced notice is necessary for the sample preparation, frequent calibration is required, and TLD is quite sensitive to environmental conditions and handling procedures. The TLD loses its signal up to 40% when used in a contact, planchet-type heating instrument[3]. This signal loss is dependent on the position of the TLD chip on the planchet. In another study, a 7% error was observed when using different trays in an automatic TLD reader[4]. These errors in TLD are not acceptable for patient dose evaluation. To achieve dosimetric confidence in TLD result, several TLD chips must be irradiated together at each position and averaged to reduce statistical random error, improving the reliability required for clinical dosimetry. Film dosimetry may be used in the very small fields, but film is energy dependent and also suffers from variations in the film coating and processing conditions which make it somewhat unreliable. The use of radiochromic film may eliminate some of the problems associated with conventional radiographic films. While better tissue equivalence, higher spatial resolution, and independence of room light are the main advantages of the radiochronic films,[5] disadvantage of these films is non-linearity of the response with respect to the dose in the clinical range.[5,6] Silicone diodes, because of the very small size of the sensitive volume, are the common choice in dosimetry of SRS beams.[7-9] However energy, dose rate, and directional dependence of response are negative factors in this application.[9-11] Diamond detectors, which is the near tissue equivalent to carbon, should act as suitable detectors,[12,13] although their dose rate dependence and the required pre-irradiation[14] could affect the result. Accurate measurements such as SRS demand the correction for the dose rate dependence due to ion recombination.

In stereotactic radiosurgery, small fields are required in which collimators open ϕ0.6 to ϕ 3.0 cm wide for circular fields including those with small irregularity or 1.0×1.0 to $3.0\times3.0\,cm^2$ wide for square fields. It is desirable to make a detector which has more sensitive response for absorbed dose with respect to position in such small field sizes used in SRS. From the motivation of this idea, a research has been performed on the optimization of a custom-made scintillation detector with a CCD - VCFD detector system for megavoltage photon and electron beam. This detector could allow low dose portal imaging used in electronic portal imaging device (EPID) and circular or square beam of radiation therapy. Dose distributions delivered by multiple-field irradiation techniques can often be significantly improved by modulating the two-dimensional intensity profile of the individual photon beams.[15-23] 3D dose distribution of the beam may be obtained from the CCD - VCFD system by digitizing and modulating fluoroscpic signals with the help of a custom-made software for a pre-treatment dosimetric verification. Beam profiles were measured using three detectors (UC-chamber[24], film and CCD - VCFD) in the range of 1.0×1.0 and $2.0\times2.0\,cm^2$ for photon beams and of ϕ1.0 and ϕ1.3 cm for electron beams. It turns out that cross beam profiles acquired from CCD - VCFD agree quite well with the ones using the UC-chamber and radiographic film and the CCD - VCFD system exhibits suitable characteristics for the relative measurements of 3D-dose distribution for the verification of dose delivery. Routine processes for measurements and analysis of data in each session are as follows: dose profiles in high energy photon and electron of small fields for radiosurgery and measurement of the relative 3D-dose distributions. Comparison of the results obtained with the CCD - VCFD, UC-chamber, and radiographic film are made where appropriate.

MATERIALS AND METHODS

Optimization method of 3D-beam profile is described using CCD-VCFD system including a custom-made scintillation detector for megavoltage photons and electrons. This detector could allow low dose portal imaging used in electronic portal imaging device (EPID) and circular or square beam of radiation therapy. The CCD-VCFD basically consists of a fluorescent screen, a right-angled prism, a CCD digital video camera, and personal computer. The fluorescent screen (scintillator) is a 1.8 mm thick stainless steel plate coated with a layer (1.5 mm thickness) of gadolinium oxysulphide for the irradiation of 15 MV photon and 9 MeV electron beams. The beam preparations for the measurement are as follows. Photon beam (15 MV) and electron beam (9 MeV) were generated from a Varian Clinear C1800 accelerator. The adjustable photon collimators were set from 1.0×1.0 to $2.0 \times 2.0\ cm^2$ for measurements. Small circular beams of ϕ 1.0 to ϕ 1.3 cm in diameter for electron beam were produced by the custom-made cerrobend collimators under the adjustable jaws.

