Computed Axial Tomography Tandem and Ovoids (CATTO) Dosimetry: *Three-Dimensional Assessment of Bladder and Rectal Doses*

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SUMMARY The purpose of this work is to compare bladder and rectal dose rates in brachytherapy for carcinoma of the cervix using two different dosimetry systems: traditional orthogonal radiograph-based dosimetry vs. computed axial tomography tandem and ovoids (CATTO) dosimetry. Twenty-two patients with carcinoma of the uterine cervix received the brachytherapy component of their radiotherapy with a computed-tomography compatible Fletcher-Suit-Delclos device. A total of 27 implants were performed. The average maximum bladder dose (B_{max}) for the implants was 85.8 cGy/hr using the CATTO system as compared to 42.6 cGy/hr using traditional dosimetry, ($P < 0.005$). The average maximum rectal dose (R_{max}) using the CATTO system was 59.2 cGy/hr as compared with 46.3 cGy/hr using the traditional system ($P < 0.05$). The traditional methods for choosing points to determine bladder and rectal dose rates underestimated the true B_{max} in all cases and the R_{max} in most. Based on the complication rates published in the literature, it is likely that the maximum tolerance dose of both the rectum and bladder, but especially the bladder, is higher than previously thought. *Radiat. Oncol. Invest. 6:268–275, 1998.*

Key words: cervix cancer; 3-D brachytherapy; dosimetry; treatment planning

INTRODUCTION

The accurate calculation of bladder and rectal doses in tandem and ovoid implants has been hampered by the inability to precisely define organ surfaces and their relationship to the radioactive sources. Although the intracavitary applicator can be easily visualized by using plane films, dose-limiting pelvic structures cannot be well delineated, even with the aid of radiopaque substances. This fact has led to the use of reference points which are easily visualized with orthogonal plane film radiography to estimate or represent organ exposure [1]. The use of standard reference points to represent organ exposure has obvious drawbacks in brachytherapy applications where large dose gradients occur and organ position may vary. Standard reference points may not predict organ exposure accurately [2]. This may also explain, at least in part, why some investigators who have attempted to determine the relationship between organ dose measured by reference points and complication rates have not found a completely dependable or reliable correlation—because the reference may not be the maximum dose point [3–6]. Undoubtedly there is a correlation between dose to the organ at risk and complications, but defining accurately the true maximum dose to the organs at risk has not been possible. The maximum dose may correlate with a surface area or volume of high dose which could be a better predictor of complications . This has been the rationale behind previous studies [6–11]. Computed tomography- (CT-) based three-dimensional (3-D) dosim-

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etry has the potential of accurately defining the true maximum dose and being a predictor of complications.

Three-dimensional computer technology has emerged as a useful tool for many applications in external beam radiotherapy: however, it has not been used extensively for gynecological brachytherapy. One of the reasons for this lag has been the lack of a good CT-compatible tandem and ovoid device. The first CT-compatible applicators were made of plastic [12–15] with significantly different geometrical properties than the more commonly used Fletcher-Suit-Delclos device. At Duke University Medical Center, a CT-compatible tandem and ovoid applicator with the same geometric dimensions of a standard Fletcher-Suit-Delclos device was developed using an aluminum alloy [16]. With good quality axial CT images, 3-D computer reconstruction of anatomy and applicator was created. With the addition of 3-D dosimetry, dose volume histograms of the rectum and bladder were easily obtained and the location of maximum doses readily visualized.

A comparison between the data obtained using computed axial tomography tandem and ovoid dosimetry (CATTO) and traditional orthogonal radiographic dosimetry is presented in this paper for a Fletcher-Suit-Delclos applicator [16].

MATERIALS AND METHODS

From August 1992 to October 1996, 27 tandem and ovoid applications with a CT-compatible Fletcher-Suit-Delclos device were performed at Duke University (Durham, North Carolina) in 22 patients. Cesium (^{137}Cs) sources were used. The CT-compatible applicator [16] is made out of an aluminum alloy and has the same physical dimensions as the standard Fletcher-Suit-Delclos device. Colpostat caps of different sizes were used to optimize the geometry of the individual implant. The major differences between the aluminum device and the standard Fletcher-Suit-Delclos device are: 1) the aluminum device is lighter in weight, and 2) the tungsten shields are after-loaded into the aluminum colpostat along with the sources and not located in the ovoid caps. This latter feature enables shielding to be used in the mini colpostats.

