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Planimetric volumetry of the prostate: how accurate is it?

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Received 22 February 1995, in final form 12 April 1995

Abstract. Planimetric volumetry is used in clinical practice when accurate volume determination of the prostate is needed. The prostate volume is determined by discretization of the 3D prostate shape. The area of the prostate is calculated in consecutive ultrasonographic cross-sections. This area is multiplied by the distance between the cross-sections and the total volume is determined by summation of all contributions. Besides the quality of the automated outlining, the accuracy of this method depends on this intersection distance and on the angle of the scan plane with the probe. Also, the location of the first cross-section is of influence. This paper describes the influences of these parameters on the accuracy of the volume determination using a simple prostate model. This theoretical influence is compared to clinical volume determinations using automated planimetric volumetry with different step sizes. From our data, it is concluded that a step size of 4 mm for planimetric prostate volume determination is a good compromise between investigation time and accuracy in a clinical setting.

Keywords: ultrasound, prostate volume, automated planimetric volumetry, discretization error

1. Introduction

The volume of the prostate is an important clinical parameter in urology: it is used as a diagnostic parameter for patients suffering from benign prostate enlargement (BPE). It is utilized to select an adequate treatment for these patients and as an evaluation criterion of (non)surgical treatment (follow-up evaluation) (Hendrikx et al 1991). Furthermore, accurate volume determination can be useful for interpretation of prostate-specific antigen (PSA) levels, to enhance the discriminating power of PSA between BPE and prostate cancer (Clements et al 1992).

For volume determination of the prostate using transrectal ultrasound (TRUS), several methods have been proposed, including morphological approximation using a mathematical formula for volume calculation (Collins et al 1993, Semjonow et al 1994) and planimetric volumetry (Bosch et al 1994, Terris and Stamey 1991). Planimetric volumetry is performed by numerical integration; discretization of the prostate by outlining the prostate area in cross-sections taken at discrete steps. The resulting areas are multiplied by the distance between the cross-sections and the total volume is obtained by summation.

The planimetric method is considered to be the most accurate for prostate volume determination, based on the comparison with volumes obtained after radical prostatectomy (Hendrikx et al 1989). The accuracy of the method depends on the restriction of numerical integration introducing theoretical errors (Davis and Rabinowitz 1975), movements of the
patient during the ultrasonographic examination and interpretation errors by the investigator, resulting in a displaced prostate contour (Aarnink et al 1995).

In our department, a method has been developed for automated detection of the prostate contour in ultrasonographic prostate images. By performing the outlining on a series of cross-sections automatically, the prostate volume is obtained (Aarnink et al 1994). This automated interpretation of the ultrasonographic cross-sections avoids the errors introduced by human interpretation. Also, the storage of images on hard disk before the outlining is performed can decrease the influence of patient movements by reducing the time needed for planimetric volumetry.

Besides the quality of the contour detection, the accuracy of the planimetric method depends on the step size between the cross-sections. In the literature, step sizes between 2 and 5 mm have been proposed (Collins et al 1993, Hendrikx et al 1991, Terris and Stamey 1991). Also, the prostate area within the cross-sections can be influenced by a scan plane not perpendicular to the probe axis. In this paper, first a model study is described to determine the theoretical influence of the step size on the results of numerical integration. Also, the effect of oblique cross-sections (cross-sections taken not perpendicular to the axis of the probe, indicated as 'salami effect') is investigated using the theoretical model. The results are verified in the clinic for in vivo prostate volume determination using planimetric volumetry. Based on this, an optimal step size for a clinical setting is derived.

2. Methods and materials

In our urology clinic, a Kretz Combison 330 scanner with a 7.5 MHz transrectal transducer (Multi-plane 3-D VRW 77AK) was used for transrectal ultrasonographic examinations of the prostate. An image processing system, consisting of an ordinary personal computer (80486DX2 66 MHz) with an additional image processing card (PCVisionplus-512-3-50 frame grabber) was connected to the video signal output of the scanner. With this system, the consecutive cross-sections in the transverse plane with 4 mm intersection distance were stored on hard disk and processed off line to obtain the prostate volume automatically (Aarnink et al 1994).

