Ultrafast Three-Dimensional Ultrasound
Application to Carotid Artery Imaging

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Background and Purpose—Three-dimensional (3-D) vascular ultrasound can be expected to improve qualitative evaluation of vessel pathology and to provide quantitative data on vascular morphology and function. The objective of this study was to develop an ultrafast 3-D vascular system and to validate its performance for quantitation of atherosclerosis and assessment of regional arterial distensibility.

Methods—The quantitative analysis of focal atherosclerotic lesions was validated in vitro on 27 phantoms of fibroadipous plaques of known volume (range, 100 to 600 mm$^3$). In vivo reproducibility of plaque volume measurement was tested in 33 patients who had a total of 47 predominantly fibroadipous carotid plaques. Distensibility assessment was validated indirectly through the evaluation of age-related changes in distensibility of common carotid artery in healthy and hypertensive subjects (25 men in each group).

Results—The volume of plaque phantoms measured from the 3-D data set showed a very close correlation with the true volume ($r=0.99$; $y=0.96x+12.38$; $P<0.01$), with the mean difference between the 2 measurements being $-3.12\pm15.1$ mm$^3$. High reproducibility was found for measurement of carotid plaque volume in vivo: the mean difference between measurements from 2 observers for the same data set was $0.60\pm11.2$ mm$^3$. Indexes of arterial distensibility decreased with age in healthy population, whereas this relationship was lost in hypertensive subjects.

Conclusions—Ultrafast 3-D ultrasound imaging of carotid artery demonstrates good accuracy and reproducibility for atherosclerotic plaque volume measurements. The system also allows the study of age-related degenerative vascular changes. (Stroke. 1998;29:1631-1637.)

Key Words: ultrasonics ■ carotid arteries ■ atherosclerosis ■ imaging

Severities of extracranial carotid atherosclerosis have been shown to be not only a major cause of ischemic cerebral events but also a reliable marker of systemic atherosclerosis.1-3 Ultrasound is increasingly used as the primary method for assessing the severity of disease in carotid artery, since it represents a noninvasive and inexpensive method, is easy to perform with adequate reproducibility, and is capable of delineation of intraluminal anatomy and assessment of the extent of the atherosclerotic process.4,5 However, because the vessel and the plaque it contains represent a complex 3-D structure, and since plaque commonly develops asymmetrically, plaque severity and luminal narrowing may be overestimated or underestimated with 2-D imaging.6 Further improvement in the qualitative and quantitative capabilities of ultrasound may be based on the 3-D approach.7-9

3-D vascular imaging can be expected to improve assessment of luminal geometry and disease process, since a 3-D data set can be freely rotated and examined along multiple planes and tomographic sections. 3-D vascular ultrasound may also contribute to assessment of the progression of atherosclerosis and age-related degenerative vascular changes through plaque volume quantification and evaluation of regional arterial distensibility.

This study was designed to address the following objectives: (1) to develop a prototype of a 3-D ultrasound system for vascular imaging capable of fast and simple acquisition and elaboration of data, (2) to assess the accuracy of the 3-D system for quantitative measurements in an in vitro phantom model of atherosclerosis, and (3) to assess the clinical applicability of the system in the evaluation of carotid artery morphology and distensibility.

Methods

Description of the System

We developed a system for controlled acquisition of multiple sequential tomographic 2-D images of the vessel and consequent elaboration of acquired data. This system was integrated into conventional US equipment (Esaote S.p.A., Florence, Italy) so that no external or additional carriage motion device or image processing board is required.

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In our system, a controlled sequential tomographic data acquisition is performed by scanning in a fanlike motion. Linear array of the high-frequency transducer (7.5/10 MHz) sweeps over an arc up to 65° in programmable steps. In each step, which can be as narrow as 1°, a 2-D vascular image is acquired. During acquisition, the long axis of the probe is aligned with the long axis of the vessel (Figure 1). The movement of the 3-D transducer is guided by a stepper motor built inside the probe and controlled by the ultrasound equipment; no external motion device is required. The dimensions of the probe are comparable to those of the conventional linear probe.