The traditional method of using orthogonal films for dosimetric calculation of dose was used in all patients to determine the loading and duration of each implant. Dosimetry calculations were performed using a commercial treatment planning system (Theraplan, Theratronics International, Ottawa, Ontario, Canada). The effect of the tungsten shielding was ignored for the calculations in the traditional system as is customary practice [3–11]. The bulb of the Foley catheter with diluted contrast for radiographic visualization was used to determine the bladder reference dose for each patient as recommended by the International Commission on Radiation Units (ICRU) Report No. 38 [1]. The reference dose for the rectum was determined by the use of either a flexible rubber rectal tube, rectal contrast, or a point 0.5 cm posterior to the posterior vaginal wall as recommended by ICRU Report No. 38 [1]. Multiple points were chosen in all cases and the maximum dose rate obtained was used as the reference dose rate. Dose to Point A was prescribed following either the Manchester or revised Manchester method [17,18] according to whether the tandem flange was inferior or superior to the front surface of the ovoids, respectively. According to both methods, Point A is located 2 cm along the axis of the tandem from an origin and then 2 cm lateral to the tandem along a line perpendicular to the plane of the lateral radiograph. The Manchester origin is located on the tandem at the front surface of the ovoids (as determined from the lateral film). The revised Manchester origin (used when the front surface of the ovoids are inferior to the tandem's flange) is at the position of the flange. In seven implants the location of Point A was determined by the Manchester definition and in the remaining 20 by the revised Manchester definition . The goal of the treatment was to administer a total (external beam plus brachytherapy) dose of 80–85 Gy to Point A without exceeding the tolerance of the rectum or bladder as defined by the dose administered to the above mentioned reference points. The tolerance of the rectum was considered 70–75 Gy and the bladder 75–80 Gy for approximately 5% complication rates [6–11].

In addition to the above dosimetry, CT scans were performed on each patient after the insertion of the applicator to enable 3-D anatomic reconstruction and dosimetry (CATTO). Approximately 7 ml of 1:5 dilute solution of contrast was used within the Foley bulb to avoid CT artifact. Each patient was scanned from 1 cm above the tandem to 2 cm below the inferior aspect of the ovoids in 3 mm slices. Outside this region, slices were 10 mm apart. Because there was no artifact from the aluminum tandem and ovoid applicator, accurate assessment of bladder and rectal surfaces was possible. The axial CT images were computer processed and the tandem, ovoids, rectum, bladder, and uterus were outlined manually or with the aid of an autocontour computer program. Three-dimensional reconstructions were then performed using an in-house, AVS- (Advanced Visual Systems,

Waltham, Ma.)-based, 3-D planning system [19]. The CT scan data was analyzed to determine the center and orientation of each radioactive source. Dose matrices were calculated around each source, then were superimposed on the anatomic 3-D reconstruction [19,20].

With CATTO, Point A is calculated relative to the radioactive source-shield geometry and is independent of patient orientation in the CT scanner. Thus in CATTO, Point A is found by measuring 2 cm superior to the tandem origin point along the tandem (the origin point is determined according to the same criteria used for film dosimetry). The perpendicular to the tandem, at this point, defines a plane in the patient. The plane which goes through this point and the line which bisects the left and right ovoids defines a second plane in the patient. The intersection of these two planes uniquely defines a line perpendicular to the tandem. Left and right Point A are a distance of 2 cm from the tandem along this line.

The volume data for 3-D reconstruction and dose volume histogram (DVH) calculations were generated by the outer surface points that were outlined in CT space. Data points were collected from axial CT images every 3 mm. The inner surface of organs was difficult to discern on the CT images. Therefore, the rectum and bladder doses were calculated over an outer surface distribution of points using 1 mm spacing. These points were determined by interpolation over the CT-outlined structure points. In this work, DVHs for the organs are presented as 3-D anatomic reconstructions. This gives a visual picture of both dose distribution and relative anatomical location of dose distribution, in particular, the location and size of the area receiving the high dose rates.