The CCD-VCFD was directed perpendicular to the scintillator and the photons and electrons incident into the scintillator are converted into the fluorescent light, which directly shows the point-to-point image of beam intensity according to the positions the beams hit. This fluorescent imaging of beam distribution is reflected at right angle to the direction by the right-angled prism which points to the CCD-Video camera. The reflected fluorescence rays has a fixed focusing distance of 100 cm from the surface of prism to CCD-Digital Video Camera, which also helps to reduce the scattering photons from gantry head shown in Fig. 1.

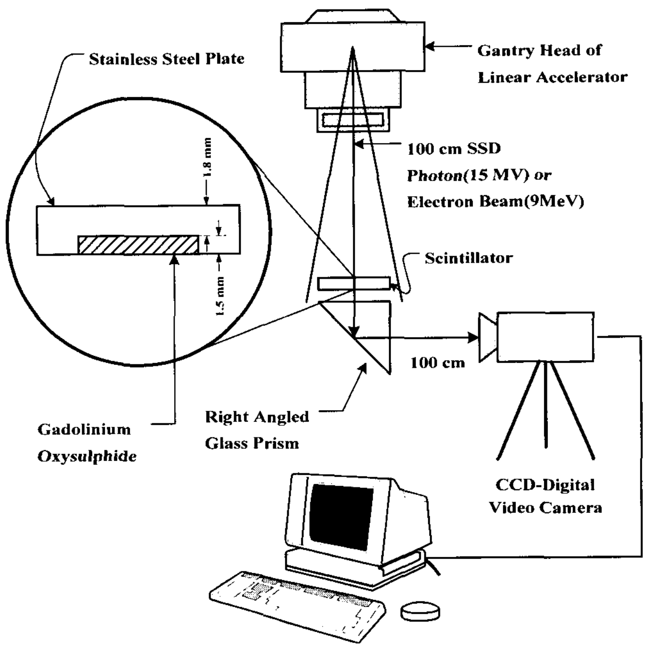

Fig. 1. The schematic diagram of a charge coupled device digital video camera connected to fluoroscopic device and computer to analyze data from scintillator (CCD-VCFD syste).

CCD-VCFD records fluorescence image of beam distribution at the speed of 60 frames per second. Once a fluorecence image across the beam is taken at CCD-VCFD, the output signals are sent to video capture board in personal computer for data storage and analysis. The image data are collected in a computer file with AVI format. Dedicated software is designed to perform data aquisition first and data analysis is carried out later to allocate maximum cpu time to data aquisition. Then frames containing useful information are sorted out manually and stored into separate files with BMP format. Some fractions of the whole frames in a AVI-formatted file are blank or contain only a part of image

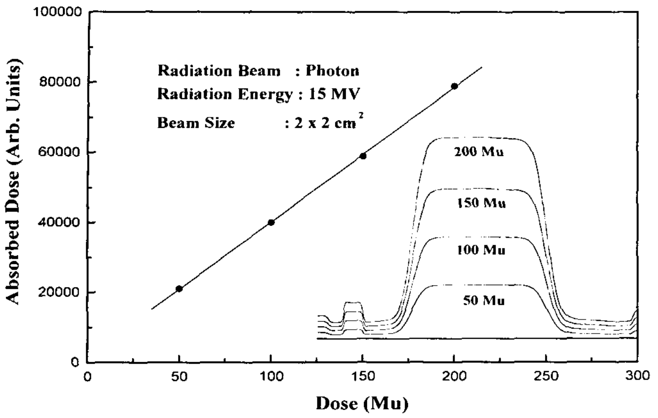

Fig. 2. The linearity of output reading from CCD-VCFD in arbitrary unit of light intensity, which shows the values of calculation as a function of relative absorbed dose in monitor unit. The inserted figure visualizes linearity as the magnitude of beam profile in proportion to absorbed dose.

