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Vessel wall and blood flow dynamics in arterial disease

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Recent developments in ultrasound techniques have made it possible to investigate patients with arterial disease non-invasively by using Doppler blood velocity signal analysis. Since January 1979, 189 patients with pre-stroke syndromes have been investigated by using pulsed Doppler and real-time B-mode ultrasound imaging and waveform analysis. The results were that both imaging systems were highly (more than 92%) sensitive and specific when compared with conventional carotid arteriography. The ultrasound systems detected turbulence and could also be used to measure the distensibility of the arterial wall. The results show that varying grades of carotid stenosis can be demonstrated by two ultrasonic imaging systems, and that lateral scans are particularly helpful.

Introduction

Cerebrovascular disease is the third most frequent cause of death in England (Haberman *et al.* 1979) and Wales, with over 70% of strokes being due to thromboembolism (Kannel *et al.* 1970). The contribution of extracranial atherosclerotic disease in the causation of stroke has been recognized only in the last 30 years (Fields *et al.* 1968; Fisher 1951; Yorks 1961). Recent investigation established that up to 88% of patients have estracranial artery lesions (Hutchinson & Acheson 1975; Eisenberg *et al.* 1977), with the majority situated at the carotid artery bifurcation (Hass *et al.* 1968). Carotid artery lesions produce cerebral ischaemia by two mechanisms: (1) by subtotal stenosis or occlusion and (2) by platelet and cholesterol emboli generated on atheromatous plaques.

As there is no known treatment to limit or reverse cerebral infarction once it has occurred, effective prevention must depend on early recognition and treatment of high-risk groups with extracranial disease. Fortunately, not all strokes occur without warning and there are pre-stroke syndromes, namely transient ischaemic attacks (t.i.as), amaurosis fugax and asymptomatic bruits, which warrant investigation in an effort to prevent stroke. However, approximately half the patients with t.i.as and two-thirds with asymptomatic bruits will not proceed to stroke if left untreated. Critical to the selection for preventative measures is the identification of significant precursors of stroke. This can be achieved by more accurate characterization of the carotid lesions.

Recent developments in ultrasound techniques have made it possible to investigate patients with arterial disease non-invasively by using Doppler blood velocity signal analysis (Woodcock *et al.* 1972; Blackshear *et al.* 1979; Baird *et al.* 1980) and direct imaging of atheromatous lesions

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at specific sites (Fish 1972; Mozersky *et al.* 1971; Barnes *et al.* 1976; Baird *et al.* 1979; Lusby 1980; Sumner *et al.* 1979). We report the use of these techniques for detecting carotid artery lesions and for defining the factors that may contribute to cerebral infarction.

Materials and methods

Since January 1979, 189 patients with pre-stroke syndromes have been investigated in the vascular laboratory of the Bristol Royal Infirmary. Two ultrasound imaging systems have been used.

Pulsed Doppler system

Mavis, a 30 channel, range-gated, 5 MHz pulsed Doppler system, was developed by Fish (1972). The 30 gates can be adjusted to a suitable depth and the movement of blood detected by the Doppler shift principle in any or all of the gates. By moving the probe manually across

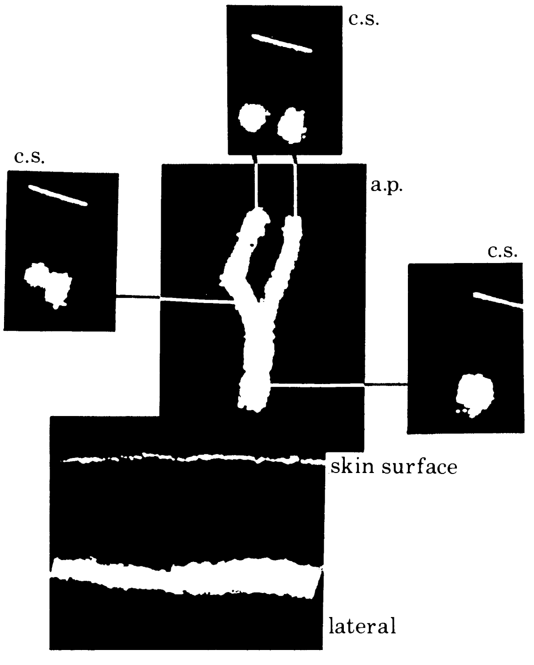

Figure 1. Mavis pulsed Doppler projections in lateral, antero-posterior (a.p.) and cross-sectional (c.s.) planes.