Image acquisition can be either asynchronous or synchronous with ECG. Asynchronous acquisition takes about 2 seconds, since it depends only on frame rate and velocity of the stepper motor of the probe (<10 ms per step). Acquisition synchronous with ECG is an acquisition of sequences of 2-D images temporally located in the cardiac cycle at different angular positions of the probe. The number of images captured in 1 cardiac cycle depends on heart rate and frame rate and varies from 16 to 18, with heart rate varying from 55 to 100 bpm. The time required for synchronous acquisition is about 1 minute because it depends on heart rate and the angle of acquisition. The sequential tomographic 2-D images are stored in a digital format using a small pixel matrix of 512 × 512 and 8-bit gray scale to preserve high image definition. During image processing, which is immediate, a realignment of 2-D images according to their position in space and in the cardiac cycle is performed, and volumetric data set information is calculated.

The 3-D data set is reconstructed with a reference system relative to the alignment of the probe. When a section through the volume data is chosen, coordinates are transformed to generate the reference system relative to the selected section. Any desired section independent of the position of the probe during data acquisition (“any plane” sectioning), as well as a number of parallel and equidistant cross sections in selected vessel segments (“paraplane” sectioning), can be computed and reconstructed by a digital processing board in nearly real time. Interpolation is used to fill the gaps between tomographic sections.

Data are displayed as a 3-D data set, which can be freely rotated along 3 orthogonal axes, and 2-D tomographic sections, which can be obtained along longitudinal, transverse, and oblique planes (Figure 2). The presentation of the 3-D data set and 2-D sections is static for the acquisition asynchronous with ECG and dynamic (cine-loop display) for the acquisition synchronous with ECG. The latter type of acquisition allows the frame-by-frame overview of a dynamic sequence of cross sections in 1 cardiac cycle, representing the systo-diastolic expansion and contraction of the vessel.

Quantitative Analysis

Volume measurement is performed through computer-guided direct planimetry. The system automatically divides the length of the measured vessel segment into N parallel and equidistant slices. The volume of N cylinders is calculated as follows:

\[
V = \sum_{i=1}^{N} A_i \times H.
\]

Dynamic presentation of the 3-D data set and any selected transverse section allows frame-by-frame display of the sequence of 2-D cross sections in 1 cardiac cycle (from 8 to 16 frames depending on heart rate) and the evaluation of the luminal area in each frame (Figure 3). This feature can be used to assess the changes in vessel area during 1 cardiac cycle (ie, in relation to systo-diastolic changes in distending pressure) so that indexes of arterial distensibility can be calculated as follows:

\[
\text{Pressure-Strain Elastic Modulus (kPa)} = \frac{\Delta p}{\Delta \text{Area}_{\text{avg}}},
\]

where \(\Delta \text{Area}_{\text{avg}}\) is the systo-diastolic difference in arterial area, \(\text{Area}_{\text{avg}}\) is the average arterial area, \(\Delta p\) is the systo-diastolic pressure difference, and \(V\) is the volume.

Figure 1. Scheme of data acquisition with 3-D vascular probe. See text for explanation.

Figure 2. Data display: 3-D data set (upper left quadrant), longitudinal display of the vessel (upper right quadrant), and 2 reconstructed transverse sections (lower quadrants). Selected transverse sections are indicated by 2 dotted lines. Top, Internal carotid artery with several plaques. The luminal geometry of the plaque can be seen in reconstructed transverse sections, where the external carotid artery and its atherosclerotic changes are also evident, even though the vessel is not displayed in 3-D data set and longitudinal section. Rotation of the entire data set along the x axis displays the external carotid artery in 3-D data set and long axis (bottom). In the 3-D data set shown in the bottom panel, the internal carotid artery is hidden behind the external; however, its reconstructed cross sections are visualized in the lower quadrants.
in arterial pressure; and Area\textsubscript{avg}, average value of arterial area throughout cardiac cycle.

**In Vitro Study**

Twenty-seven phantoms of fibroadipous plaque were prepared. They consisted of pieces of bovine fibro-fatty tissue of known volume (range, 100 to 600 mm\(^3\)) measured by Archimedes’ principle. Phantoms were inserted into cylindrical tubes (polyurethane) of known diameter (range, 4.5 to 8 mm; ie, corresponding to the wide diameter range of extracranial carotid vessels), and tubes were filled with saline. Each tube was placed into a block of 1.2% agar-agar\(^1\) in such a way that the distance of the tube from the superior surface of the agar block was 1.5 cm and that from 1 of the lateral surfaces was 2.5 cm. 3-D acquisition was performed twice, once with the probe placed on the superior surface of the agar block and once with the probe placed on its lateral surface; during both acquisitions, the long axis of the probe was aligned with the long axis of the tube (Figure 4). Thus, 54 data sets were used for validation. Intraindividual variability of measurement was assessed in 45 phantom volumes with an interval between the 2 readings of at least 1 month. Interindividual variability was tested in 32 phantom volumes.

