Stroke volume and EF are important factors for assessment of LV systolic function and provide information required for diagnosis and prognosis of cardiac diseases. Stroke volume is the volume of blood ejected during each heart contraction and is measured as the difference between the amount of blood within the ventricle at the end of filling (EDV) and the amount of blood that remains within the ventricle at the end of ejection (ESV). Various methods, including echocardiography, MDCT, single-photon emission CT, and CMRI are used to obtain accurate and reliable measurements of SV and EF.

**Objective**—To compare echocardiographic measurements of left ventricular (LV) volume obtained via a modified Simpson or Teichholz method with those obtained via dual-source CT (DSCT).

**Animals**—7 healthy Beagles.

**Procedures**—Each dog was anesthetized for DSCT; LV volume was determined from contrast-enhanced images of the LV lumen during all phases of contraction. Echocardiography was performed with dogs awake and anesthetized. End-diastolic volume (EDV), end-systolic volume (ESV), stroke volume, and ejection fraction were measured via a modified Simpson method and Teichholz method. Each dog was anesthetized twice with a 1-week interval between anesthetic sessions.

**Results**—Results obtained while dogs were anesthetized revealed that the modified Simpson method underestimated LV volume (mean ± SD EDV, 24.82 ± 2.38 mL; ESV, 12.24 ± 1.77 mL), compared with that estimated by the Teichholz method (EDV, 32.57 ± 2.85 mL; ESV, 14.87 ± 2.09 mL) or DSCT (EDV, 34.14 ± 1.57 mL; ESV, 16.71 ± 0.76 mL). Ejection fraction (modified Simpson method, 48.53% ± 4.24%; Teichholz method, 54.33% ± 4.26%; DSCT, 51.00% ± 2.71%) differed significantly among the 3 methods. Echocardiographic results obtained while dogs were awake revealed that EDV, ESV, and stroke volume differed significantly between the modified Simpson and Teichholz methods.

**Conclusions and Clinical Relevance**—LV volume determined via the Teichholz method was more similar to that determined via DSCT than was the LV volume determined via the modified Simpson method. The modified Simpson method underestimated LV volume, compared with that obtained via the Teichholz method, in both anesthetized and awake dogs. (Am J Vet Res 2013;74:62–69)

**ABBREVIATIONS**

<table>
<thead>
<tr>
<th>Acronym</th>
<th>Definition</th>
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<tbody>
<tr>
<td>BP</td>
<td>Blood pressure</td>
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<tr>
<td>CMRI</td>
<td>Cardiac MRI</td>
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<tr>
<td>DSCT</td>
<td>Dual-source CT</td>
</tr>
<tr>
<td>EDV</td>
<td>End-diastolic volume</td>
</tr>
<tr>
<td>EF</td>
<td>Ejection fraction</td>
</tr>
<tr>
<td>ESV</td>
<td>End-systolic volume</td>
</tr>
<tr>
<td>HR</td>
<td>Heart rate</td>
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<tr>
<td>LV</td>
<td>Left ventricular</td>
</tr>
<tr>
<td>MDCT</td>
<td>Multidetector CT</td>
</tr>
<tr>
<td>SV</td>
<td>Stroke volume</td>
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</table>

Left ventricular volume has been measured via both 2-D and 3-D echocardiography. The American Society of Echocardiography recommends use of the modified Simpson method for calculation of LV volume in humans, and this method has also been used for calculation of LV volume in various species of veterinary interest. However, the modified Simpson method is...
labor intensive; 2 (left apical 2-chamber and 4-chamber) planes of view are needed, and manual tracing of the endocardial border is required, which can be difficult because superimposition of the papillary muscles may obscure the endocardial border such that the long-axis of the LV is often foreshortened. In contrast to the modified Simpson method, obtaining LV M-mode images and calculation of LV volume are easier via the Teichholz method. Despite the technical advantages of the Teichholz method, its use for calculation of LV EF in clinical practice is controversial because volume measurement from linear dimensions of the left ventricle may be overestimated in patients with distorted ventricle and abnormal wall motions.10

Results of multiple studies11–13 suggest that a 64-slice MDCT is a feasible diagnostic tool for the combined assessment of coronary artery and LV function in humans. Calculation of LV volume via MDCT is almost as accurate as calculation of LV volume via CMRI, the current gold standard for determining LV volume.14,15 A disadvantage of the 64-slice MDCT is that it requires administration of a β-adrenoceptor antagonist to decrease the patient’s HR because motion-induced artifacts from a high HR decrease the quality of the cardiac image, which may impair LV measurements.

