The decision to operate on a patient with an asymptomatic abdominal aortic aneurysm (AAA) involves weighing the risks of rupture against those of operative repair. Although cohort studies indicate that rupture is related to maximum AAA diameter (Dmax), growth rate, and blood pressure (BP), none of these variables reliably predicts the behavior of individual aneurysms.1 Because no size of AAA is entirely free from risk of rupture, a variable that provides a more precise quantification of risk is required. Previous work has suggested that AAA wall compliance (expressed as elastic strain modulus \([E_p]\) and stiffness and measured by means of a commercially available ultrasound echo-tracking system [Diamove; Teltec AB, Sweden]) may be related to future growth rate and risk of rupture.2

Compliance is a measure of the relationship between stress (force per unit area of wall) and strain (fractional deformation of wall). In the context of the normal arterial wall, compliance is most accurately described by the change in volume of a segment of artery in relation to pulsatile change in BP.3 However, measurement of changes in wall thickness in response to changes in pressure and vessel volume are necessary to calculate true vessel compliance.4 At present, neither variable can be reliably measured in the aorta in vivo. Arterial wall distensibility (which describes the relationship between relative diameter growth rate, and blood pressure (BP), none of these variables reliably predicts the behavior of individual aneurysms.1 Because no size of AAA is entirely free from risk of rupture, a variable that provides a more precise quantification of risk is required. Previous work has suggested that AAA wall compliance (expressed as elastic strain modulus \([E_p]\) and stiffness and measured by means of a commercially available ultrasound echo-tracking system [Diamove; Teltec AB, Sweden]) may be related to future growth rate and risk of rupture.2

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change and pressure) has been used by a number of researchers\textsuperscript{4-6} as a surrogate measure of compliance. Peterson et al\textsuperscript{3} introduced the equation $E_p = K \frac{(P_{\text{systolic}} - P_{\text{diastolic}})}{([D_{\text{systolic}} - D_{\text{diastolic}}]/D_{\text{diastolic}})}$, where $K = 133.3$, $P$ = pressure, and $D$ = aortic diameter. $E_p$ is a measure of the structural distensibility of the artery, rather than a measure of the elasticity of the arterial wall material.\textsuperscript{4}

Hayashi\textsuperscript{7} proposed the term stiffness ($\beta$) to describe the viscoelastic behavior of arteries within the physiologic pressure range: $\beta = \ln(P_{\text{systolic}}/P_{\text{diastolic}})/([D_{\text{systolic}} - D_{\text{diastolic}}]/D_{\text{diastolic}})$. Both $E_p$ and stiffness are inversely related to distensibility and compliance. These concepts are discussed more fully in two recent reviews.\textsuperscript{8,9}

Measurement of aortic compliance with the use of an echo-tracking device (Diamove) is reproducible in healthy subjects with no aneurysm.\textsuperscript{10} However, this may not be true in patients with AAA because of cardiorespiratory comorbidity, obesity, and variable aneurysm morphologic condition. Preliminary data have suggested a relationship between aortic compliance, future growth, and rupture.\textsuperscript{2} However, before it can be used to aid the selection of patients for repair, it is essential to quantify the reproducibility of this method. The aim of this study therefore was to examine, for the first time, the intraobserver and interobserver variability associated with a commercial ultrasonic phase-locked echo-tracker in the measurement of AAA compliance with the use of an ultrasound echo-tracking technique.

**METHODS**

The use of the echo-tracking ultrasound system (Diamove) has been discussed in detail previously.\textsuperscript{8,11-14} A 3.5-MHz linear array transducer was used to provide a standard real-time B-scan image. The transducer was placed over the AAA to obtain a longitudinal section at the point of maximal anteroposterior diameter. The anterior and posterior vessel walls were echo tracked after the initial placement of a cursor within the vessel (Fig 1). During the tracking, the ultrasound pulses were time shared equally between the B-scan image and the A-scan line of interest, allowing the pulsatile changes in vessel diameter to be monitored. A phase-locked loop restored the position of an electronic gate relative to the moving echo; the compensatory movement of the gate yielded the movement of the echo.