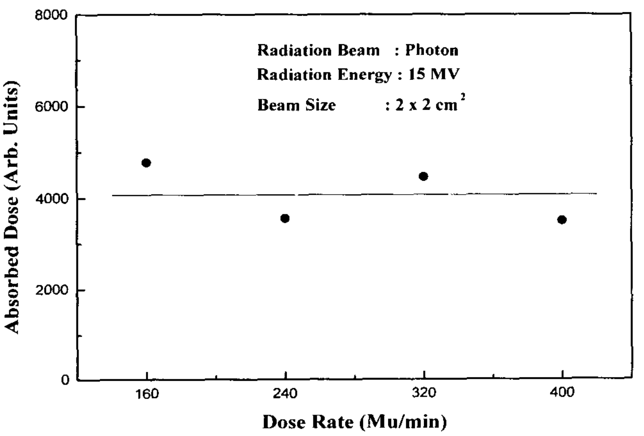

Fig. 3. The CCD-VCFD is independent of dose rate from 160 to 400 MU/min for 15MV photon beams at 2.0× 2.0 cm^2 field size at 100 cm SSD.

because recording speed in CCD-VCFD is not synchronous to that of capture speed in video capture board. The frames containing whole image are selected and used for the analysis.

The pixel(600×600) brightness in an image is proportional to the intensity of the irradiated beam passing through the scintillator and implies dependence on the beam position. From the relation between pixel brightness and beam intensity, the brightness of each pixel can be converted into a intensity number across the selected lines in the beam cross section and consequently reveals the 3D-dose distribution of beam profile after reconstruction through the computer algorithm. For data analysis, a software has been developed which reads a BMP file produced in the previous step of data aquisition as input and may select an interested line in any direction across the beam cross section, which allows to study the various shapes of beam profile. Dose profiles are obtained in the same way as the one from the electronic portal imaging device (EPID) at the 100 cm position from the central beam line in dark treatment room.

RESULTS AND DISCUSSION

The CCD-VCFD is exposed with fluorescence light equivalent to 50-200 MU photon and electron beams. The output readings from CCD-VCFD were measured in the unit of relative light intensity for 15MV photon and 9MeV electron beam at square field size of 1.0×1.0 cm^2~ 2.0× 2.0 cm^2 and circular beam of ϕ 1 .0 ~ ϕ 1.3 cm in diameter, respectively. The linearity of relative output reading and calculated values are shown in Fig. 2.

The measurements coincides well with the calculated line within the difference of 1.5%. It should be pointed out that neither supra- nor infra-linearity is indicated at large monitor units, considering that the linearity of dosimetry is fundamental and important property in the therapeutic radiation beam detections. Especially, when the line of linearity is extrapolated to zero MU, it reaches the point above zero at 3.0% of the signal intensity at 100 MU for 15 MV photon beam. It implies that the CCD-VCFD, in spite of the wide range of the irradiated monitor unit, hardly produces background noise in itself. The contribution from the illumination of treatment room to the signal may be subtracted with a software and has a constant intensity compared with the ones from the radiation photon and electron beam. The CCD-VCFD which shows good response for a high dose is fortunately also independent of dose rate in the range of 160~400 MU/min in megavoltage photon beam as shown in Fig. 3. If CCD-VCFD is calibrated by exposing the dosimeter to a known amount of radiation, it can be used for the measurement of a point surface dose and 3D dose distribution of patient in intensity modulated radiation therapy (IMRT) for both small and large field size.