Determination of the prostate volume is performed by integration of a three-dimensional function. In in vivo measurements, this integration is approximated by numerical integration. In this study, numerical integration is performed using the midpoint rule (Davis and Rabinowitz 1975). The numerical result is equal to the exact analytical solution if the step size $h$ is zero, implying an infinite number of samples. However, for planimetric volumetry of the prostate, a finite number of samples is used, introducing a remainder error. Also, the selection of the starting point $p_i$ can influence the numerical result.

To assess the total discretization error introduced by different step sizes and starting points, the numerical integration was applied on a mathematical description of the prostate. A simple model of the prostate was used, described by the function

$$ y = f(x) = y_m \pm b \sqrt{1 - \left(\frac{x - x_m}{a}\right)^2} $$  \hspace{1cm} (1)

with $a$ half the length of the prostate in millimetres, $b$ half the width of the prostate in millimetres, and $(x_m, y_m)$ the midpoint of the ellipse.

In figure 1, an overview of this prostate model is given with a length of 50 mm ($a = 25$ mm) and a height of 40 mm ($b = 20$ mm), with the midpoint at $(a, b)$. Also, cross-sections are indicated in figure 1 taken with an intersection distance $h$ and the scan angle with the probe axis indicated with $\alpha$. This model was based on the ellipsoid formula, which is often used in the clinic for a fast assessment of the prostatic volume. The prostate
Discretization errors in prostate volume measurements

Figure 1. The ellipsoid-shaped prostate model used for theoretical analysis of planimetric volumetry. Indicated are the intersection distance \( h \) and the scan angle \( \alpha \) with the axis of the probe.

shape is described by a 2D ellipsoid function with normal anatomical dimensions: length of 50 mm and height of 40 mm. Simulations were performed with step sizes of 2, 4, 5, 8, 12 and 16 mm. Since the exact analytical solution of the integration of the model is expressed by \( \pi (\text{length}/2)(\text{height}/2) \), it was used as a reference for the numerical results.

The influence of the prostate length on the theoretical analysis was also investigated. These influences could have been obtained from the data calculated with different step sizes, because it makes no difference whether the step size is increased or the prostate length and height are decreased with the same ratio. For example, the error calculated for a step size of 5 mm in a prostate of 50 mm length and 40 mm height is the same as the error for 4 mm step size obtained in a prostate of 40 mm length and 32 mm height. The error ranges calculated for the step sizes 2, 4, 5, 8, 12, and 16 mm for 50 mm prostate length are also applicable to a fixed step size of 4 mm for 100, 50, 40, 25, 16.7, and 12.5 mm length respectively, with the prostate height defined as 0.8 length. However, to obtain theoretical data in the range of clinically important prostate lengths, the analyses were performed with 4 mm step size for prostate lengths of 30, 40, 50, and 60 mm. The height of the prostate has no influence on the relative theoretical error, since the function value as described in formula (1) as well as the exact numerical solution are linear related to the height \( b \). This means that the error obtained by division of the numerical and exact solution is not dependent on the height of the prostate.

The effect of taking oblique cross-sections through the prostate (salami effect) was investigated theoretically by varying the angle \( \alpha \) of the scan plane with the axis of the probe. This salami effect occurs when the scan plane is not perpendicular to the axis of the probe. It can lead to a larger number of cross-sections, depending on the angle and starting point, while the effective intersection distance is decreasing with increasing scan angle. Because the intersection distance used for multiplication is set to a fixed number,
the salami effect will lead to an overestimated prostate volume.

The results of the theoretical error analysis were compared to the results of in vivo prostate volume determination performed in 214 patients. Transverse ultrasonographic cross-sections were obtained every 4 mm. This distance was selected to reduce the investigation time and consequently the discomfort for the patient. A smaller step size (e.g. 2 mm) would lead to a large amount of images (i.e. 25 images for a prostate with a length of 50 mm) and would increase the time of investigation and therefore the influences of patient movements. Larger step sizes would reduce the information available. In every image, the prostate contour was located automatically using edge detection algorithms. The volume was obtained by multiplying the prostate area in all images with the distance between consecutive cross-sections (Aarnink et al 1995).

The in vivo prostate volumes were transformed to volumes with different step sizes: 4, 8, 12, and 16 mm. Using the contours detected in the cross-sections taken at 4 mm distance as a basis, volumes using other step sizes were obtained by summation of the areas in cross-sections with that particular distance between them. For 8 mm, two different prostate volumes were obtained, one with the odd images and one with the even images. For 12 mm step size, three different volumes were obtained, depending on the selection of the first cross-section: the first using images 1, 4, 7, . . . , the second using images 2, 5, 8, . . . , and the third with images 3, 6, 9, . . . . Four volumes resulted when a step size of 16 mm was used. The results obtained for every step size were compared to the corresponding result obtained with 4 mm step size using a paired $t$ test.