the skin, an image of the moving column of blood is built up on a storage oscilloscope, a permanent record of which is made with a Polaroid photograph. The machine is directional, producing separate images of arterial blood moving towards the beam and venous blood moving away. Images can be produced in three orthogonal planes (figure 1). The resolution is of the order of 1 mm.

Real-time B-mode imaging

The Duplex real-time mechanical scanner produces a two-dimensional B-mode image from three 5 MHz transducers, which rotate in a plastic boot. The images obtained in longitudinal or cross-sectional planes are displayed on an oscilloscope. Superimposed on the display is a line corresponding to the location of a depth-sensitive pulsed 5 MHz ultrasound beam (figure 2), which can be adjusted to provide signals from selected sites for analysis. A photocopy of a frozen image is obtained for the permanent record. The Duplex scanner also has the facility for generating time–position M-mode scans. In this mode, echoes are recorded from moving structures such as the vessel walls and displayed as vertical deflexions (Lusby *et al.* 1981). The vessel wall distensibility with each pulse can therefore be displayed dynamically on the screen. By adding a scale, changes in vessel diameter with each pulse can be quantified. By using the B-mode scan the vessel to be observed was clearly identified and distensibility measured in the common carotid and at the origin of the internal carotid arteries.

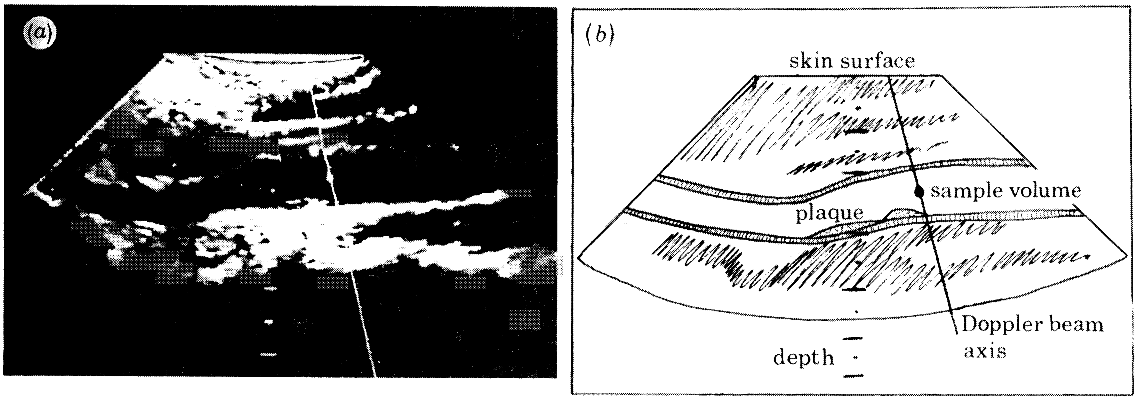

Figure 2. Duplex scan (*a*) of carotid artery with diagram (*b*) showing the pulsed Doppler beam and Doppler sample volume.

For more information about the dynamic properties of the carotid bifurcation, biplanar video tape recordings and cineangiography films at 50 frames per second were made during the injection of contrast into 12 carotid arteries of patients undergoing investigation for t.i.as. To ensure complete mixing of contrast material with blood and to limit boundary layer separation, the catheter tip was placed in the proximal common carotid artery near its origin from the aortic arch.