Data was collected using both dosimetry systems, traditional system, and CATTO. The effects of tungsten shielding as well as colpostat geometrical asymmetries [16] are included in the calculation of dose in CATTO. With the traditional system, tungsten shielding is ignored and the attenuation effect of the colpostats was accounted for by using a reduced (95%) strength of the cesium sources. A statistical comparison of maximum dose rates was then performed. Mean, median, analysis of variance, and correlation coefficients were calculated.

RESULTS

The dose calculated with the two systems was compared for identical source applicator geometries. For points in the patient that were not in the shadow of the tungsten shielding (such as Point A), the dose calculated with the two systems agreed to within 1%. For the clinical cases, Point A (left and right) always had different locations (relative to the source geometry) for CATTO and the standard system. A small part of this difference comes from random input error in both systems. The major difference arises because the film method of determining Point A is dependent on applicator orientation relative to the films. In CATTO, the definition of Point A is independent of applicator position in the CT scanner. It does not make sense to modify the 3-D definition to account for how the applicator is rotated relative to the orthogonal films. Thus a comparison of dose rates at Point A between the film and CT-based methods is a check of the justification for ignoring applicator rotation effects in the plane film method.

Comparison of Point A Dose Rates

The dose rate at Point A obtained using CATTO was compared to the dose rate at Point A calculated with the standard system for each patient. The Point A dose rate for each patient was calculated by averaging the left and the right values. As expected, there were only minimal differences between most patients. The average dose rate at Point A using CATTO was 56.4 cGy/hr with a standard deviation of 7.4 cGy/hr and was 59.0 cGy/hr using the film dosimetry system, with a standard deviation of 7.0 cGy/hr. The ratio of the Point A calculation with the two systems was 1.05 with a standard deviation of 0.07.

Comparison of Bladder Dose Rates

The maximum bladder dose rate calculated using the CATTO system was higher in all 27 implants when compared with the bladder reference point doses calculated with the standard system (Fig. 1). The average bladder dose rate for all patients using the film dosimetry system, which defined the bladder dose rate following the guidelines established by ICRU No. 38, was 42.6 cGy/hr with a standard deviation of 11.9 cGy/hr. The median dose rate was 41.5 cGy/hr. The average of the maximum dose rate for all patients as measured on CATTO was 85.8 cGy/hr with a standard deviation of 49.0 cGy/hr. The median value was 79.0 cGy/hr. Dose rate differences between the groups reached statistical significance ($P < 0.005$). The ratio of the maximum dose rate with the two systems was 2.0 with a standard deviation of 0.7. The ratio ranged from 1.1–4.6. Although the bladder reference point obtained with the standard system underestimated the true bladder maximum by twofold, on average, there was a wide range in the dose rates calculated with these two systems. Despite this large variation, the correlation coefficient between these groups was

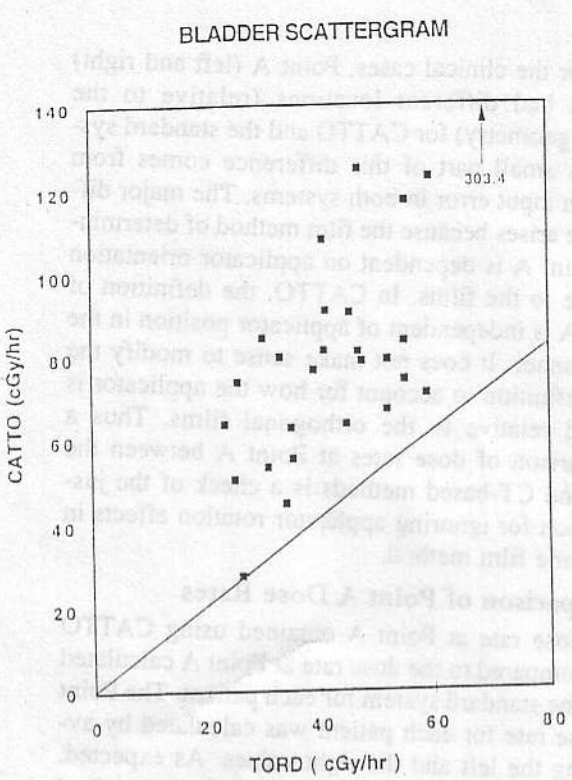

Fig. 1. Bladder scattergram comparing CATTO (3-D CT dosimetry) with traditional orthogonal film dosimetry (TORD). The line of unity is provided for reference.

