Validation of a Blood-Sampling Method for the Measurement of $^{99m}$Tc-Methylene Diphosphonate Skeletal Plasma Clearance

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Quantitative studies of bone using $^{99m}$Tc-methylene diphosphonate (MDP) reflect bone remodeling. The simplest method of evaluating $^{99m}$Tc-MDP kinetics involves taking multiple blood samples and measuring total clearance ($K_{\text{total}}$) from the area under the plasma curve (AUC) and deriving bone clearance ($K_{\text{bone}}$) by subtracting glomerular filtration rate (GFR) from $K_{\text{total}}$. However, the accuracy of the AUC method is uncertain because of assumptions that the terminal exponential is reached by 2 h and that the rate constant $k_4$, representing the backflow of tracer from bone to plasma, is negligibly small. The aim of this study was to validate the accuracy of the AUC method by comparing $K_{\text{bone}}$ values obtained by that method with those obtained by $\gamma$-camera imaging. Methods: Seventy-one patients were injected with 600 MBq of $^{99m}$Tc-MDP. For the first 22 patients, whole-body images were acquired at 15 min and at 1, 2, 3, and 4 h after injection, whereas the remaining 49 were imaged at 15 min and at 1 and 3 h. Two-minute static images of the thighs were acquired immediately before each whole-body scan. Multiple blood samples were taken between 5 min and 4 h, and free $^{99m}$Tc-MDP was measured using ultrafiltration. Two $\gamma$-camera methods were used to evaluate $K_{\text{bone}}$, the Patlak plot method and the Brenner method, which is based on measuring soft-tissue uptake in the thighs. The soft-tissue data were also used to measure $k_4$. Results: The soft-tissue data gave a $k_4$ value of 0.0003 min$^{-1}$ (95% confidence interval, 0.0002-0.0004 min$^{-1}$). The mean ($\pm$ SD) $^{99m}$Tc-MDP $K_{\text{bone}}$ was 56.0 $\pm$ 32.4 mL min$^{-1}$ with the AUC method, 49.5 $\pm$ 32.1 mL min$^{-1}$ with the Patlak method, and 42.8 $\pm$ 32.0 mL min$^{-1}$ with the Brenner method. Correcting the AUC values of $K_{\text{total}}$ by factors of 0.95 and 0.90 gave $K_{\text{bone}}$ values in agreement with the Patlak and Brenner methods, respectively. Conclusion: Values of $k_4$ are too small to affect values of $K_{\text{bone}}$ measured using the AUC method. Correcting $K_{\text{total}}$ by factors in the range of 0.90–0.95 corrects for the error in the terminal exponential and brings $K_{\text{bone}}$ values measured using the AUC method into agreement with the $\gamma$-camera results.

Key Words: bone plasma clearance; $^{99m}$Tc-methylene diphosphonate

model shown in Figure 1 (14). Provided that the rate constant $k_4$ describing the backflow of tracer from the bound bone compartment to plasma is sufficiently small, values of $K_{\text{bone}}$ can be estimated by first calculating the total clearance ($K_{\text{total}} = K_{\text{bone}} + K_{\text{renal}}$) by dividing the amount of tracer injected, $Q$, by the area under the plasma clearance curve (AUC) (14):

$$K_{\text{total}} = Q/\int_0^\infty P(t)\,dt = Q/\text{AUC}. \quad \text{Eq. 1}$$

In Equation 1, $P(t)$ represents the plasma concentration of free $^{99m}\text{Tc-MDP}$ at time $t$. Because the renal clearance of free $^{99m}\text{Tc-MDP}$ is the same as that of $^{51}\text{Cr-EDTA}$ (17,18), the value of $K_{\text{bone}}$ is found by subtracting GFR from $K_{\text{total}}$:

$$K_{\text{bone}} = K_{\text{total}} - \text{GFR}. \quad \text{Eq. 2}$$

We refer to this method of evaluating $K_{\text{bone}}$ as the AUC method. Using this technique, Blake et al. (14) reported a statistically significant difference in values of $K_{\text{bone}}$ (40.3 vs. 44.2 mL min$^{-1}$) between estrogen-treated postmenopausal women and age-matched untreated women. However, the accuracy of $K_{\text{bone}}$ measurements using the AUC method is subject to several uncertainties (14). One of these is that, like the measurement of GFR using $^{51}\text{Cr-EDTA}$ method is subject to several uncertainties (12,13). The evaluation of AUC for free $^{99m}\text{Tc-MDP}$ depends on the assumption that the terminal exponential is reached by 2 h. If there is a delay, then values of $K_{\text{bone}}$ will be overestimated (19). A second reason for uncertainty in $K_{\text{bone}}$ measurements is whether the value of $k_4$ in Figure 1 is sufficiently small to justify the use of Equation 1 (14).

The aim of this study was to validate the accuracy of AUC measurements of $K_{\text{bone}}$ by comparing them with measurements performed using 2 $\gamma$-camera methods. The $\gamma$-camera techniques were the Patlak plot method (20) and a modified version of the $\gamma$-camera method described by Brenner et al. (12). Because of the delay in reaching equilibrium between $^{99m}\text{Tc-MDP}$ in blood and soft tissue (14), the Patlak method has a bias to overestimate and the Brenner method to underestimate the true value of $K_{\text{bone}}$. If the AUC method is quantitatively correct, the results should lie between the 2 $\gamma$-camera methods. A second aim of the study was to use the $\gamma$-camera data to measure $k_4$.

![FIGURE 1. Compartimental model describing whole-body kinetics of $^{99m}\text{Tc-MDP}$. Total plasma clearance is sum of $K_{\text{bone}}$ and $K_{\text{renal}}$.](image-url)
uptake of $^{99m}$Tc-MDP in soft tissue. A valid method for quantifying the soft-tissue uptake is described below.

**Data Analysis**

The soft-tissue retention of $^{99m}$Tc-MDP at time $t$ [$\text{ST}(t)$] is found by subtracting the amount of tracer in urine [$\text{U}(t)$] and bone [$\text{B}(t)$] from the initial injected activity $Q$:

$$ \text{ST}(t) = Q - \text{U}(t) - \text{B}(t) = Q - (K_{\text{renal}} + K_{\text{bone}}) \times \text{AUC}. \quad \text{Eq. 3} $$

The total $^{99m}$Tc-MDP plasma clearance was measured from the $\gamma$-camera data by plotting the 1-, 2-, 3-, and 4-h measurements of soft-tissue retention against AUC and extrapolating the straight-line fit to find the value of AUC (AUC$_1$) at the intercept on the horizontal axis (Fig. 2A). $K_{\text{total}}$ was calculated from the relationship:

$$ K_{\text{total}} = \frac{Q}{\text{AUC}_1}. \quad \text{Eq. 4} $$

The value of AUC$_1$ is independent of the scaling of the vertical axis in Figure 2A, and the true values of soft-tissue retention can be estimated by rescaling to make the intercept on the vertical axis 100%. The renal plasma clearance of $^{99m}$Tc-MDP ($K_{\text{renal}}$) was measured by a similar plot of the bladder- and kidney-corrected whole-body retention of $^{99m}$Tc-MDP and extrapolating the straight-line fit to find the value of AUC (AUC$_2$) at the intercept on the horizontal axis (Fig. 2B). $K_{\text{renal}}$ was calculated from the relationship:

$$ K_{\text{renal}} = \frac{Q}{\text{AUC}_2}. \quad \text{Eq. 5} $$

$K_{\text{bone}}$ was determined by subtracting $K_{\text{renal}}$ from $K_{\text{total}}$. Because of its use of the soft-tissue region of interest over the adductor muscles, we shall refer to this method of evaluating $K_{\text{bone}}$ as the Brenner method (12).

The Patlak plot (20) provides an alternative $\gamma$-camera method of determining whole-skeleton $K_{\text{bone}}$ by dividing the $^{99m}$Tc-MDP retention in bone and soft tissue and the AUC values by the total $^{99m}$Tc-MDP plasma concentration and fitting a straight line to the 2-, 3-, and 4-h points (Fig. 2C). $K_{\text{bone}}$ values were estimated from the slope of this line.