To evaluate the morphology of the carotid bifurcation and its relation to ultasonic and angiographic images, Perspex casts impregnated with barium were made from endarterectomy specimens of patients undergoing carotid surgery and from vessels obtained at post-mortem.

Results

Ultrasonic imaging

Both imaging systems provided images of the vessels without discomfort or complication and were highly acceptable to the patients; 71 patients subsequently underwent angiography, at the discretion of the referring physician, with corroboration of the ultrasonic findings in 68 patients (90%). A detailed prospective evaluation of the systems was done on 78 vessels in which three planar angiography was performed, each being reported on independently without knowledge of the other findings (Lusby *et al.* 1980, 1981).

Pulsed Doppler imaging

Results with Mavis imaging and angiography are compared in table 1. Of 43 lesions causing less than 50% decrease in vessel diameter, 39 (91%) were detected. There were four false negatives, i.e. lesions detected angiographically but missed on ultrasound imaging; two were associated with atheromatous plaques in bulbous origins of the internal carotid artery. The lateral scan was better at detecting lesions situated on the posterior wall and provided diagnostic information in 20 vessels (48%) with less than 50% decrease in diameter. All five occlusions of the internal carotid artery were detected.

Duplex B-mode imaging

Duplex imaging and angiography are compared in table 2. While 39 lesions (91%) were detected, four were given a classification of variance with that for angiography. All lesions with more than 50% diameter decrease were detected, but only four out of five of those that were totally occluded.

TABLE 1. MAVIS PULSED DOPPLER CAROTID BIFURCATION ASSESSMENT

angiographic findings	number of vessels	positive number	positive (%)	negative (%)	positive other† estimate
normal	16	1	—	94	—
less than 25%	26	22	85	4	—
25–50%	17	14	82	—	3 under
50–99%	14	12	86	—	2 under
occluded	5	5	100	—	—
total	**78**				

† Where a lesion was detected but the estimate of severity did not agree with that seen on angiography.

TABLE 2. DUPLEX B-MODE CAROTID BIFURCATION ASSESSMENT

angiographic findings	number of vessels	positive number	positive (%)	negative (%)	positive other† estimate
normal	16	1	—	94	—
less than 25%	26	19	73	4	3
25–50%	17	16	94	—	1
50–99%	14	13	93	—	1
occluded	5	4	50	1	—
total	**78**				

† Where a lesion was detected but the estimate of severity did not agree with that seen on angiography.

The essential difference between the two imaging systems is shown in figure 3, where in the lateral MAVIS scan the lesion is seen as a defect in the blood flow map, while the Duplex scan shows a vessel wall plaque encroaching on the lumen.

The ultrasonic classification of lesions was made solely on imaging although in producing the image the operator, with experience, was guided by the presence of turbulent flow in the Doppler audio signal to look further for a lesion not obvious at first. Several images were made of each vessel to confirm a persistent defect. The overall sensitivity in detecting all grades of lesion was 95% for the MAVIS pulsed Doppler and 93% for the Duplex system. The specificity for both was 94%.

Atheromatous plaque turbulence commonly occurred; an example is shown in figure 4. The profile of blood velocity in the common carotid artery was essentially normal proximal to a stenotic lesion; distally there were an increase in maximum velocity and a broader range of velocities, arising from turbulence and disorganization of normal laminar flow.

With the Duplex system it was necessary to confirm the presence of arterial flow. In five

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patients, soft thrombus completely occluded the internal carotid artery but the B-mode image failed to identify the occlusion due to the low acoustic impedance of thrombus which is similar to fluid blood. In four of the patients, failure to obtain a Doppler signal when the sample volume was placed in the vessel lumen indicated an absence of flowing blood even though the image appeared relatively normal; in the fifth, a patent external carotid artery was mistaken for the internal carotid artery.