Dual-source CT was designed primarily to increase the temporal resolution of the CT system.16 The DSCT has 2 tubes and 2 detectors mounted at orthogonal orientations in the gantry such that the transmission data required for reconstruction of a single image can be acquired in half the time needed by a conventional spiral 64-slice MDCT. At a gantry rotation time of 0.33 seconds, the temporal resolution of the DSCT equals a quarter of the rotation time17; therefore, high-quality diagnostic cardiac images can be obtained with DSCT at a temporal resolution of 83 milliseconds independent of the patient’s HR and without administration of a β-adrenoceptor antagonist to the patient.

Results of multiple studies18–21 suggest that both DSCT and MDCT provide adequate images for accurate measurement of LV volume. In a study in which a moving heart phantom was evaluated via MRI, DSCT, and 64-slice MDCT, calculation of LV volume from images obtained via DSCT provided the closest approximation to the actual LV volume. Calculation of LV volume via images obtained from DSCT also approximated the actual LV volume in another study19 in which a moving heart phantom was used. Additionally, EF and SV determined from DSCT images were highly correlated with those values determined from CMRI images.20 Because EF and SV can be easily measured via CT with high temporal resolution, DSCT is a useful method to assess the diagnostic accuracy of LV volume measurements.18 Even though CMRI is the gold standard for measurement of cardiac volumes, it overestimates EDV and ESV structurally.21 To our knowledge, evaluation of the accuracy of DSCT for measurement of cardiac volume in species of veterinary interest has not been performed.

In our clinical practice, we have observed differences in LV volume measurements calculated by the modified Simpson method, compared with those calculated by the Teichholz method. The purpose of the study reported here was to evaluate the accuracy of echocardiography for the measurement of EDV, ESV, SV, and EF via both the modified Simpson and Teichholz methods, compared with the measurement of those values via DSCT in anesthetized dogs. We also compared echocardiographic measurements of EDV, ESV, EF, and SV calculated via the modified Simpson method with those calculated via the Teichholz method in awake dogs.

Materials and Methods

Animals—Seven Beagles (6 males and 1 female) that weighed from 9.0 to 10.5 kg and ranged from 18 to 24 months of age were used for the study. Each dog was considered healthy on the basis of results of a physical examination, CBC, serum biochemical analysis, thoracic radiography, and ECG. All study protocols were approved by the Institutional Animal Care and Use Committee of Konkuk University.

Anesthesia protocol—Anesthesia was induced in each dog with medetomidine (20 μg/kg, IV). Each dog was then intubated, and anesthesia was maintained with 1.5% isoflurane in 100% oxygen. While anesthetized, each dog’s cardiac function was monitored via ECG, and BP was monitored with an oscillometric method via a cuff applied to a forelimb. Each dog was anesthetized twice (once for echocardiography and once for DSCT) with at least a 1-week interval between anesthetic sessions.

DSCT evaluation—An 18-gauge catheter was placed in a cephalic vein of each anesthetized dog immediately prior to DSCT examination. Anesthetized dogs were positioned in dorsal recumbency on the CT table, and a DSCT examination was performed. Thoracic images were obtained of the region from the origin of the aorta to the cardiac apex for initial measurement of LV volume. A test bolus of iopromide contrast medium (4 to 5 mL) was then administered at a rate of 1.5 mL/s through the catheter in the cephalic vein via a dual-head power injector to determine the time to peak contrast. Subsequently, a 3-phase bolus was administered at a rate of 2.0 mL/s, IV. The first phase consisted of iopromide (2 mL/kg), followed by 10 to 15 mL of a mixture of iopromide contrast medium and saline (0.9% NaCl) solution (60:40) and, finally, 10 mL of saline solution.