**Clinical Study**

Interindividually and intraindividual variability of in vivo carotid plaque volume measurement was assessed in 33 patients (21 men; mean age, 65±14 years) who had a total of 47 plaques (range, 7 to 450 mm\(^3\)) in either right or left common, internal, or external carotid artery. Plaques were classified as minor (lumen reduction ≤50%) and predominantly fibroadipous (Figure 5). In the entire data set of 47 plaques, repeated measurements were performed on the same 3-D data set; in 16 plaques (range, 12 to 237 mm\(^3\)), repeated measurements also were performed on 2 different data acquisitions.

**Figure 3.** Two of 16 frames displaying changes in arterial cross-sectional area during 1 cardiac cycle in a selected segment of the vessel. Frame 1 (top) corresponds to the minimum cross section (21.6 mm\(^2\)), while frame 5 (bottom) represents maximum area (25.4 mm\(^2\)).

**Figure 4.** Example of fibroadipous plaque phantom volume measurement. Top, 3-D data set, longitudinal section, and 2 different reconstructed transverse sections. Bottom, Direct planimetry of 1 parallel slice at the level of the yellow dotted line.

**Figure 5.** Example of plaque volume measurement in vivo. The length of the plaque (indicated by 2 green dotted lines) was electronically divided into 13 equidistant slices. Each slice was displayed in transverse section, and plaque area was manually traced.
The performance of the 3-D prototype for arterial distensibility assessment was tested in 25 healthy control subjects (all men; mean age, 42.8 ± 18.4 years) and in 25 hypertensive subjects (all men; mean age, 59.1 ± 13.6 years; \( P < 0.05 \) versus control) without regional atherosclerotic changes in carotid vessels. At the time of the study, blood pressure in hypertensive subjects was controlled by \( \beta \)-blocker therapy, since our goal was to compare the 2 groups at the same level of distending pressure.\(^\text{16} \) In all subjects, the right common carotid artery was studied at 2 different segments, the first 1 cm and the second 3 cm distal to flow divider. In both segments, a dynamic sequence of transverse sections in 1 cardiac cycle was displayed, and in each frame the luminal area was manually traced (Figure 3). The intima-media thickness of the far wall of the common carotid artery was measured at the same vascular level as area changes, but in longitudinal display.\(^\text{17} \)

Before the acquisition, all subjects were allowed to relax in the supine position for at least 20 minutes, and 3-D acquisition was performed when blood pressure, monitored at the site of brachial artery (Dinamap 845-XT), was stable. Intraindividual variability of measurements was assessed in 20 subjects, with an interval of at least 1 month between the readings of the same 3-D data set. Interindividual variability was assessed in 12 subjects. In both populations studied, the correlations of age with systolic blood pressure, pulse pressure, intima-media thickness, diastolic cross-sectional area, carotid strain, and pressure-strain elastic modulus were evaluated.

**Data Analysis**

Data are expressed as mean ± SD. For multiple comparisons, ANOVA was used as appropriate; to assess statistical significance between groups, Scheffé’s \( t \) test was applied, with \( P < 0.05 \) considered significant. Regression analysis was performed using a simple linear model. The agreement between 2 readings was evaluated by estimating the consistent bias between readings, as recommended by Bland and Altman.\(^\text{18} \) Statistical analysis was performed using commercially available software (StatView SE+ Graphics, Abacus Concepts Inc).

**Results**

**In Vitro Study**

In all phantoms, high-quality images were obtained (Figure 4). The phantom volume ranged from 100 to 600 mm\(^3\), with a mean value of 264.8 ± 157.7 mm\(^3\) by Archimedes’ principle, and from 92.2 to 597.5 mm\(^3\), with a mean value of 267.5 ± 152.6 mm\(^3\) by direct planimetry from 3-D data set. The correlation between the 2 measurements was high \((r = 0.99, y = 0.96x + 12.38; P < 0.01)\). Mean difference was \(-3.12 ± 15.1\) mm\(^3\) (range, \(-29.1\) to 28.0 mm\(^3\)) or 6.9 ± 6.7%, respectively, with good agreement between the 2 measurements, since all points but 2 were within ±2SD of the mean difference. No differences in phantom volume were observed between 2 different acquisitions of the same phantom \((269.2 ± 153.8\) versus 265.8 ± 154.2 mm\(^3\), \( P = 0.45)\).