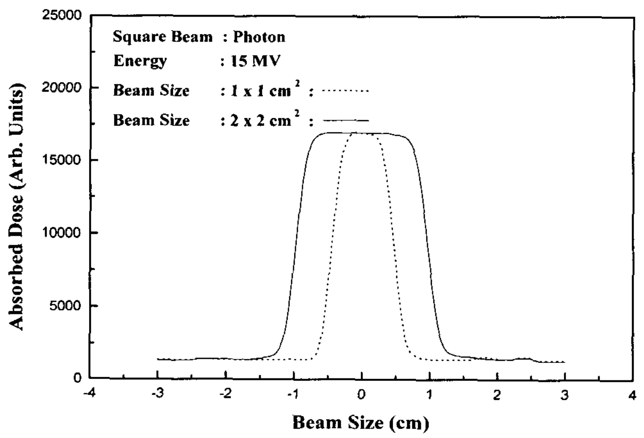

Fig. 4. Beam profiles of square fields of 1.0×1.0 and 2.0×2.0 cm^2 for 15 MV Photon beam measured with CCD-VCFD system. The curves are shown to be symmetric.

In order to evaluate the influence of small field size on profile measurements, profiles of rectangular and circular field were obtained with the CCD-VCFD, UC-chamber and radiographic film. Beam profiles were measured across the square and the circular beams passing through the boundaries. Profile measurement with the UC-chamber was performed with the stem parallel to the central axis of the beam. The profiles acquired by CCD-VCFD are shown in Fig. 4 for square field size from 1.0×1.0 cm^2 to 2.0×2.0 cm^2 and profiles in Fig. 5 are for circular field from ϕ 1.0 to ϕ1.3 cm in diameter. The different results were obtained between square and circular fields. The curves obtained from square field size show smaller amount of scattered photon around periphery than those from circular beams for electron beam. The profiles of both square and circular beams look like almost identical, but those from circular beams show sharper corn shape around the center region than those from rectangular beams.

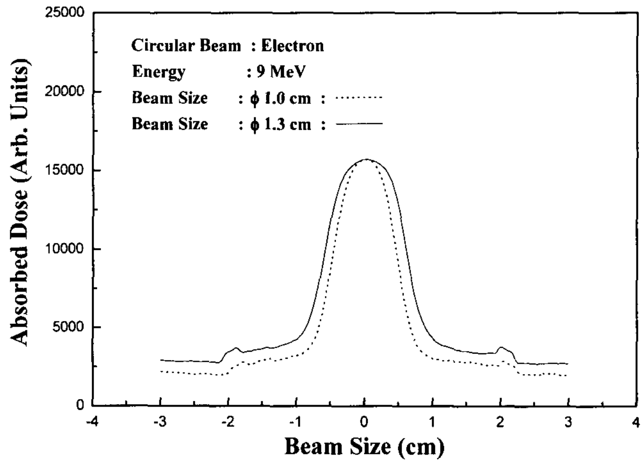

Fig. 5. Beam profiles of circular fields of ϕ 1.0 and ϕ 1.3 cm collimator for 9 MeV electron beam measured with CCD-VCFD system. The curves are shown to be symmetric.

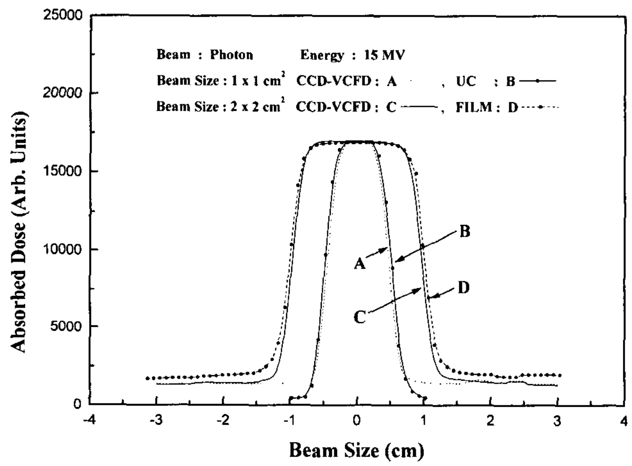

Fig. 6. Beam profiles of a 1.0×1.0 cm^2 and 2.0×2.0 cm^2 for 15 MV photon beam measured with CCD-VCFD, UC-chamber, and radiographic film which was exposed on a solid polystyrene phantom. The profiles measured with CCD-VCFD are more narrower than those measured with other dosimeters.