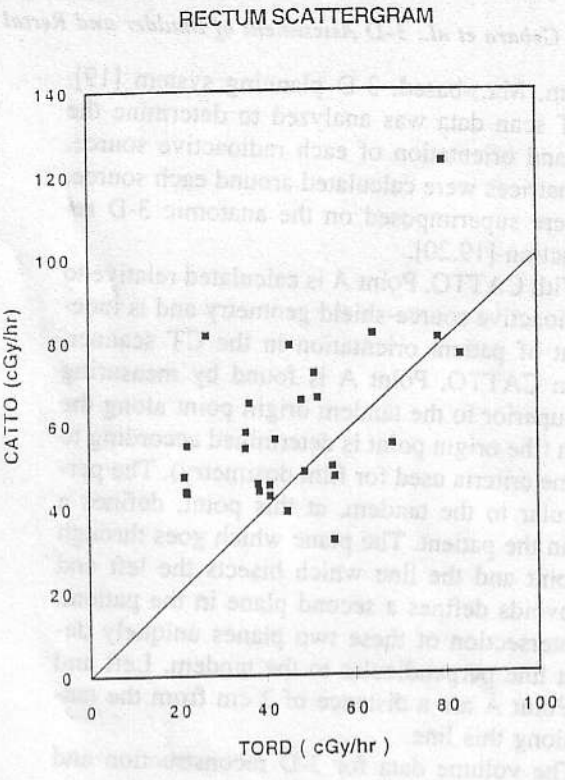

Fig. 2. Rectal scattergram comparing CATTO (3-D CT dosimetry) with traditional orthogonal film dosimetry (TORD). The line of unity is provided for reference.

positive (0.59). A scattergram plot of bladder D_{max} dose with the two systems is presented in Fig. 1.

Comparison of Rectal Dose Rates

The maximum rectal dose rate calculated using the CATTO system was higher in 20 out of 27 implants when compared with the reference dose rate obtained with the standard system (Fig. 2). The average reference dose rate for all patients using the film dosimetry system was 46.3 cGy/hr with a standard deviation of 17.5 cGy/hr. The median dose rate was 44.0 cGy/hr. The average maximum dose rate using the CATTO system was 59.2 cGy/hr with a standard deviation of 19.2 cGy/hr. The median value was 54.7 cGy/hr. Dose rate differences between the groups were statistically significant ($P < 0.05$). The ratio of the average maximum dose rate measured with CATTO and the film dosimetry system was 1.41 with a standard deviation of 0.57. The ratio ranged from 0.58 to 3.0. A positive correlation between the groups was noted with a coefficient of 0.52. As seen with the bladder dose rates above, there was a large variation in the difference between dose rates calculated with these two systems, however the magnitude of the difference and variation was somewhat less. This is demonstrated in the scattergram plot of the maximum rectal dose with the two systems shown in Fig. 2. Note that the points on the rectal scattergram lie closer to the line of unity in comparison with the bladder scattergram.

Anatomic Location of Bladder Maximum Dose Rates on the 3-D Reconstruction

In 16 of 27 implants, the location of the maximum bladder dose rate was 0–1 cm superior to the colpostats and just anterior to the tandem (Fig. 3b). This area has dose contribution from all sources and is not shielded by the tungsten within the colpostats of the applicator. The position of the tandem is an important factor in determining the location of the hot spot. The more anteverted the uterus or the more curved the tandem, the closer the tandem is to the bladder and the further superior the maximum bladder dose rate is located. A distended bladder has the same effect by bringing the superior bladder surface closer to the tandem (Fig. 3d). In either case, not only does a shift in the location of the maximum dose rate occur but also a larger volume of the bladder (i.e., the surface just inferior to the anteverted tandem) receives doses very close to maximum.