Intraobserver and interobserver agreement was good (for both, \( r = 0.99\) and \( P < 0.01\)) with a mean percent difference of 3.5 ± 2.9% and 5.8 ± 4.7%, respectively. A plot of the differences between the 2 observers in each volume measurement against the mean of the 2 measurements showed a mean difference of \(-0.81 ± 15.2\) mm\(^3\) (range, \(-18.7\) to 33.7 mm\(^3\)), with good agreement (all points but 3 within ±2 SD of the mean difference).

**Clinical Study**

**Plaque Volume Measurement**

In all patients, good-quality 3-D images and tomographic sections were obtained. The ability to scroll through the 3-D data set and to stop at any desired segment facilitated the evaluation of the luminal geometry (Figure 6). The rotation of the entire data set along 3 orthogonal axes facilitated the visualization of both internal and external carotid arteries independently of their spatial relationship (Figure 2).
Blood Pressure, Carotid Geometry, and Distensibility Indexes in Healthy and Hypertensive Subjects

<table>
<thead>
<tr>
<th></th>
<th>Healthy Control (n=19)</th>
<th>Hypertensive (n=19)</th>
<th>P</th>
</tr>
</thead>
<tbody>
<tr>
<td>Systolic blood pressure, mm Hg</td>
<td>130.2±17.4</td>
<td>144.8±13.5</td>
<td>0.05</td>
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<tr>
<td>Diastolic blood pressure, mm Hg</td>
<td>74.9±10.2</td>
<td>77.2±12.4</td>
<td>NS</td>
</tr>
<tr>
<td>Pulse pressure, mm Hg</td>
<td>55.2±12.5</td>
<td>67.6±15.9</td>
<td>0.05</td>
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<tr>
<td>Diastolic cross section, mm²</td>
<td></td>
<td></td>
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<tr>
<td>Segment 1</td>
<td>25.3±9.7</td>
<td>28.9±10.5</td>
<td>NS</td>
</tr>
<tr>
<td>Segment 2</td>
<td>24.1±7.3</td>
<td>27.8±9.9</td>
<td>NS</td>
</tr>
<tr>
<td>Intima-media thickness, cm</td>
<td></td>
<td></td>
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</tr>
<tr>
<td>Segment 1</td>
<td>0.69±0.17</td>
<td>1.05±0.51</td>
<td>0.01</td>
</tr>
<tr>
<td>Segment 2</td>
<td>0.70±0.19</td>
<td>0.97±0.21</td>
<td>0.01</td>
</tr>
<tr>
<td>Carotid strain, %</td>
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<td></td>
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<tr>
<td>Segment 1</td>
<td>17.4±5.5</td>
<td>10.6±2.5</td>
<td>0.01</td>
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<tr>
<td>Segment 2</td>
<td>16.9±4.8</td>
<td>10.7±2.7</td>
<td>0.01</td>
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<tr>
<td>Pressure-strain modulus, kPa</td>
<td></td>
<td></td>
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</tr>
<tr>
<td>Segment 1</td>
<td>52.1±21.9</td>
<td>98.9±37.8</td>
<td>0.01</td>
</tr>
<tr>
<td>Segment 2</td>
<td>52.6±19.9</td>
<td>97.8±32.9</td>
<td>0.01</td>
</tr>
</tbody>
</table>

Carotid plaque volume ranged from 7.4 to 435.1 mm³, with a mean value of 109.4±101.4 mm³, when measured by the first observer and from 7.7 to 449.0 mm³, with a mean value of 109.7±104.2 mm³, according to the second observer. The correlation between the 2 observers was high (r=0.99, y=1.02x−2.03; P<0.01). Mean difference was 0.60±11.2 mm³ (range, −32.3 to 27.0 mm³) or 6.4±4.1%, respectively, with good agreement, since all points but 4 were within ±2SD of the mean difference.

Intraobserver agreement was high (r=0.99, y=1.03x−1.89; P<0.01), with a mean difference of −1.4±6.2 mm³ (range, −17.2 to 14.3 mm³) or 4.0±2.7%, respectively, and good agreement between the 2 readings (all points but 4 were within ±2SD of the mean difference).