In order to compare the characteristics of radiation detectors (CCD-VCFD, UC-chamber, and radiographic film), beam profiles were measured for rectangular field of $1.0 \times 1.0\,cm^2$ and $2.0 \times 2.0\,cm^2$. As shown in Fig 6, all beam profiles measured with three detectors are almost similar in shape, but profiles acquired with CCD-VCFD are more narrower than those measured with other dosimeters. CCD-VCFD could reproduce 3D absorbed dose distribution with respect to positions in small beam ranges of $1.0 \times 1.0\,cm^2$ to $2.0 \times 2.0\,cm^2$ for photon beam and circular fields of ϕ 1.0 to ϕ 1.3 cm for electron beam as shown in Fig 7 and Fig 8, respectively, while other dosimeters such as UC-chamber, commercialized ionization chamber, semiconductor-type diode chamber, and radiographic film could not.

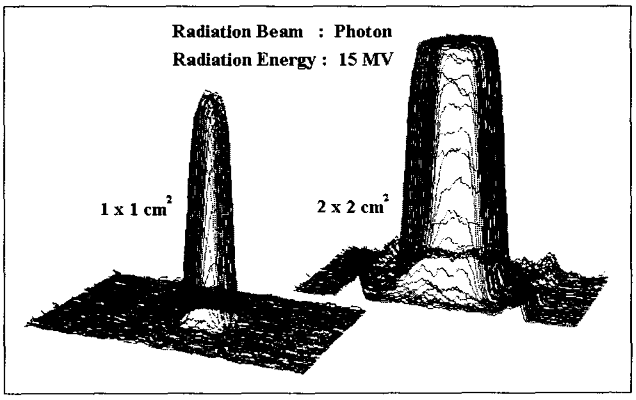

Fig. 7. The three dimensional dose distribution of a $1.0 \times 1.0\,cm^2$ and $2.0 \times 2.0\,cm^2$ for 15 MV photon beam measured with CCD-VCFD. Notice a couple of small peaks near the beam peripheries. These are not dose distribution from the beam but rather noise peak by reflecting luminescent signal at the right angled prism and can be removed by adjustment of structure.

The 3D beam profile measurements of photon and electron beam with CCD-VCFD are almost identical, but profile of photon is slightly narrower than that of electron beam. It should be noticed from relative 3D dose distribution in Fig. 7 and Fig. 8 that 3D-beam profiles from the electron beams has much more amount of zigzagging lines

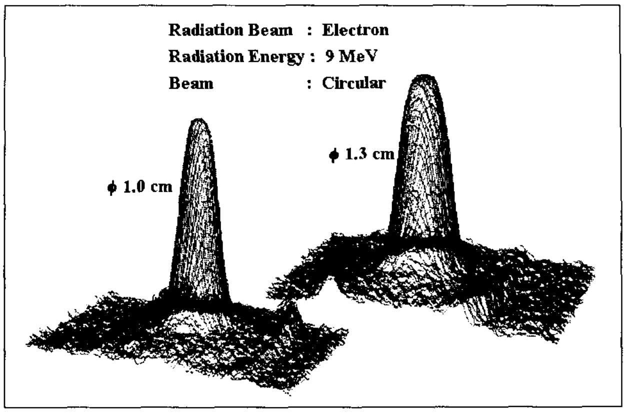

Fig. 8. The three dimensional dose distribution of a ϕ 1.0 cm and ϕ 1.3 cm for 9 MeV electron beam measured with CCD-VCFD. Also there exist another two small peaks near the beam boundaries. This is the same effect as the ones in Fig. 7. It can be removed by adjustment of structure.