3. Results

The total discretization error of numerical integration was calculated using a 2D mathematical description of the prostate shape with anatomical dimensions. The theoretical discretization errors for 2 mm step size showed an error range between $-0.8\%$ and $0.3\%$, depending on the starting point. The theoretical discretization errors for 4 mm step size showed an error range between $-0.8\%$ and $1.0\%$, while for 8 mm step size, the theoretical error ranged from $-1.9\%$ to $1.7\%$. For 12 and 16 mm, these ranges were $-4.0$ to $1.7\%$ and $-6.9$ to $3.4\%$, respectively. Also, a step size of 5 mm was used (error range, $-3.3$ to $1.0\%)$ to compare theoretical results to the results reported in the literature. In figure 2, an overview is presented of the discretization errors introduced by different step sizes, as a function of the starting point of the numerical integration. The discontinuities in the error curves were caused by the fact that the number of cross-sections that fit within the prostate is dependent on the starting point: e.g. when using a step size of 4 mm, 13 cross-sections will be taken in a prostate of 50 mm length if the starting point is selected between 0 and 2 mm. If the starting point is selected between 2 and 4 mm, only 12 cross-sections will fit within the prostate region.

In figure 3, the theoretical errors obtained for different prostate lengths are plotted as a function of the starting point. Presented are the errors obtained with a fixed step size of 4 mm for prostates with a length of 30, 40, 50, and 60 mm, and a height of 0.8 length. When comparing figure 2 to figure 3, it can be seen that the error obtained with a step size of 4 mm for a prostate length of 40 mm and a height of 32 mm is the same as the error obtained with 5 mm step size for 50 mm length and 40 mm height. The maximum error occurred for a prostate length of 30 mm, showing an error range of $-1.8$ to $2.3\%$.

The dependence on the angle variation of the scan plane to the axis of the probe is presented in figure 4. In this figure, the errors are plotted for a step size of 4 mm as a function of the starting point. The errors are given for perpendicular scanning ($\alpha = 90^\circ$).
Discretization errors in prostate volume measurements

Figure 2. The theoretical discretization errors introduced by different step sizes (4, 5, 8, 12, and 16 mm) as a function of the starting point obtained in a prostate model based on a mathematical description using an ellipsoid function. The starting point of the numerical integration can be chosen between zero and step size $h$; the results are presented as fractions of the step size. The errors are presented as percentages of the exact solution.

and for a scanning angle of $\alpha = 80, 70, \text{and } 60^\circ$ with the probe axis. As expected, the resulting volume increases with decreasing angle between scan plane and length axis.

Table 1. In vivo results of 214 prostate volume measurements obtained with four different step sizes and the theoretical variation as calculated for a prostate model with normal dimensions.

<table>
<thead>
<tr>
<th>Step size (mm)</th>
<th>Means ± SD (ml)</th>
<th>SD of means (ml)</th>
<th>Variation (%)</th>
<th>Theoretical variation (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>4</td>
<td>39.2 ± 18.6</td>
<td>—</td>
<td>—</td>
<td>0.9</td>
</tr>
<tr>
<td>8</td>
<td>39.2 ± 18.7</td>
<td>2.3</td>
<td>5.9</td>
<td>1.8</td>
</tr>
<tr>
<td>12</td>
<td>39.2 ± 18.9</td>
<td>3.3</td>
<td>8.4</td>
<td>2.9</td>
</tr>
<tr>
<td>16</td>
<td>39.2 ± 19.2</td>
<td>4.8</td>
<td>12.2</td>
<td>5.2</td>
</tr>
</tbody>
</table>

In table 1, the in vivo results of 214 volume measurements are presented for different step sizes including the mean volume and the standard deviation, the standard deviation when comparing the means of different step sizes with the results for 4 mm step size using a paired $t$ test, the variation defined as the standard deviation obtained with the paired $t$ test divided by the mean volume, and the theoretical variation obtained for the prostate model.
Figure 3. The theoretical discretization errors introduced by different prostate lengths (30, 40, 50, and 60 mm) for a fixed step size of 4 mm as a function of the starting point obtained in a prostate model based on a mathematical description using an ellipsoid function. The starting point of the numerical integration can be chosen between zero and step size \( h \) so the results are presented as fractions of the step size. The errors are presented as percentages of the exact solution.

with mean dimensions. In figure 5, the errors obtained for individual volumes with 8 mm step size are plotted as function of the prostatic size obtained in vivo with 4 mm step size. As in the theoretical analysis, the errors in this figure decrease with increasing volume.