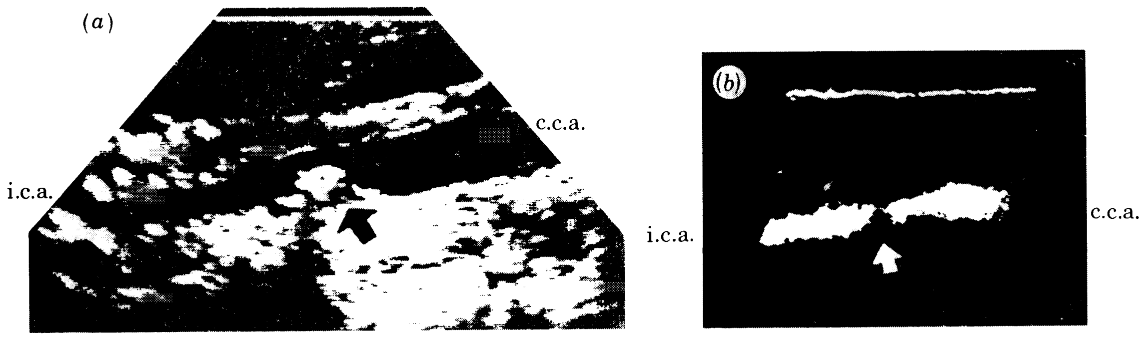

FIGURE 3. Lateral Duplex (*a*) and MAVIS (*b*) scans of carotid artery showing a lesion (arrowed). The Duplex scan shows encroachment onto the lumen of the lesion while the MAVIS scan shows a defect in the image of the moving column of blood. I.c.a., internal carotid artery; c.c.a., common carotid artery.

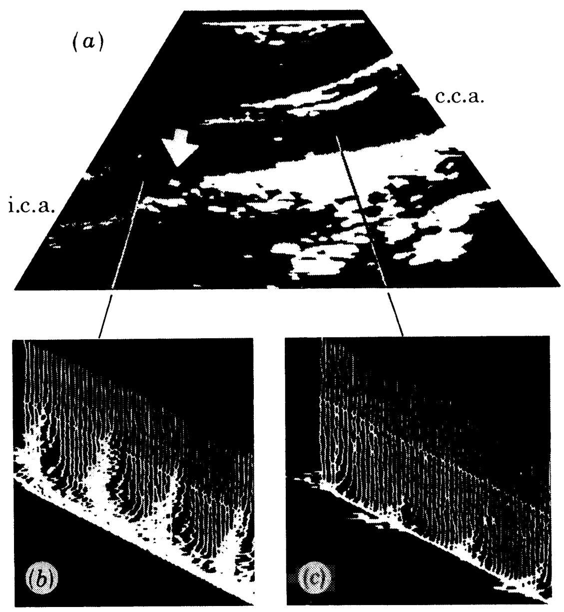

FIGURE 4. Duplex scan (*a*) of carotid artery, and Doppler velocity spectral analysis distal (*b*) and proximal (*c*) to a small lesion in the carotid bulb. There is a turbulent pattern with increased velocity just distal to the lesion.

Vessel distensibility

The real-time Duplex system showed up the systolic–diastolic changes in vessel wall distension. Recordings of contrast injection during angiography of 12 vessels showed that the internal diameter of the common carotid artery varied by $16.2 \pm 8.5\,\%$ (mean ± s.e.m.), and the bulbous origin of the internal carotid artery by $26.1 \pm 9.6\,\%$ ($p < 0.005$, Wilcoxon) (figure 5). In 10 patients time position M-mode scans showed that the average distensibility of the common

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carotid artery was 12.6 ± 2.4 % (mean ± s.e.m.) and the bulbous origin of the internal carotid arteries 19.7 ± 5.4 % ($p < 0.005$) (figure 6). In 23 vessels with bulbous origins, the average bulb internal diameter was 157 % (range 120–246 %) that of the distal internal carotid artery.