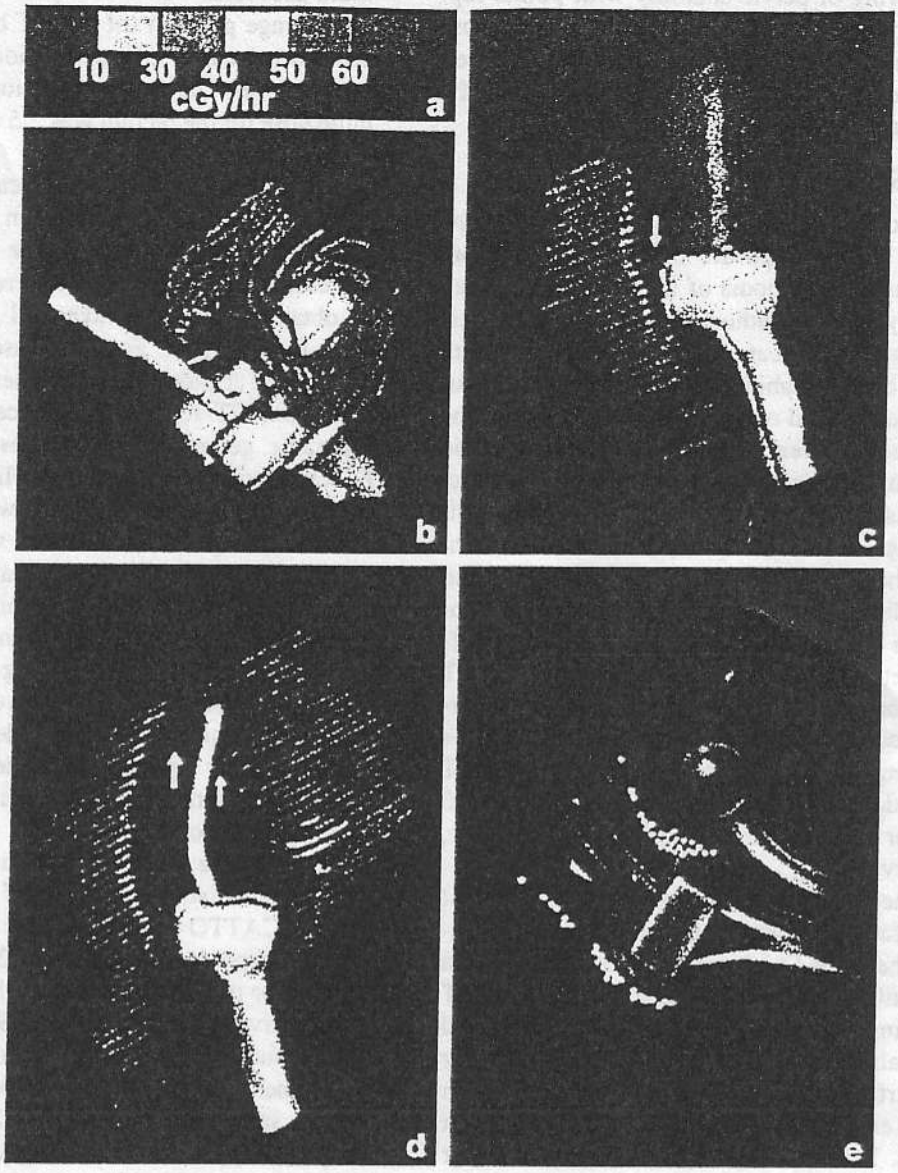

Fig. 3. Dose rate to volume relationships. The tandem and ovoid applicator and the bulb of the Foley catheter are white. The rectal and bladder surfaces are color washed with dose rates as defined by the color spectrum. **a:** Dose rate to color correspondence. **b:** Typical location of B_{max} (indicated by arrow) and the bladder dose volume distribution. **c:** Typical location of R_{max} (indicated by arrow) and the rectal dose volume distribution. The uterus is shown in red. **d:** Rectal and bladder dose distributions for a patient with a distended bladder. The arrows point to the location of R_{max} and B_{max}. **e:** Location of maximum dose rates to the rectum and bladder relative to the applicator for the 27 implants. The applicator and the bulb of the Foley catheter are shown inside the pelvic anatomy. Yellow dots represent the location of B_{max} and R_{max}.