4. Discussion

Numerical integration with a finite number of samples introduces discretization errors. The discretization rule can be expressed as a function of the number of samples. The accuracy is also dependent on the selection of the starting point. In a clinical application such as planimetric volumetry, the starting point of the summation cannot be identified exactly. The error introduced by the discretization is therefore bounded between the maximum underestimation error and the maximum overestimation error as calculated with different starting points.

The description of the prostate shape used for theoretical analysis was based on a formula for prostate volume determination that is often used for a quick volume estimate in the clinic. The sizes of the prostate used in this model are based on mean results of measurements in our clinic. Although application of the ellipsoid formula for prostate volume determination leads to an underestimated prostate size because of the difficulty of
Discretization errors in prostate volume measurements

Figure 4. The volume results for different angles between the scan plane and the length axis of the probe. Presented are the results for perpendicular scanning ($\alpha = 90^\circ$) and for $\alpha = 80, 70$ and $60^\circ$, for a step size of 4 mm.

measuring the prostate dimensions correctly with TRUS (Semjonow et al. 1994, Terris and Stamey 1991), the description is an acceptable approximation of the natural shape of the prostate. Also, the availability of the analytical result of the integration is important to evaluate the numerical results obtained with different step sizes.

Analysis of the theoretical results of numerical integration using the prostate model with different step sizes showed the influence of the number of cross-sections (figure 2). The curves can be divided into two parts, with a breaking point at the starting point where a difference in number of cross-sections occurs. For a step size of 5 mm, the number of cross-sections that fit within the model is independent of the starting point, because exactly 10 images fit within the prostate of 50 mm length. It should be noted that for a small range of the starting point, the theoretical error for 5 mm step size is larger than for 8 mm step size.

The model simulations for different step sizes were performed for a prostate model with a fixed length of 50 mm, while the in vivo prostate lengths varied between 30 and 60 mm. Model simulations with 4 mm step size for prostate lengths selected in the clinically important range (30–60 mm) showed a maximum error range of $-1.8$ to $2.3\%$ for the smallest prostate length.

Comparison of theoretical analysis to a practical application showed that the errors introduced by different step sizes are larger than expected theoretically. This can be caused by the difference between the mean of errors for different prostate lengths (in vivo results) and the error obtained with mean prostate length (theoretical results). Furthermore, the theoretical estimate is an error estimate for volumes found by integrating over slices in
Figure 5. The errors of the transformed individual volumes obtained in the clinic for a step size of 8 mm as a function of the volume obtained with 4 mm. Also, the 5% error ranges are indicated.

Table 2. Theoretical and adjusted theoretical error ranges and adjusted variance in prostate volume determination for three different step sizes when taking the 4 mm results as basis, assuming an error in the 4 mm results of -0.8 to 1.0%.

<table>
<thead>
<tr>
<th>Step size (mm)</th>
<th>Error range (%)</th>
<th>Adjusted error range (%)</th>
<th>Adjusted variance (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>8</td>
<td>-1.9 to 1.7</td>
<td>-2.7 to 2.7</td>
<td>2.7</td>
</tr>
<tr>
<td>12</td>
<td>-4.0 to 1.7</td>
<td>-4.8 to 2.7</td>
<td>3.8</td>
</tr>
<tr>
<td>16</td>
<td>-6.9 to 3.4</td>
<td>-7.7 to 4.4</td>
<td>6.1</td>
</tr>
</tbody>
</table>

an ellipse, while the bounds on the errors in prostate volumes are only approximations: the in vivo measurements were based on the results obtained with 4 mm step size, which already contained a discretization error. In theory, this error is bounded between -0.8 and 1.0%. In table 2, the adjusted error ranges for step sizes of 8, 12, and 16 mm are presented taking the 4 mm results as basis, assuming an underestimation of 0.8% and an overestimation of 1.0% in the results for 4 mm. Multiplication of the underestimation errors obtained theoretically with the error of 4 mm (0.992) gives the adjusted underestimation error, while the adjusted overestimation is obtained by multiplication of the overestimation errors with the overestimation error of 4 mm (1.01). Also, patient movements during the ultrasonographic examination can influence the result.