Agreement for plaque volume measured by the same observer in 2 different data sets (or acquisitions, respectively) was also good (r=0.99; y=1.01x+0.47); mean difference was 1.36±4.8 mm³ or 6.1±4.1%, respectively.

Assessment of Arterial Distensibility

Good-quality dynamic 3-D volume sets and 2-D tomographic sections were obtained in 19 of 25 healthy control subjects and 19 of 25 hypertensive subjects; in 12 of 50 subjects (24%), the presence of respiratory artifacts prevented the accurate measurement of vessel area changes. Even during therapy, systolic pressure of hypertensive subjects was still higher than that of control subjects, whereas no difference was observed for diastolic pressure. As a result, pulse pressure was higher in hypertensive subjects (Table).

The values of carotid strain and pressure-strain elastic modulus, as well as intima-media thickness, are reported in the Table. No differences were observed between the 2 segments of right carotid artery evaluated, whereas significant differences were found between healthy control and hypertensive subjects. In healthy control subjects, age correlated directly with systolic blood pressure (r=0.52, P<0.05) but not with pulse pressure, and with intima-media thickness (r=0.69, P<0.01), diastolic carotid cross section (r=0.48, P<0.05), and pressure-strain elastic modulus (r=0.79, P<0.01), and it correlated inversely with carotid strain (r=0.86, P<0.01). In hypertensive subjects, age correlated directly with systolic blood pressure (r=0.56, P<0.05), pulse pressure (r=0.57, P<0.05), and pressure-strain elastic modulus (r=0.50, P<0.05) but not with intima-media thickness, carotid cross section, and carotid strain.

Intraindividual variability of measurements was 6.3±4.8% for carotid strain and 6.4±4.6% for pressure-strain elastic modulus. The correlation between the 2 measurements was good (r=0.96 and r=0.97, P<0.01 for both), and the mean difference was −0.17±1.31% (range, −3.4% to 2.6%) and 0.84±0.35 kPa (range, −6.79 to 15.59 kPa).

Interindvidual variability was 9.6±8.0% for carotid strain and 9.8±8.5% for pressure-strain elastic modulus. Correlation between the 2 observers was r=0.94 and r=0.98 (P<0.01 for both). Mean difference was 1.06±1.91% (range, −1.1% to 4.6%) and 0.65±7.99 kPa (range, −9.87 to 17.86 kPa), with good agreement (all points but 1 within ±2SD of the mean difference).

Discussion

This study of a prototype of a 3-D vascular system demonstrates that such a system (1) can be of clinical interest in patients with carotid artery disease because it delineates the presence and extent of carotid atherosclerosis, (2) yields reliable and reproducible quantitative data, and (3) may be used for assessment of regional arterial distensibility.

The ability to slice and reslice the acquired 3-D data set in any desired plane and segment and to rotate the data set along 3 orthogonal axes allows the assessment of luminal geometry and vascular pathology from a single data acquisition (Figures 2 and 6). In this way, the distribution and shape of atherosclerotic lesions can be better appreciated. In addition to its use in qualitative evaluation of the disease process, a 3-D system allows the collection of quantitative data on vascular morphology and function, thus offering a more comprehensive insight into carotid artery disease.

Carotid Atherosclerosis

An important clinical contribution of the 3-D vascular approach is represented by the opportunity to study the progression and regression of the atherosclerotic process. Quantitative analysis of atherosclerotic plaque may provide information on the natural history of atherosclerosis and the effectiveness of lifestyle and pharmacological interventions,19,22 potentially useful for epidemiological and follow-up studies.

Thus far, B-mode vascular ultrasound has presented methodological difficulties for serial evaluation of the extent of atherosclerosis, since the slight differences in probe position in consecutive examinations of the same patient may influence spatial definition of atherosclerotic plaque and hence its quantification.6,23 Acquisition of an entire 3-D data set containing information about spatial distribution of the plaque...
should overcome this problem. In an in vitro validation on plaque phantoms, very good accuracy and reproducibility of volume measurements were achieved. The reproducibility of measurements also was confirmed in the clinical study on carotid atherosclerotic process.

**Arterial Distensibility**

Assessment of arterial compliance or distensibility is supposed to provide clinically relevant information on biological age, early atherosclerotic changes, vascular changes associated with systemic hypertension, and the effectiveness of lifestyle and drug interventions.\(^5,6,16,24–28\) Compliance represents the change in vessel volume per unit change in pressure. Because the change in arterial long axis during the cardiac cycle is minimal, the monitoring of arterial cross section may be adequate for estimation of arterial distensibility.