To prevent motion artifacts on the CT images, each dog was ventilated with positive pressure (tidal volume, 15 mL/kg) for 1 second to stimulate a brief holding of breath at the end of inspiration, during which images were acquired. Dual-source CT scanner settings were as follows: detector collimation, 2 × 32 × 0.6 mm; slice acquisition, 2 × 0.6 × 0.6 mm by means of a z-flying local spot; gantry rotation time, 330 milliseconds; pitch, 0.22; tube voltage, 100 kV; and tube current-time product, 320 mA/rotation.

A retrospective gating technique was used for synchronization of data reconstruction with the ECG signal. A monosegment ECG gating algorithm was implemented that used data from both CT sources such that 10 axial data sets were reconstructed for each 10th percentile (range, 0 to 90th percentile) of the cardiac volume.
cycle. Axial images were reconstructed with an effective slice thickness of 2 mm and a reconstruction increment of 2 mm. The data sets were then transferred to an external workstation where the contrast-enhanced LV lumen on each CT image was painted via manual editing. The EDV, ESV, EF, and SV were automatically measured by means of a threshold-based 3-D segmentation algorithm on the basis of the painted LV volume (Figure 1). All assessments of the DSCT data sets were performed by 2 experienced veterinary radiologists (YK and SK) who were unaware of the DSCT results for each dog.

Transthoracic echocardiography—Echocardiography was performed on each dog twice (once with the dog awake and once with the dog anesthetized) with a 1-week interval between echocardiographic examinations. All echocardiographic examinations were performed by 2 veterinary radiologists (ML and JJ) who were unaware of the DSCT results for each dog.

Transthoracic echocardiography was performed with a 7-MHz sector transducer.1 Each dog was initially positioned in left lateral recumbency, and the left apical 2- and 4-chamber images were obtained for LV volume calculation via the modified Simpson method. The dog was then positioned in right lateral recumbency, and the right parasternal 5-chamber image was obtained for LV volume calculation via the Teichholz method from M-mode images.

For each dog during echocardiography, a simultaneous lead II ECG was recorded and superimposed on the monitor display. The 2-D echocardiographic images were used to calculate LV EDV and ESV via the modified Simpson method, and the M-mode echocardiographic images were used to calculate LV EDV and ESV via the Teichholz method. For the modified Simpson method, the end-diastolic and end-systolic endocardial border was manually traced on both the left apical 2- and 4-chamber images; the end-diastolic image was defined as the image obtained immediately after mitral valve closure and the end-systolic image was defined as the image obtained immediately before mitral valve opening. The endocardial border was traced carefully to avoid inclusion of the papillary muscles.10 The M-mode images were obtained with 2-D guidance, and endocardial measurements were made via the leading edge–to–leading edge method. All echocardiographic examinations and measurements were performed in accordance with guidelines established by the American Society of Echocardiography; the mean of 3 representative measurements obtained at the end of expiration was used as the value for each area measured.

Statistical analysis—Statistical analyses were performed with computer software.3 The mean ± SD was reported for each continuous variable. For data obtained while the dogs were anesthetized, differences among the mean values for the 3 methods (DSCT, modified Simpson method, and Teichholz method) used to calculate LV volume were compared via repeated measures ANOVA, and post hoc analyses were performed by means of a Tukey test and Duncan multiple range test. Bland-Altman analyses were used to display the systematic error and the limits of agreement among the 3 methods used to calculate LV volume. The extent of agreement between the echocardiographic measurements obtained by the 2 radiologists was assessed with Pearson correlation coefficients. For echocardiographic data, the LV volume measured while dogs were awake was compared with the LV volume measured while dogs were anesthetized.

![Figure 1—Representative DSCT images of the left side of the heart of a healthy adult Beagle from the region of the origin of the aorta to the apex of the left ventricle that depict application of the threshold-based 3-D segmentation algorithm for measurement of LV volume at the end of diastole (A) and end of systole (B). Notice the contrast-enhanced LV lumen has been painted blue via manual editing to assist with determination of LV volume. Bar = 3 cm.](image)

Table 1—Mean ± SD LV EDV, ESV, SV, and EF as measured from DSCT images and echocardiographic images via the modified Simpson method and Teichholz method for 7 healthy Beagles while awake and anesthetized.