Anatomic Location of Rectal Maximum Dose Rates on the 3-D Reconstruction

The location of maximum rectal dose on 3-D reconstruction was directly posterior to the tandem and 0–1 cm. superior to the ovoids in 12/27 implants (Fig. 3c). As in the situation of bladder exposure, this area has contribution from all sources and is not shielded by the tungsten within the colpostats of the applicator. Seven implants had maximum dose rates scattered far superior to the colpostats and the remaining eight implants had maximum dose rates located just slightly inferior to the ovoids. The location of the hot spot was highly dependent upon the patient's bowel anatomy, in particular how close to the tandem, above the colpostats, the anterior rectal wall was located (Fig. 3d).

To summarize the positions of the bladder and rectal maximum points in our experience, an ide-

alized drawing of pelvic anatomy with points representing both bladder and rectal maximum dose rates obtained from CATTO was created (Fig. 3e). All points on this drawing are placed relative to the superior surface of the colpostats.

DISCUSSION

Attempts to use CTs to more accurately determine rectal and bladder exposure in tandem and ovoid applications for carcinoma of the cervix have been reported by several authors [21–25]. The earliest attempts to use CT scanning in this capacity were hampered by the inability to delineate with accuracy the bladder and rectal locations relative to the sources due to streak artifact from the metallic Fletcher-Suit applicator. The problem of artifact was addressed by Ling et al. [23] by adjusting window settings, level settings, and contrast concentrations. The axial CT images were magnified and the dose distribution at each level was superimposed. The data obtained revealed significant differences between the dose rates estimated with CT assistance and the dose rates obtained by using orthogonal radiograph reference points. Among the eight patients treated in that study, average CT maximum dose to orthogonal film dose ratios of 2.0 and 1.9 for the rectum and bladder respectively, were observed.

Another approach to overcome the problem of streak artifact commonly encountered with standard Fletcher-Suit-Delclos applicators is to use a CT-compatible device. Yu et al. [12] obtained CT images using a plastic applicator which enabled better visualization of anterior rectal and posterior bladder surfaces by avoiding artifact production commonly encountered with standard Fletcher-Suit applicators. This applicator did not have bladder or rectal shielding. Weeks et al. [13,14,15] developed an acrylic CT-compatible version of the Fletcher system referred to as the Ann Arbor applicator. Tungsten shields were afterloaded with the radioactive sources to provide bladder and rectal shielding. The disadvantage of the system was the difficulty of obtaining proper placement of the colpostats because of their large size.

Schoeppel et al. [24] compared dose rates obtained with the Ann Arbor applicator with reference point dose rates obtained with orthogonal radiographs. Twelve out of 22 patients were not evaluable because of poor geometry. The remaining 10 patients were studied. They obtained CT maximum dose to orthogonal film dose ratios of 2.1 and 1.6 for the bladder and rectum, respectively. These results were uncorrected for the dosimetric effect of the tungsten shields. The location of maximum dose rates were also reported. They noted that the average position (of the CT bladder maximum dose) was located 1.3 cm superior to the mid-ovoid surface level. The average location of the CT maximum dose for the rectum was 2.5 cm superior to the mid-ovoid surface level.

At Duke University Medical Center, we initially attempted to use the Ann Arbor applicator described above. However, due to the geometric dimensions of the device, we were clinically unable to obtain adequate intravaginal geometric placement for treatment. For this reason the use of this device was abandoned. The present applicator is an aluminum CT-compatible device [16] which has the same geometric dimensions as the standard Fletcher-Suit-Delclos device. Mini colpostats are available for patients with narrow vaginal fornices, and shielding is afterloaded with the cesium sources. This has the advantage of providing shielding even with the use of mini colpostats. Using axial CT images and 3-D computer technology, detailed information regarding the location of maximum dose rates and dose volume histograms are easily obtained for the bladder and rectum.