Correlation of ultrasonic and clinical observations

There were 189 patients referred to the vascular laboratory with symptoms suggesting episodes of transient cerebral ischaemia or amaurosis fugax. In 86 % of them, vessel wall

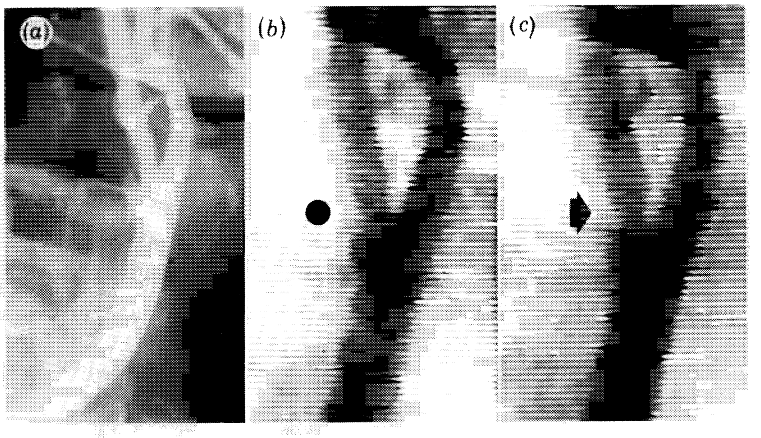

FIGURE 5. Single X-ray (*a*) and two video frames (*b*, *c*) of a carotid angiogram. The lesion arrowed is not so obvious in an earlier frame (dot) nor in the angiogram.

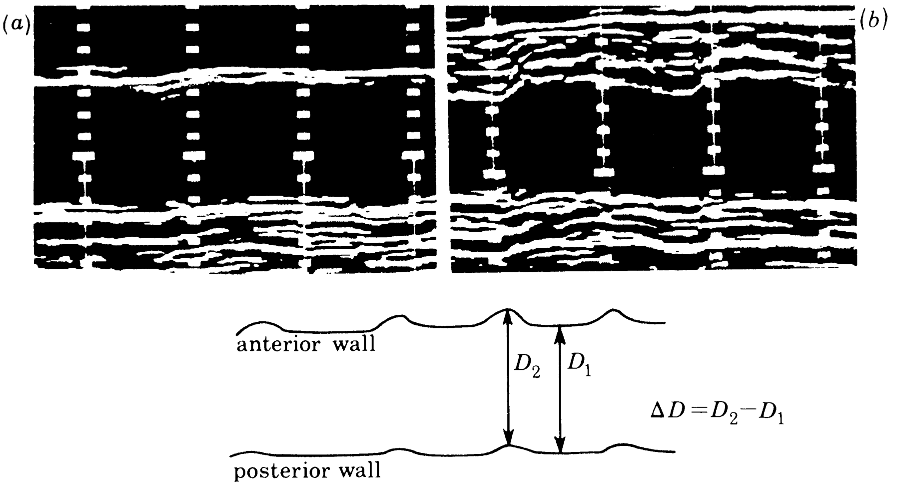

FIGURE 6. M-mode distensibility showing the movement in anterior and posterior walls of the carotid artery: (*a*) c.c.a.; (*b*) origin of i.c.a. An increase in percentage distensibility ($100\,\Delta D/D_1$) is noted at the origin of the internal carotid artery.

abnormalities were detected by ultrasound imaging. Among the 16 % without evidence of lesions at the carotid bifurcation were patients known to have valvular disease of the heart, cardiac arrhythmias or evidence of subclavian or vertebral artery lesions.

Of patients with unilateral transient ischaemic attacks of amaurosis fugax, 45 % had bruits in the neck over the corresponding carotid artery; 54 % of bruits were associated with stenoses of more than 50 % and the other 46 % with lesser narrowings. There was no correlation between degree of stenosis and manifestation of transient ischaemic attacks or amaurosis fugax.