<table>
<thead>
<tr>
<th>Variable</th>
<th>Method</th>
<th>Awake</th>
<th>Anesthetized</th>
<th>P value*</th>
</tr>
</thead>
<tbody>
<tr>
<td>EDV (mL)</td>
<td>DSCT</td>
<td>—</td>
<td>34.14 ± 1.57*</td>
<td>—</td>
</tr>
<tr>
<td></td>
<td>Modified Simpson</td>
<td>23.07 ± 1.10</td>
<td>24.62 ± 2.38*</td>
<td>0.15</td>
</tr>
<tr>
<td></td>
<td>Teichholz</td>
<td>34.51 ± 2.36</td>
<td>32.57 ± 2.85*</td>
<td>0.16</td>
</tr>
<tr>
<td>ESV (mL)</td>
<td>DSCT</td>
<td>—</td>
<td>16.71 ± 0.76*</td>
<td>—</td>
</tr>
<tr>
<td></td>
<td>Modified Simpson</td>
<td>7.16 ± 1.17</td>
<td>12.24 ± 1.77*</td>
<td>0.001</td>
</tr>
<tr>
<td></td>
<td>Teichholz</td>
<td>11.14 ± 2.36</td>
<td>14.87 ± 2.09*</td>
<td>0.02</td>
</tr>
<tr>
<td>SV (mL)</td>
<td>DSCT</td>
<td>—</td>
<td>17.43 ± 1.51*</td>
<td>—</td>
</tr>
<tr>
<td></td>
<td>Modified Simpson</td>
<td>15.91 ± 1.33</td>
<td>12.07 ± 1.45*</td>
<td>0.01</td>
</tr>
<tr>
<td></td>
<td>Teichholz</td>
<td>23.37 ± 1.73</td>
<td>17.70 ± 1.82*</td>
<td>0.01</td>
</tr>
<tr>
<td>EF (%)</td>
<td>DSCT</td>
<td>—</td>
<td>51.00 ± 2.71*</td>
<td>—</td>
</tr>
<tr>
<td></td>
<td>Modified Simpson</td>
<td>68.97 ± 4.74</td>
<td>48.53 ± 4.24*</td>
<td>0.01</td>
</tr>
<tr>
<td></td>
<td>Teichholz</td>
<td>67.87 ± 5.52</td>
<td>54.33 ± 4.28*</td>
<td>0.01</td>
</tr>
</tbody>
</table>

*Comparison of awake values with anesthetized values via a paired t test.

— Not determined.

Dual-source CT was only performed on anesthetized dogs. Each dog was anesthetized twice (once for DSCT examination and once for echocardiographic examination) with at least a 1-week interval between anesthetic sessions.

The original article is available at the American Journal of Veterinary Research (AJVR).
tized via a paired t test. For all analyses, values of $P < 0.05$ were considered significant.

**Results**

Mean LV volumes determined from DSCT images and echocardiographic images via the modified Simpson method and Teichholz method were summarized (Table 1). While anesthetized, the mean ± SD HR for the study dogs was $73 ± 21$ beats/min, $79 ± 13$ beats/min, and $74 ± 20$ beats/min for the DSCT, modified Simpson, and Teichholz methods, respectively, and did not vary significantly among the 3 methods. The mean ± SD BP was $115 ± 11.34$ mm Hg, $118 ± 7.39$ mm Hg, and $104.86 ± 9.03$ mm Hg for the DSCT, modified Simpson, and Teichholz methods, respectively, and did not vary significantly among the 3 methods. During the echocardiographic examinations that were performed while the dogs were awake, the mean ± SD HR and BP for the dogs

![Figure 2 parts G and H appear on the next page](image-url)
were 98 ± 17 beats/min and 137.71 ± 7.63 mm Hg, respectively.

Results of the Bland-Altman analyses, which calculated the mean differences in LV volume determined from DSCT images, compared with those determined from echocardiographic images via the modified Simpson method and Teichholz method, were plotted (Figure 2). Evaluation of the Bland-Altman plots revealed no systematic error.

For LV volumes obtained while dogs were anesthetized, the EDV, ESV, and SV calculated via the modified Simpson method were significantly lower than those calculated via the Teichholz method or DSCT (Table 1). The EF calculated via the modified Simpson method was the lowest, compared with the EFs calculated via the Teichholz method and DSCT. However, the EF calculated via the modified Simpson method did not differ significantly from the EF calculated via DSCT but did differ significantly from the EF calculated via the Teichholz method. For LV volumes obtained while the dogs were awake, the EDV, ESV, and SV calculated via the modified Simpson method were generally lower, compared with those calculated via the Teichholz method.