Electronic gates were represented on the screen by two cursors. These locked onto the echoes from the posterior lumen/wall interface of the anterior wall and the anterior interface of the posterior wall of the AAA and subsequently measured the Dmax. The output signal from the echo-tracking circuits represented the distance between the vessel walls. The repetition frequency was 870 Hz, producing a time resolution of 1.15 msec. The calculated smallest detectable movement was 8 $\mu$m. Data acquisition and analysis were performed on a Pentium 24X computer (Datalink Computers, Edinburgh, Scotland). The pressure-diameter curve was registered on the computer in real time, and at least three consecutive waves were analyzed. The Diamove software automatically identified the start and end of each cardiac cycle. The operator manually selected the wave forms of interest, and an average wave was produced (Fig 2). Brachial artery pressures were entered, and the derived variables, including $E_p$ and stiffness, were then displayed on the screen. Pulse pressure and diameter change were calculated by Diamove.

BP was measured from the brachial artery in the right arm with a hand-held sphygmomanometer. The right arm was used to prevent bias, based on the assumption that neither arm was more prone to hemodynamically significant vascular disease. The cuff was wrapped around the upper arm and inflated.
until the radial pulse could no longer be felt. The stethoscope was placed over the brachial artery at the antecubital fossa. Systolic pressure was registered as the pressure where the first Korotkoff sounds (phase 1) were heard, although cuff pressure was reduced. Diastolic pressure was registered as the pressure where the final Korotkoff sounds (phase 5) disappeared.¹⁵

Two recordings of diameter change over 4 to 11 seconds were collected on each patient, during each session, with brachial artery pressure measured each time. The best of the two pressure-diameter traces was selected for analysis on the basis of the following criteria: (1) The maximum diameter measurements were within 5% of the estimated value (estimated diameter being taken from a static image of systolic diameter) or 2 mm, if the aneurysm was less than 4 cm wide; (2) at least three consecutive cardiac cycles producing uniform waves were available for analysis; (3) any obvious arrhythmias were excluded; and (4) if all of above were the same, the wave form with the largest diameter and pulsatile diameter change was selected because this was assumed to indicate the point of highest stress: strain ratio.

Observer A underwent 5 months of training in the Departments of Radiology and Vascular Surgery at the University of Edinburgh. Observer B received 2 months of training in the Department of Vascular Surgery at the University of Edinburgh before the study began.

Observers were blind to Dmax, Ep, and stiffness because these variables were only shown on the computer screen once analysis had been performed at the end of the study. The observers examined each patient alone and were therefore blind to each other’s BP measurements.

Ethics committee approval was given for this study, and informed written consent was obtained from each patient.

Data collection

Study 1. Observer A performed two AAA compliance measurements during two sessions 30 to 60 minutes apart on each of 13 patients during a single visit to the Vascular Studies Unit.

Study 2. Observers A and B performed two AAA compliance measurements on a further 23 patients during each of two visits to the Vascular Studies Unit.

Statistical methods. Data were analyzed with the use of a statistical package (SPSS-X; SPSS, Inc, Chicago, Ill).¹⁶ Medians of the variables in studies 1 and 2 were compared with the Wilcoxon signed rank test to check for systematic bias between the sessions and the observers. The coefficient of variation expresses the SD of a single set of measurements as a percentage of the sample mean. However, in this study, we undertook to express the degree of variability between two sets of measured data. For that reason Bland and Altman’s coefficient of variation of method error (CVₘₑ)¹⁷ was used. Spearman’s rank correlation coefficient¹⁷ was used to assess the linear association of all measurements between and within observers and visits.
RESULTS

**Study 1: Intraobserver variation.** Table I shows the median and interquartile range of the variables measured by observer A during sessions 1 and 2. There were no statistically significant differences between the first and second sessions with regard to the distributions of any of the compliance measurements. The intraobserver CVME values for measurements by observer A were low for the directly measured variables (systolic BP, 7.3%; diastolic BP, 5.4%; and Dmax, 2.6%). The intraobserver CVME values of the derived variables were higher (Ep, 21.2%, stiffness, 17.6%, and diameter change, 18.2%).

**Study 2: Interobserver variability.** Table II shows the median and interquartile range for variables when measured by each observer at each session. Significant interobserver differences were only found in diastolic BP at visit 2 and Dmax at visit 1. Intra- and interobserver measurement of Dmax demonstrated a significant and high degree of correlation (r \( \geq 0.96 \) and r \( \geq 0.94 \), respectively). CVME values for intraobserver and interobserver variation were 10% or less for the variables directly measured by the observers (diastolic BP, systolic BP, and Dmax) and 35% or less for the mathematically derived parameters (Table IV). However, when the values were log transformed before the calculation of the CVME value, the CVME value was much reduced. For example, stiffness in Table IV became, for observer A, 10.2%, for observer B, 8.6%, for visit 1, 6.6%, and for visit 2, 10.22%. This is not the correct usage of this test; we have only calculated stiffness to show the effect of skewness on CVME values.