Because no gold standard method exists for distensibility assessment, we performed an indirect validation of the system by comparing the mechanical properties of the common carotid artery and their relationship with age in normotensive and hypertensive subjects. Age and hypertension are reported to increase large-artery stiffness.\(^16,27–31\)

Our results are in agreement with previous data.\(^13,14,25–27,30,31\)

In healthy populations, carotid intima-media thickness and cross section increased and indexes of carotid distensibility worsened with advancing age. In hypertensive populations, the relationship between age and morphological or functional characteristics of the carotid artery was not significant, since the correlation observed between age and pressure-strain elastic modulus was probably related only to age-dependent increase in pulse pressure. These findings suggest that chronically elevated blood pressure accelerates the degenerative process in arterial wall and modifies age-related changes in large arteries.

Furthermore, regional carotid distensibility was significantly decreased in hypertensive subjects compared with a healthy population, and the difference between the 2 populations was much greater than the reproducibility limits of the technique. However, looking at these results, we must take into account the fact that elastic modulus can change significantly with distending pressure,\(^32,33\) and pulse pressure was still significantly higher in hypertensive subjects compared with healthy men despite pretreatment with \(\beta\)-blockers.

**Comparison With Other Diagnostic Systems**

3-D reconstruction of the vessels and atherosclerotic plaques has been attempted using other systems,\(^7,8,19,20,34\) some of which also applied volume-rendering methods to display vessels and plaques in a 3-D perspective. These systems required external carriage motion devices and image processing boards; consequently, data acquisition and elaboration were much more demanding and time-consuming. We suppose that the most important contribution of a 3-D approach for vascular diagnosis is the possibility of electronic “any plane” and “paraplane” sectioning of the 3-D data set. However, a volume-rendering algorithm can be easily applied to the data set collected by our system, since all needed information is already available.

Echo-tracking systems were used recently for assessment of arterial distensibility.\(^13,16,25,29,31\) The advantages of these systems are high temporal and spatial resolution. On the other hand, they evaluate pulse pressure–dependent changes of the vessel in 1 dimension only, assuming isotropic behavior of the arterial segment. This assumption is not completely met because the vessel has a complex 3-D structure that can have different pressure-strain relationships in different directions.\(^32\)

A dynamic 3-D system evaluating changes in arterial luminal cross section may provide more accurate information; however, its temporal resolution is lower because it allows the acquisition of no more than 16 frames per cardiac cycle.

**System and Study Limitations**

The lateral resolution of the system is inferior to axial resolution because the transverse focalization of the linear array is controlled by the silicon lens only and thus is fixed, whereas a longitudinal focalization is dynamically swept in electronic way.

When a dynamic presentation of data volume is used, the image acquisition should be synchronized with respiration. In \(~25\%\) of subjects, appropriate dynamic images could not be obtained because of respiratory artifacts. A significant improvement may be expected from the superimposition of the arterial pressure curve captured during dynamic 3-D acquisition.

The implementation of an automated or semiautomated border detection technique in the assessment of plaque volume and arterial distensibility can be expected to reduce the time of analysis and subjectivity of manual tracing and to provide a further advance in collection of volumetric data for distensibility measurement.

In the present study, the feasibility of plaque volume measurement was evaluated in minor predominantly fibro-dipous plaques, since we believe that assessment of the progression or regression of atherosclerotic process can be studied in this type of atherosclerotic alterations. Therefore, on the basis of our results, we cannot comment on the accuracy of the system in quantification of severe and calcified atherosclerotic changes.

**Conclusion**

A 3-D vascular approach capable of fast and easy volume data acquisition and real-time interactive tomographic sectioning in any desired plane, together with quantitative estimation of plaque volume and arterial distensibility, allows better evaluation and quantification of vascular morphology and function. Above all, this approach may be promising for the study of the atherosclerotic process in humans because it allows accurate quantitative assessment of atherosclerotic lesions together with evaluation of regional arterial distensibility. Changes in local distensibility of the vessel are known to anticipate the development of macroscopic lesions.\(^35\)

However, further improvements are needed to increase the feasibility and accuracy of the system, including automated border detection technique, synchronization with respiratory wave, and superimposition of the blood pressure curve on digitized vascular images.
References

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