Mean EDV measured while the dogs were awake did not differ significantly from the mean EDV measured while the dogs were anesthetized, regardless of whether it was calculated by the modified Simpson method or Teichholz method (Table 1). Mean ESV measured while the dogs were awake was significantly lower, compared with the mean ESV measured while the dogs were anesthetized, for both the modified Simpson method and Teichholz method. Conversely, the mean SV and EF measured while the dogs were awake were significantly higher, compared with the mean SV and EF measured while the dogs were anesthetized, for both the modified Simpson method and Teichholz method.

### Interobserver variability of LV volume measurements

Interobserver correlation coefficients for LV volumes obtained via echocardiography ranged from 0.72 to 0.82. Interobserver correlation coefficients for LV volumes obtained via DSCT were 0.93 for EDV, 0.92 for ESV, 0.94 for SV, and 0.93 for EF.

### Discussion

In the present study, the modified Simpson method consistently underestimated LV EDV, ESV, and SV, compared with those values calculated via the Teichholz method or DSCT while dogs were anesthetized. Similarly, for echocardiographic measurements obtained while dogs were awake, EDV, ESV, and SV calculated via the modified Simpson method were significantly lower, compared with those calculated via the Teichholz method. Mean EDV, ESV, and SV calculated via the Teichholz method were more similar to those calculated via DSCT, compared with the mean EDV, ESV, and SV calculated via the modified Simpson method. However, evaluation of Bland-Altman analyses revealed that the precision of measurements calculated via the Teichholz method was low. Although the modified Simpson method is currently recommended for the calculation of LV volume in patients with ischemic heart disease, clinical interpretation of results obtained by this method should be done with caution given that the modified Simpson method consistently underestimated LV volume in the present study.

Results of another study indicate that LV EDV, ESV, and EF measured via a 64-slice MDCT were more strongly correlated with those measured via the gold standard, CMRI, compared with those obtained via 2-D echocardiography with the modified Simpson method. The authors of that study attributed the poor correlation between LV volumes determined via the modified Simpson method and those determined via CMRI to the fact that the modified Simpson method is subjective and dependent on the operator’s experience and interpretation as well as image clarity.

Several other errors are inherent in the modified Simpson method for determination of LV volume. The modified Simpson method assumes that the shape of the LV lumen is a truncated ellipsoid; unfortunately, even the LV lumen of a healthy heart rarely conforms well to that geometric shape. Also, it is difficult to visualize the lateral portion of the LV apex on 2-D echocardiography.
cardiography. Thus, it is difficult to accurately trace the endocardial border in the region of the LV apex, and evaluators often fail to recognize and avoid foreshortening of the left ventricle when measurements are obtained. Moreover, results of another study indicated that LV volumes obtained via 2-D echocardiography with the modified Simpson method did not correlate as well with those obtained via 64-slice MDCT as did LV volumes obtained via 3-D echocardiography.

In contrast to the modified Simpson method, the Teichholz method is a simple manual method, for which the cardiac images required for calculation of LV volume are easily obtained and reproduced. The Teichholz method assumes that the shape of the left ventricle is an ellipse, and most clinically normal LV lumens conform well with those obtained via 64-slice MDCT as did LV volumes measured via 2-D echocardiography.

The threshold-based 3-D segmentation algorithm is a function of the volume of contrast medium contained in the left ventricle. High attenuation differences between the myocardium and contrast medium in combination with near isotropic CT data allow threshold-based segmentation of the left ventricle. Segmentation of the left ventricle can be performed with little user interaction, which allows for quick calculation of global LV functional parameters.