**DISCUSSION**

There were no statistically significant differences in intraobserver measurements of any of the compliance variables. Significant interobserver differences were only found in diastolic BP at visit 2 and Dmax at visit 1. Intra- and interobserver CVME values for
directly measured variables were low (≤ 10%), although CVME values for the derived variables were higher (≤ 35%). Variability of the Diamove echo-tracking device has not previously been reported in patients with AAA. However, present data are comparable with those obtained in a previous methodologic study that used healthy subjects with normal aortas (Table V). A third study also investigated aortic compliance in four young (aged, ≤ 35 years) subjects with no aneurysm and reported on four compliance measurements from each subject during one visit. These authors expressed their methodologic error for $E_p$ and stiffness in terms of SD. SD was not appropriate for the analysis of this group of subjects with AAA because compliance measurements were not normally distributed and were highly variable. The results of Lanne et al are therefore less comparable with the present findings than those of Hansen et al. The present study is also unique in that measurements were taken in two distinct sessions up to 2 weeks apart.

BP and maximum aortic diameter were the two variables directly measured by the observers and therefore the only variables that were prone to observer bias. The low CVME value for these variables indicates that this echo-tracking equipment can be reliably used in the follow-up of AAA maximal diameter. There may, however, be some random error in the values calculated for $E_p$ and stiffness because these are derived values and are thus not directly measured. The use of brachial artery pressure rather than central aortic pressure will tend to underestimate $E_p$ and stiffness. However, the error will be systematic, affecting all patients approximately equally. Invasive measurement of aortic pressure is not practicable for routine compliance follow-up. Most previous studies that used Doppler phase-locked loop echo tracking have assumed that brachial BP is consistently related to aortic pressure.

### Table III

Median and interquartile range of variables obtained at two sessions by two observers and Spearman’s rank correlation coefficients for intraobserver and interobserver measurements of parameters in study 2

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Median (IQR)</th>
<th>Intraobserver correlation (r)</th>
<th>Interobserver correlation (r)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Observer A</td>
<td>Observer B</td>
<td>Visit 1</td>
</tr>
<tr>
<td>Systolic BP (mm Hg)</td>
<td>140 (123-153)</td>
<td>0.62*</td>
<td>0.81*</td>
</tr>
<tr>
<td>Diastolic BP (mm Hg)</td>
<td>78 (70-84)</td>
<td>0.81*</td>
<td>0.78*</td>
</tr>
<tr>
<td>Pulse pressure (mm Hg)</td>
<td>58 (50-73)</td>
<td>0.50*</td>
<td>0.83*</td>
</tr>
<tr>
<td>Maximum diameter (mm)</td>
<td>51.6 (45-55)</td>
<td>0.98*</td>
<td>0.96*</td>
</tr>
<tr>
<td>Diameter change (mm)</td>
<td>1.3 (0.86-2.0)</td>
<td>0.85*</td>
<td>0.77*</td>
</tr>
<tr>
<td>Elasticity ($10^5$ N/m²)</td>
<td>3.1 (2.1-4.6)</td>
<td>0.64‡</td>
<td>0.62‡</td>
</tr>
<tr>
<td>Stiffness</td>
<td>22.3 (15.5-32.6)</td>
<td>0.71*</td>
<td>0.68*</td>
</tr>
</tbody>
</table>

IQR, Interquartile range; P ≤ .001
*P ≤ .001
†P ≤ .05
‡P ≤ .01

### Table IV

Coefficients of variation of method error (CVME) between intraobserver and interobserver measurements of BP, aortic diameter and diameter change, elasticity, and stiffness from study 2