The predicted linear relationship between soft-tissue retention and AUC (Eq. 3) is exact only if $k_4 = 0$. It follows that any curvature in the plot shown in Figure 2A due to tracer passing from bone to soft tissue can be used to estimate the value of $k_4$. In the 22 patients with the 1-, 2-, 3-, and 4-h soft-tissue images, the data were analyzed by estimating the cumulative urine excretion of tracer at time $t$ from the equation (14):

$$ \text{U}(t) = K_{\text{renal}} \times \int_0^t \text{P}(\tau)d\tau. \quad \text{Eq. 6} $$

The retention of tracer in bone was estimated from the equation (14):

$$ \text{B}(t) = \alpha \times K_{\text{bone}} \times \int_0^t \text{P}(\tau)\exp^{-k_4(t-\tau)}d\tau. \quad \text{Eq. 7} $$

In Equations 6 and 7, $\tau$ is the time variable of integration and varies between 0 and $t$, with $t$ being the time point for which values of $\text{U}(t)$ and $\text{B}(t)$ are being determined. The values of $K_{\text{renal}}$ and $K_{\text{bone}}$ were those determined from Equations 4 and 5, and $\alpha$ is a scaling factor that adjusts the value of $K_{\text{bone}}$ to allow for the error in its determination due to the nonzero value of $k_4$ (14).
values of $U(t)$ and $B(t)$ are substituted in Equation 3, the ratio of the measured to the predicted values of the soft-tissue retention at each of the 4 time points is found as a function of $\alpha$ and $k_4$. The value of $\alpha$ was determined individually in each patient for each value of $k_4$ by requiring the slope of the plot of the ratio of the measured to predicted soft-tissue retention against time to be zero. The residual curvature was then used to find the optimum value of $k_4$ using a least-squares fit to the data in all 22 patients.

### Statistical Analysis

The agreement between the different methods of measuring GFR, $K_{total}$ and $K_{bone}$, was assessed using linear regression analysis and Bland–Altman plots (21). The 95% confidence interval (CI) in the measurement of $k_4$ was assessed using a $\chi^2$ test (19,22).

### RESULTS

Clinical reports of the 71 bone scan examinations gave the following interpretations: metastatic bone disease ($n = 22$), Paget’s disease ($n = 4$), fractures ($n = 8$), degenerative or inflammatory changes ($n = 34$), or normal findings ($n = 3$). γ-Camera measurements of $K_{renal}$ using Equation 5 were in close agreement with the $^{51}$Cr-EDTA measurements of GFR in the 10 patients studied (Fig. 3). The mean ($\pm$SD) for the γ-camera method was $62.8 \pm 18.2$ mL-min$^{-1}$, compared with $60.9 \pm 17.8$ mL-min$^{-1}$ for the $^{51}$Cr-EDTA measurements. When the value of $k_4$ was estimated from the ratio of the measured to the predicted values of soft-tissue retention for the 22 patients with the 1-, 2-, 3-, and 4-h static images of the adductor muscles, the minimum value of $\chi^2$ was $\chi^2_{min} = 0.64$ at $k_4 = 0.0003$ min$^{-1}$ (95% CI, $-0.0002 < k_4 < 0.0008$ min$^{-1}$) (Fig. 4). The minimum value of $\chi^2$ was within the expected range of values for 2 degrees of freedom (95% CI, 0.05 $< \chi^2 < 7.38$).

The mean value ($\pm$SD) of the total $^{99m}$Tc-MDP plasma clearance ($K_{total}$) obtained by the Brenner method was $112.1 \pm 45.6$ mL-min$^{-1}$, compared with $125.3 \pm 46.7$ mL-min$^{-1}$ obtained by the AUC method. When the 2 values of $K_{total}$ were plotted against each other (Fig. 5), a straight-line relationship was obtained with a correlation coefficient of 0.970. When linear regression analysis was performed, the intercept was not statistically significantly different from zero and a straight line fitted through the origin gave a slope of 0.901 (95% CI, 0.891–0.911). A similar evaluation for the Patlak method was performed by adding the γ-camera measurements of $K_{renal}$ to the Patlak plot measurements of $K_{bone}$ and plotting against the AUC values of $K_{total}$ (data not shown). A straight-line relationship through the origin was obtained with a correlation coefficient of 0.986 and a slope of 0.951 (95% CI, 0.944–0.958).