Errors caused by taking oblique cross-sections showed that the prostate volume is overestimated. This salami effect is also important when reconstructing the 3D prostate from
Discretization errors in prostate volume measurements

the consecutive transverse cross-sections. Reconstruction of the prostate in 3D using oblique cross-sections will lead to displacement in the 3D plane, which can be important when relating the ultrasonographic findings to, e.g., histopathological findings or other imaging techniques. This salami effect can be overcome by taking cross-sections in the longitudinal plane. In that case the offset in the angle is overcome by taking the cross-sections at certain angles with a fixed intersection angle. For the calculation of the contribution of every longitudinal cross-section to the total volume, the angle dependence of the intersection distance should be taken into account.

To investigate the reproducibility of different methods for volume determination, Stone et al (1991) performed volume measurements of patients taking a placebo in a randomized trial of treatment for BPE. They concluded that planimetric volumetry is the method of choice in determining prostatic size. In 15 patients, they found a mean variability (the mean of standard deviations in sequential volume measurements divided by the mean volume) of 5% in planimetric volume determination with a step size of 5 mm, which should be acceptable in any clinical study of treatment for BPE. This variability is slightly higher than the error expected theoretically using the prostate model (between −3.3% and 1.0%). However, the authors did not obtain the exact volume of the prostate (by radical prostatectomy). It is only concluded that they are able to reproduce their planimetric TRUS measurements within 5% variability.

A more extensive study on reproducibility of volume measurements was performed by Styles et al (1988). They compared suprapubic and transrectal measurements and determined the degree of observer variation with the two methods. Comparison of the two methods showed a good Spearman rank correlation between both, but also a considerable variation for the individual patient. However, the Spearman rank correlation is based on the ranks of the data rather than on the actual values and is therefore not very suitable to compare the results of different volume measurements. They concluded that because of the degree of interobserver variation in the individual patient, small changes in prostate volume are difficult to measure using planimetric volumetry when performed by different observers.

The introduction of the automated method for prostate volume determination provides the urologist with a possibility of overcoming the observer variation. This method has been evaluated for 56 patients in the urology clinic using a step size of 4 mm (Aarnink et al 1995). The results of this method were very promising: an average variation of 4% was found in the automated volume when compared to exact manual outlining in quiet surroundings by an experienced urologist.

From the theoretical data presented in figure 2, it can be concluded that the step size to obtain an accuracy of 95% in prostate volume measurements should be smaller than 12 mm. However, these data are obtained with the mean prostate length of 50 mm. To be able to measure smaller prostates with the same accuracy, a smaller step size should be used. From figure 3 it can be concluded that a step size of 4 mm or smaller will lead to an accuracy of 95% or higher for prostates of 30 mm length or more.

Concerning the clinical data, a maximum variability of 5% allows a mean difference of $39.2 \times 0.05 = 2.0$ ml in the mean prostate volume obtained with different step sizes. From table 1 it can be concluded that a step size of 8 mm gives a mean variation in the prostate volume of 5.9%. For 8 mm step size, around 60% of the measurements are within the 95% accuracy range, which is illustrated by figure 5.

It can be concluded that a varying step size dependent on the length of the prostate can be helpful in determining the prostate volume in an accurate and fast way. Using a ratio of six or more between step size and prostate length gives an accuracy of 95% in the volume assessment. This means that, before the step size is set, the prostate length has to
be measured. To overcome this problem, a fixed step size of 4 mm can be used, which is suitable for prostates with a length of 24 mm or more.

5. Conclusion

An accuracy of 95% or more in the prostate volume measurement is suitable for clinical studies. To obtain this accuracy, a ratio between step size and prostate volume (reflecting the number of cross-sections) of six or more should be used. This means that planimetric volumetry with a step size of 4 mm is capable of measuring prostates with a length of 24 mm or more within this accuracy. This finding is supported by clinical data obtained from 214 patients with automated prostate volume assessment. From this point of view, it is concluded that a step size of 4 mm is a good compromise between time and accuracy in a clinical setting. In theory, the error range in volume measurements for prostates with normal dimensions is bounded by $-1.8$ and $2.3\%$.

References