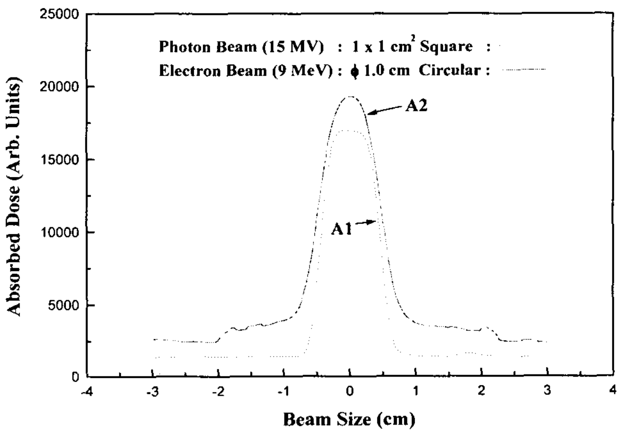

Fig. 9. The beam profiles of $1.0 \times 1.0\,cm^2$ square for 15 MV photon(Curve "A1") and ϕ 1.0 cm for 9 MeV electron beam(Curve "A2") were measured with CCD-VCFD.

out of beam boundaries than those from the photon beams shown in Fig. 7. It means that the photon beam of higher energy (15 MV) has lower scattered photons near the boundary of field than that by electron beam (9 MeV). In Fig. 9, the curve "A1" denotes the beam profile from $1.0 \times 1.0\,cm^2$ square field with respect to position for the photon beam of 15 MV energy, and the curve "A2" for electron beam of 9 MeV energy and Φ 1.0 cm circular field. The differences of beam outputs between curve "A1" and "A2" indicates

Table I. Penumbra widths of the photon beams for SRS measured with CCD-VCFD system at the SSD 100 cm

Field Size	Penumbra Width(20~80%)		Penumbra Width(10~90%)	
	Left(mm)	Right(mm)	Left(mm)	Right(mm)
10×10 mm^2	2.08 (2.19)*	2.17 (2.47)*	3.11 (3.42)*	3.28 (3.98)*
20×20 mm^2	2.34 (2.67)*	2.43 (2.35)*	3.59 (4.00)*	3.83 (3.57)*

* values measured with UC-Chamber[24]

that the curve "A2" has the larger surface dose and scattered dose than curve "A1". It is therefore implied that the photon beam of 15 MV energy has lower surface dose and scattered photons than that by the electron beam of 9 MeV energy.

One of the most important factors in radiation dosimetry is the penumbra broadening due to sensitive volume or geometric structure of the detector[9,10]. The values of penumbra (i.e. the distance between 20% and 80% or 10% and 90% of relative dose levels) are measured with the CCD-VCFD. The measured penumbra widths are shown in Table I and it turns out that those are one of the smallest that have ever been measured.

CONCLUSION

The CCD-VCFD demonstrated that it could be one of the most suitable detectors for small photon beam used in SRS and also for large beam for intensity modulated radiation therapy (IMRT), considering its dosimetric characteristics. This dosimeter is able to scan across the very small beam profile down to 1.0×1.0 cm^2 and ϕ 1.0 cm dimension, and shows one of the smallest width of penumbra for small beams. This CCD-VCFD has proven not only an excellent linearity but also independence of the dose rate of photon beams It could accurately reproduce three dimensional relative dose distribution by means of the digitized fluoroscopic signal for small field sizes(1.0 × 1.0 cm^2 square, ϕ 1.0 cm circular). Also notice that signal intensity in CCD-VCFD increases more for the electron than the photon beam.

In view of the results achieved so far, we conclude that CCD-VCFD may play an important role in performing the measurements of entrance, surface dose and 3D dose distributions in solid water phantom, irrespective of the beam size, in the ranges from the very small photon beams used in stereotactic radiosurgery to large beam of photon for intensity modulated radiation therapy (IMRT).

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