The mean ($\pm$SD) values of $K_{bone}$ determined using the 3 methods were 49.5 $\pm$ 32.1 mL-min$^{-1}$ for the Patlak method, 42.8 $\pm$ 32.0 mL-min$^{-1}$ for the Brenner method, and 56.0 $\pm$ 32.4 mL-min$^{-1}$ for the AUC method. A plot of the AUC value of $K_{bone}$ against the Patlak value gave a straight-line relationship with a correlation coefficient of 0.970 (Fig. 6A). A Bland–Altman plot gave a mean

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**FIGURE 3.** Scatter plot (A) and Bland–Altman plot (B) of values of GFR determined using $^{51}$Cr-EDTA, compared with equivalent values from whole-body retention measurements obtained using γ-camera in subset of 10 patients who participated in GFR investigation. Solid lines represent line of identity, and dashed lines represent mean and 95% CI.

**FIGURE 4.** Least-squares fit to 1-, 2-, 3-, and 4-h soft-tissue data from first 22 patients to determine value of $k_4$. Minimum value of $\chi^2$ was 0.64 at $k_4 = 0.0003$ min$^{-1}$; 95% CI ($-0.0002 < k_4 < 0.0008$ min$^{-1}$) was determined by adding 95% upper limit of $\chi^2$ for 1 degree of freedom (3.84) to $\chi^2_{min}$.

**FIGURE 5.** Scatter plot (A) and Bland–Altman plot (B) of values of $K_{total}$ determined using Brenner method vs. values of $K_{total}$ determined using AUC.
DISCUSSION

Although the quantification of $^{99m}$Tc-MDP studies using bone uptake measurements such as whole-body retention have been popular in the past (10–13), the measurement of bone plasma clearance provides a truer measure of the factors such as bone blood flow and osteoblastic activity that determine $^{99m}$Tc-MDP uptake in the skeleton (7). The limitation of bone uptake measurements is that they reflect merely the competition for a finite amount of tracer between the kidneys and different areas of the skeleton.

The simplest method of measuring the whole-skeleton clearance of $^{99m}$Tc-MDP is to measure the 0- to 4-h plasma clearance curve, with $^{51}$Cr-EDTA used as a cotracer to measure GFR (14,17,23). The AUC method can be used to evaluate the total (bone plus renal) clearance of $^{99m}$Tc-MDP, and the GFR can be subtracted from $K_{\text{total}}$ to give the value of $K_{\text{bone}}$ (14). However, the absolute accuracy of the resulting values of $K_{\text{bone}}$ is uncertain because of the assumption made that the 2- to 4-h points on the $^{99m}$Tc-MDP plasma curve represent the true terminal exponential. It is likely that, as is the case with $^{51}$Cr-EDTA measurements of GFR (19), the extrapolation of the 2- to 4-h data to infinity underestimates the true value of the AUC and results in overestimation of $K_{\text{bone}}$ values.

A second cause for uncertainty in $K_{\text{bone}}$ measurements using the AUC method is whether $k_d$ describing the flow of tracer from the bone compartment to plasma can be neglected (14). Fogelman and Martin (24) evaluated $k_d$ from whole-body retention measurements of $^{99m}$Tc-HEDP from 24 to 96 h in 10 patients and reported mean values of 0.00015 min$^{-1}$ in 4 patients with normal bone scan findings and 0.00007 min$^{-1}$ in 6 patients with abnormal scan findings. These values of $k_d$ correspond to biologic half-lives of 3–6 d, and if they also apply to the period from 0 to 4 h after injection, they have a negligible effect on the measurement of $K_{\text{bone}}$ (14). However, it is possible that on shorter time scales, values of $k_d$ might be significantly larger. When the soft-tissue data from the present study were used to measure $k_d$, the 95% CI was found to lie in the range of 0–0.0008 min$^{-1}$. The ending value of the range corresponds to a biologic half-life of 14 h and is sufficiently small to have only a minor effect on values of $K_{\text{bone}}$ estimated using the AUC method (14). The value of $k_d$ determined in this study was a collective value measured in a group of 22 patients, none of whom had any extensive bone disease. For statistical reasons, we were unable to provide any values of $k_d$ in individual patients. Fogelman and Martin (24) found that $k_d$ values were smaller in patients with more extensive disease. The situation in patients with osteolytic disease is unclear, but it is possible that $k_d$ values are increased.