<table>
<thead>
<tr>
<th>CVME</th>
<th>Intraobserver (%)</th>
<th>Interobserver (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Observer A</td>
<td>Observer B</td>
</tr>
<tr>
<td>Systolic BP</td>
<td>10.0</td>
<td>8.5</td>
</tr>
<tr>
<td>Diastolic BP</td>
<td>7.0</td>
<td>7.8</td>
</tr>
<tr>
<td>Pulse pressure</td>
<td>23.0</td>
<td>13.4</td>
</tr>
<tr>
<td>Maximum diameter</td>
<td>2.2</td>
<td>3.5</td>
</tr>
<tr>
<td>Diameter change</td>
<td>18.2</td>
<td>27.0</td>
</tr>
<tr>
<td>Elasticity ($10^5$ N/m²)</td>
<td>35.3</td>
<td>26.0</td>
</tr>
<tr>
<td>Stiffness</td>
<td>32.0</td>
<td>25.6</td>
</tr>
</tbody>
</table>
The high CV_ME values of both Ep and stiffness must be viewed in the context of the wide range of compliance observed in this particular study group (Table I). For example, Ep varied by a factor of 12.75, ranging from 0.74 to 9.44 \(10^5\) N/m², and stiffness varied by a factor of 12.0, ranging from 5.6 to 66.8 \(10^5\) N/m². It should also be noted that, with the exception of BP, the variables measured were all skewed to the right. Because there is no nonparametric equivalent of the CV_ME value, the effect of this skewness on the values of CV_ME cannot be ascertained. However, if a logarithmic transformation had been applied to the data before the CV_ME value was calculated, the resultant CV_ME value would have been substantially reduced. For example, the nontransformed CV_ME value from observer A for intraobserver stiffness was 32% and for observer B, 25.6%. After transformation, these CV_ME values were 10.2% and 8.6% respectively. The use of the CV_ME value calculated from transformed data does not allow direct comparison of variabilities with previous studies. However, it does suggest that the Bland and Altman\(^{17}\) test for CV_ME value is not applicable to skewed data. More importantly for this study, it also suggests that the high level of variation is in fact due to the large variation of Ep and stiffness within the study population rather than because of the technique. The diameter and compliance variations that were observed between visits in study 2 may also reflect a certain degree of real variation in AAA wall movement.

When the raw data were examined, there were two particular subjects in whom markedly different diameters were measured; these patients were difficult to scan because of obesity and cardiac and respiratory disease. We did not remove these subjects from the study because it would have biased the assessment of reproducibility. Nevertheless, approximately 10% of these study subjects could not be satisfactorily scanned because of the factors mentioned earlier. Excluding such patients would have increased the apparent reproducibility of the technique.

The longitudinal view of the AAA was more informative than the transverse because it allowed a true anteroposterior measurement to be made perpendicular to the aneurysms' long axis. Three compliance measurements were made at each examination. Each was slightly different because of slight differences in probe position and because the cursors inevitably locked onto different layers of the wall. Slight changes in the angle of the probe may also have increased the variability of diameter change, but this was not investigated specifically in this study.

The echo-tracking technique involves placing the cursors onto the echoes of the anterior and posterior walls while the vessel is moving with each cardiac cycle. Tracking of the same points within the wall structure is difficult because the quality of the B-mode imaging does not allow easy differentiation between thrombus, calcification, intima, and media. It is likely that improvements in the image quality and echo-tracking technology will reduce the effect of these factors on reproducibility.

The learning curve associated with echo-tracking compliance measurements was steep for observer A who had no previous experience with ultrasonic scanning. However, intensive training by radiology staff in the recognition of abdominal structures and variations in AAA wall morphologic features meant that the curve leveled off after about 3 months. At this point, the measurements from observer A were within 2 mm of those reported by the ultrasound department. Observer B was subsequently taught the technique by observer A. This may have introduced some systematic bias into the study, although observer B had previous experience scanning AAA, thus reducing the learning curve considerably. At the time of the study, observer A had 2 years of experience with the equipment; observer B had 3 months of experience because it was not possible to
provide a longer training period. This also may have contributed to the intraobserver CV ME values (Table IV).

To date the effect of intraluminal thrombus has not been specifically studied. At present, it is not possible to measure thrombus volume with ultrasound scanning. However, the ratio of AAA volume to thrombus can be measured by computed tomography, and the effect of thrombus on AAA wall compliance is currently being studied.

There are therefore many factors that might influence AAA compliance. As such, it is perhaps unsurprising that the CV ME values were high. However, the following selection criteria can be used to minimize variability: (1) The maximum diameter measurements should be within 5% of the estimated value or 2 mm, if the aneurysm is less than 4 cm wide; (2) at least three consecutive cardiac cycles producing uniform waves should be selected for analysis; and (3) obvious arrhythmias should be excluded. It is recommended that both intraobserver and interobserver variability should be measured, albeit in a small number of subjects, in any study of compliance. Variability should be reassessed regularly.

These results suggest that the Diamove echo-tracking technique is a reliable method of measuring AAA diameter (to within 2%-3.5% of the true value), and pulsatile diameter change, enabling calculation of Ep and stiffness. The clinical utility of these variables is currently being investigated in a prospective natural history study of 220 subjects with AAA to determine whether compliance is related to future growth and/or rupture.

We thank Mrs Eileen Kerracher for her assistance in the collection of these data.

REFERENCES

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