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Discussion

The aim of non-invasive investigations of carotid artery disease is the accurate characterization of all grades of lesions. This report shows that varying grades of stenosis can be demonstrated by two ultrasonic imaging systems. The pulsed Doppler system with range-gating has the advantage that it can produce images in three orthogonal directions, thus providing three-dimensional information about the arterial lumen. In many cases where antero-posterior views failed to show a lesion it was detected on lateral scans. The predilection of atheroma for the posterior wall makes it necessary to obtain them in clear views, which are provided by the Duplex system and the lateral Mavis scan. The techniques have provided similarly accurate detection of carotid artery lesions for others (Blackshear *et al.* 1979; Barnes *et al.* 1976; Sumner *et al.* 1979).

Carotid artery bruits are caused by vessel wall movements at high frequency in the audible range (McDonald 1974). There is evidence that particular frequencies cause changes in structural components (Gersten 1956; Bougner & Roach 1971) of the vessels walls, i.e. in collagen and elastin. These changes can lead to dilation, ulceration and exposure of wall components, e.g. collagen and basement membrane, which can activate platelets.

The variations in arterial diameter associated with pulsation appear much greater than appreciated before. In exposed intact vessels these variations are only 1–2% (Heath *et al.* 1973), whereas both M-mode and dynamic angiographies show them to be greater, confirming an early report (Arndt 1968) based on echo tracking. A new observation of ours is the great distensibility of the carotid bulb, even in the presence of atheromatous lesions. This distensibility is apparently due to a decrease in thickness of the media, which results in a structure similar to that of the pulmonary arteries (Heath *et al.* 1973).

Observed variations in distensibility probably indicate sudden differences in compliance, particularly at the origin of the internal carotid artery. These abrupt differences are associated with disruptive stresses in the walls, which may lead to dilation of the carotid bulb (Gonza *et al.* 1974; Eiken 1961; Baird & Abbott 1976). The same forces may also bring about fracture of atheromatous plaques, which is an immediate cause of obstructive thrombosis (Born 1978).

Turbulence is invariably present in lesions so large as to produce drops in pressure and flow to the brain (Blackshear *et al.* 1979). Distal to stenotic lesions, disorganization of laminar flow as detected with the pulsed Doppler and characterized by spectral analysis contribute to platelet thrombosis and embolism. These haemodynamically significant lesions frequently result in cerebral infarction and stroke (Machleder 1979). Increased velocity gradients and jet streaming effects may affect vascular endothelium (Fry 1968; Payling Wright & Born 1971). These investigations indicate that ultrasound and related techniques provide information about abnormalities in vessel walls and blood flow that determine thromboembolic events in arteries.