In principle, the 0- to 4-h $^{99m}$Tc-MDP plasma clearance curve can be used to solve the compartmental model shown in Figure 1 for values of $K_{\text{bone}}$ and $k_d$ (15). In practice, however, the high correlation between the errors in the 2 parameters prevents this from being a practical method of evaluating either variable (14). Additional data are required to constrain values of $K_{\text{bone}}$ and $k_d$ and the present study was based on the premise that $\gamma$-camera measurements could provide such data. Two $\gamma$-camera methods were used to measure $K_{\text{bone}}$, one based on the Patlak plot method (20) and the other adapted from a method described by Brenner et al. (12) using quantification of soft-tissue uptake over the thighs. The $\gamma$-camera methods have several limitations— including the subtraction of counts from regions over the kidneys and bladder—that will not completely correct for urinary activity, because some scattered photons will still be counted outside these regions. In addition, both methods require equilibration between tracer in the vascular system and tracer in soft tissue to provide accurate values of $K_{\text{bone}}$.

However, the failure to reach full equilibration in the
required time causes opposite errors, with the Patlak method having a bias to overestimate and the Brenner method to underestimate the true value of $K_{\text{bone}}$.

As expected from the effects of tracer equilibration between plasma and soft tissue, the mean value of $K_{\text{bone}}$ estimated using the Patlak method was slightly higher than that estimated using the Brenner method (49.5 mL min$^{-1}$ vs. 42.8 mL min$^{-1}$). Also, as predicted from the expected underestimate of AUC from the extrapolation of the 2- to 4-h exponential, the mean value of $K_{\text{bone}}$ estimated using the AUC method was, at 56.0 mL min$^{-1}$, the highest of the 3 figures. The Bland–Altman plots showed that the AUC method overestimated Patlak values of $K_{\text{bone}}$ by an average of 6.5 mL min$^{-1}$ (Fig. 6B) and Brenner values by an average of 13.2 mL min$^{-1}$ (Fig. 6D). The overestimate of $K_{\text{bone}}$ by the AUC method is believed to be due to an error in determining the terminal exponential. This conclusion would be more definitive if it were supported by plasma data from later time points, but unfortunately, blood sampling was continued only until completion of the patients’ routine bone scan at 4 h. Given the range of different values of GFR, the correction for the underestimate of AUC is best made to $K_{\text{total}}$. If Equation 2 is modified to read:

$$K_{\text{bone}} = \beta \times K_{\text{total}} - \text{GFR}, \quad \text{Eq. \ 8}$$

then a factor $\beta = 0.90$ will make the AUC method agree with the Brenner method (Fig. 5A) and $\beta = 0.95$ will make it agree with the Patlak method.

There was no healthy group in this study, and therefore it is not possible to determine a reference range of values of $K_{\text{bone}}$. However, the mean value of $K_{\text{bone}}$ was determined in a group of 39 patients showing minimal changes on their bone scans. In patients with high bone turnover in, for example, extensive metastatic bone disease, one would expect to observe high values of $K_{\text{bone}}$ because $^{99m}$Tc-MDP is cleared more rapidly from plasma into the bone mineral compartment.

**CONCLUSION**

We have used whole-body and static $\gamma$-camera imaging to evaluate the accuracy of measurements of whole-skeleton $^{99m}$Tc-MDP plasma clearance made using the AUC method. When $k_d$ describing the backflow of tracer from bone to plasma was evaluated by quantifying soft-tissue uptake, the backflow was shown to be negligibly small. As expected, when the 2- to 4-h plasma data are assumed to represent the terminal exponential, slightly overestimated figures for $K_{\text{bone}}$ result. Corrections of $K_{\text{total}}$ values by factors in the range of 0.90–0.95 bring $K_{\text{bone}}$ values derived by the AUC method into agreement with those measured using the $\gamma$-camera.

**REFERENCES**