This study reports the dosimetry on the first 27 implants (22 patients) evaluated using both, the traditional film dosimetry system and the CATTO system at Duke University Medical Center. Eighteen implants required the use of mini ovoids. The ratio of CATTO maximum dose rates to standard system reference dose rates was 2.0 for the bladder and 1.4 for the rectum. Similar bladder ratios were also observed by Ling [23] and Schoeppel [24]. In Ling's study the average ratio for the rectal dose was higher. This may be due, in part, to the method used to select the rectal reference point. In a CT study by Kapp et al. [2] of 15 patients treated with high dose rate (Ir-192 sources), the rectal doses were similar to the ones reported in our study. In Kapp's study, CT maximum dose to orthogonal film ratios of 2.42 and 1.37 were reported for the bladder and rectum, respectively. The wide range of bladder dose ratios seen in that work compares well with our experience. Steggerda et al. [25] used a CT analysis of 15 patients to study the effect of tungsten shields on the high dose areas of bladder and rectum. They found that the shields have little effect on the bladder high doses because the high dose region lies superior to the ovoids. This agrees with our experience. They found that the rectal high dose region occurred inferior to the ovoids in 8 out of 15 patients. In 8 out of 27 patients in our series, the rectal maximum dose was below the ovoids (see Fig. 3d).

We found, as expected, that the ICRU recom-

mended calculation points usually do not represent the true point of maximum dose. In all patients who had nondistended bladders and good applicator geometry (i.e., tandem, not anteverted), maximum bladder dose rates were located approximately 0–1 cm superior to the colpostats and just anterior to the tandem. It is in this area that there is convergence of dose from both the colpostat sources which are unshielded in that direction and the tandem sources. In those patients who had anteverted tandems or distended bladders, the maximum dose rate occurred further superiorly on the bladder surface. It is also in these patients that there is a large area of bladder exposed to dose rates close to maximum directly above the tandem. Approximately one half of the rectal maximum points were located near the reference point recommended by ICRU No. 38. The proximity of the rectum and tandem superior to the ovoids, which cannot be determined with the standard dosimetry system, was a major factor in determining the area and location of the maximum rectal dose rate. The large variability in the location of maximum dose rates for both the bladder and rectum noted in our study is similar to that reported by others [2,24,25].

The maximum bladder and/or rectal dose rates noted with CATTO were higher than those considered acceptable. Despite the tendency to adjust treatment time, source strengths, or applicator position based on the results found with CATTO, it was the department policy to use the standard film dosimetry system data alone when making treatment decisions. In our experience, CT imaging has allowed us to evaluate the limitations of ICRU points, rectal tubes, and rectal contrast localization. To make a transition from film-based dosimetry, more data on correlation of dose with complications will be needed. Because complications are probably related to the maximum dose rate and the volume exposed, dose volume histogram analysis will contribute to determining the true bladder and rectal radiation tolerance. From the complication data reported in the literature, it appears from our work that the bladder and rectum can tolerate a higher dose than traditionally thought. Thus far, one complication has occurred in this group of patients: a nonhealing rectal ulcer. In this patient the average Point A dose rate was 68.0 cGy/hr. CATTO measured R_{max} to be 122 cGy/hr while 79 cGy/hr was obtained with the standard system. This patient received 4,140 cGy with external beam radiation therapy. The total maximum rectal point dose (external plus brachytherapy) was 8,722 cGy and 11,185 cGy calculated with the film and CATTO dosimetry, respectively. This patient also had a large area of the anterior surface of her rectum exposed to a high dose rate (Fig. 3d). The relative significance of hot-spot dose vs. volume of tissue at some lesser but still high dose is unclear at this time.

We are currently in the early stages of applying 3-D computer technology to determine more accurately the bladder and rectal dose from brachytherapy applications. With additional patient accrual and follow-up, a better understanding of the correlation between dose, volume, and complications will be possible. The use of this information in clinical practice may result in a decrease in the complication rates. Changes in dose prescriptions or the combination of external beam and brachytherapy must be made cautiously. Standard therapy for carcinoma of the cervix is well tested and its efficacy should not be compromised.

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