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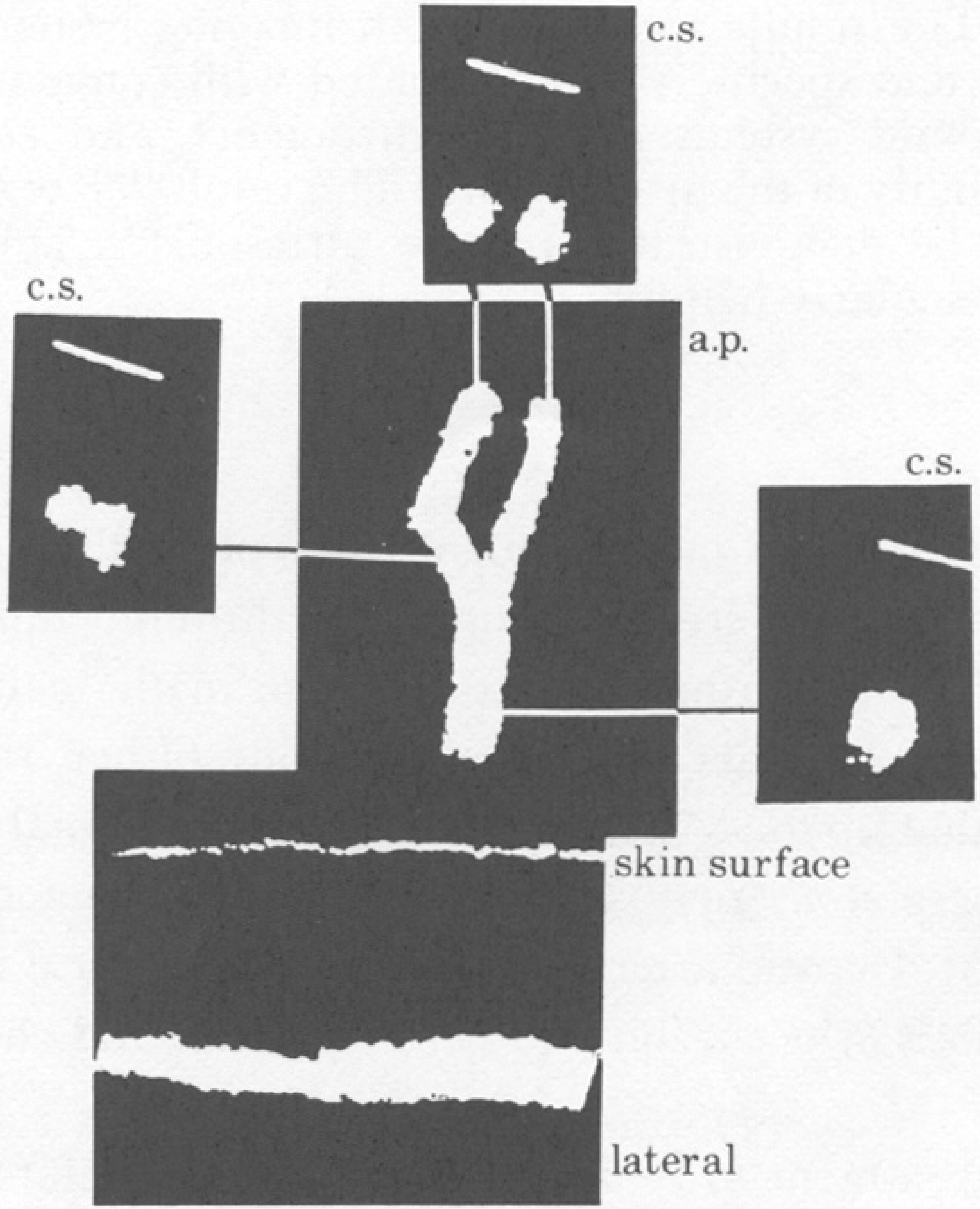


FIGURE 1. MAVIS pulsed Doppler projections in lateral, antero-posterior (a.p.) and cross-sectional (c.s.) planes.