Measurements of LV volume via the Teichholz method or DSCT may occasionally be overestimated. The Teichholz method uses M-mode images to measure ventricular dimensions at the end of diastole and end of systole. The measurement can be inaccurate if the M-mode cursor is positioned incorrectly because measurements in 1 dimension may not be representative of the entire LV chamber. Therefore, the Teichholz method is not recommended for human patients with cardiac dysfunction because ischemic heart disease may dramatically distort the chamber configuration or for dogs with mitral valve disease because the shape of the LV in affected dogs progressively changes from elliptical to globoid. The threshold 3-D segmentation algorithm of DSCT requires homogeneous opacification of the LV lumen because a large difference in the attenuation values for the LV lumen and myocardial wall is necessary for accurate delineation of the endocardium. Excessive administration of a contrast medium during DSCT may result in infiltration of the contrast medium into the endocardium such that the endocardial border becomes obscured and LV volume is overestimated. In the present study, we used healthy dogs that had no evidence of abnormal LV shape and an appropriate dose of contrast medium; therefore, we believe overestimation of LV volume via either the Teichholz method or DSCT was unlikely.

Results of another study indicate that the Teichholz method overestimates LV volume, compared with the LV volumes determined via 2-D echocardiography and real-time 3-D echocardiography, whereas LV EDV and ESV measured via real-time 3-D echocardiography were similar to those measured via 2-D echocardiography. Unfortunately, LV volume was not measured by a gold standard such as CMRI in that study; therefore, it was not possible to determine whether the LV volume measured via the Teichholz method overestimated the actual LV volume or whether the LV volumes measured via 2-D echocardiography and real-time 3-D echocardiography underestimated the actual LV volume. In studies that involved human patients in which LV volumes measured via 2-D echocardiography and real-time 3-D echocardiography were compared with LV volume measured via CMRI (gold standard), 2-D echocardiography more frequently underestimated LV volume than did real-time 3-D echocardiography. Because the modified Simpson method is performed on 2-D echocardiographic images, we believe it will tend to underestimate LV volume.

In the present study, the mean EF and SV calculated while the dogs were awake were significantly greater than those calculated while the dogs were anesthetized, whereas the mean ESV calculated while the dogs were awake was significantly lower than the mean ESV calculated while the dogs were anesthetized. This was most likely a consequence of the administration of medetomidine, an α2-adrenoceptor agonist, for anesthetic induction; medetomidine induces bradycardia, which in turn affects LV function. On the basis of the results of the present study, it appears that both medetomidine and isoflurane have negative effects on LV systolic function. Conversely, anesthesia had no effect on LV diastolic function as evidenced by the fact that the mean EDV calculated while the dogs were anesthetized did not differ significantly from the mean EDV calculated while the dogs were awake. Additional research is necessary to determine why anesthesia had no effect on EDV.

A limitation of the present study was that CMRI, which is currently considered the gold standard for measurement of LV volume, was not performed; therefore, we cannot make any definitive interpretations regarding the accuracy of the measurements of LV volume obtained via any of the 3 methods evaluated. Another limitation was the possibility that the contrast medium injected for ventricular attenuation may have caused negative inotropic effects during DSCT scanning.

To our knowledge, the present study was the first to compare measurement of LV volume in dogs via DSCT with that via 2 echocardiographic methods, the modified Simpson method and the Teichholz method. Despite the fact that the Teichholz method for measurement of LV volume is controversial, the results of the present study suggested that LV volume calculated via the Teichholz method was more similar to that calculated via DSCT than was the LV volume calculated via the modified Simpson method. Assuming that the LV volume measurements obtained via DSCT were accurate, the results of the present study indicated that the modified Simpson method underestimates LV volume. Moreover, the modified Simpson method underestimated LV volume, compared with the LV volume calculated...
via the Teichholz method, while dogs were both awake and anesthetized.

b. Domitor, Pfizer Korea, Seoul, Republic of Korea.
d. Cardell 9401 veterinary vital signs monitor, Midmark Corp, Tampa, Fla.e. Somatom Definition, Siemens Medical Solutions, Forchheim, Germany.
f. Ultravist 370, Bayer Healthcare Pharmaceuticals, Berlin, Germany.
g. Stellant D, Medrad Inc, Indianola, Pa.

References
10. Lang RM, Bierig M, Devereux R, et al. Recommendations for chamber quantification: a report from the American Society of Echocardiography’s Guidelines and Standards Committee and the Chamber Quantification Writing Group, developed in conjunction with the European Association of Echocardiography, a branch of the European Society of Cardiology. J Am Soc Echocardiogr 2005;18:1440–1463.