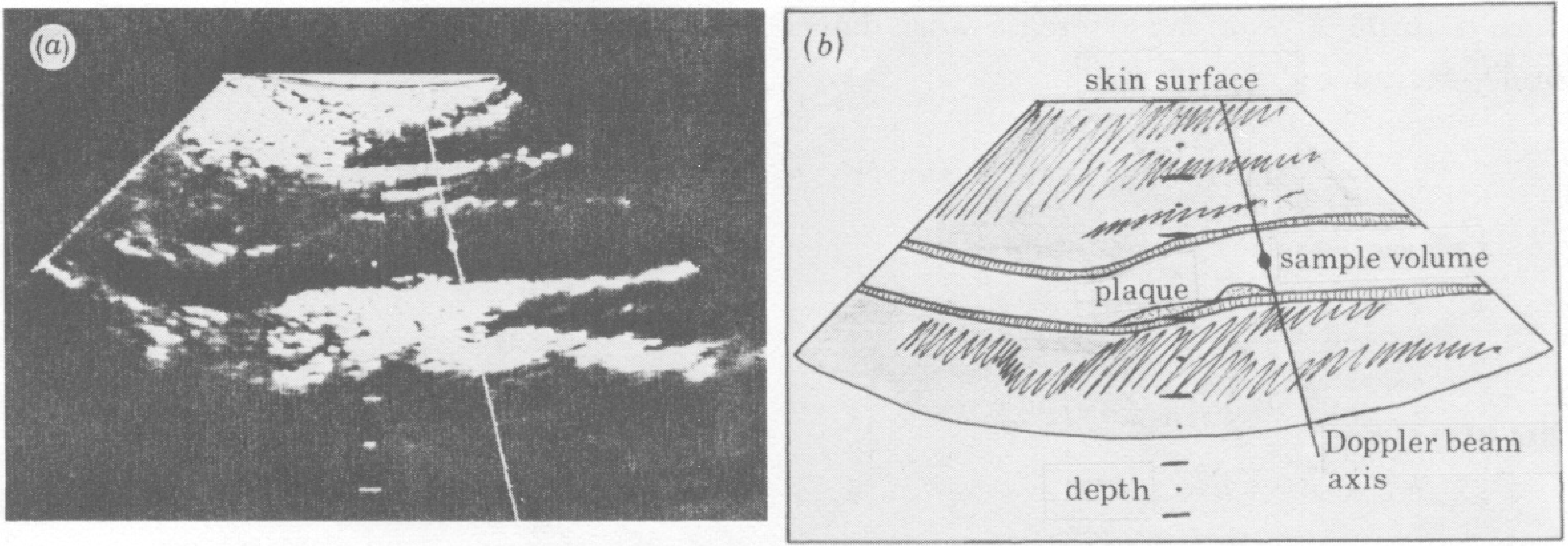
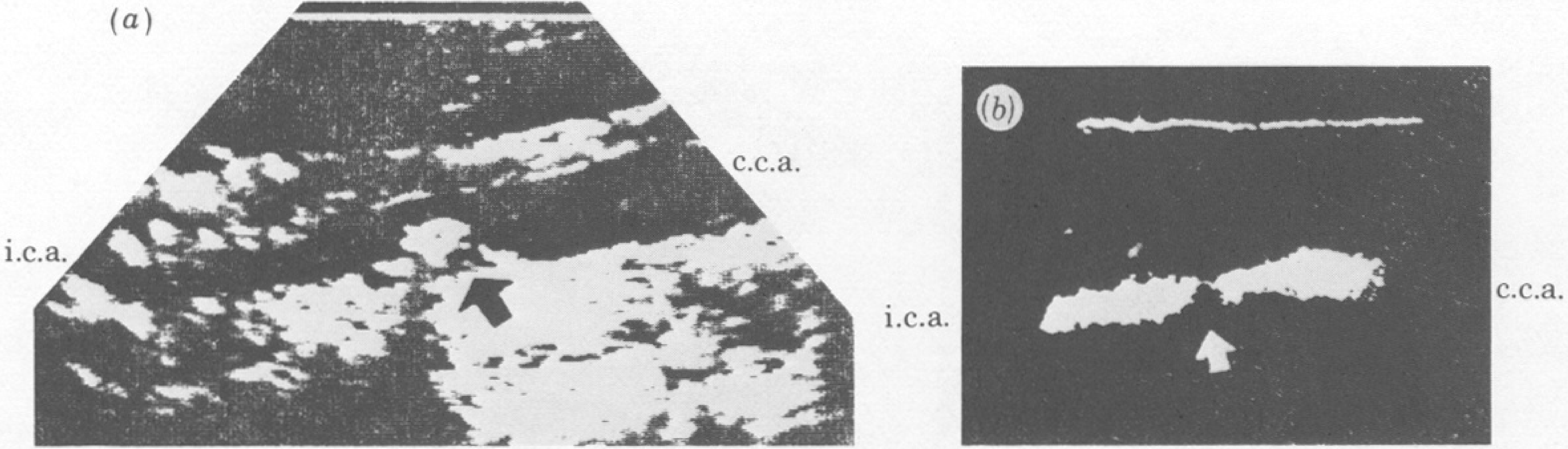


FIGURE 2. Duplex scan (*a*) of carotid artery with diagram (*b*) showing the pulsed Doppler beam and Doppler sample volume.



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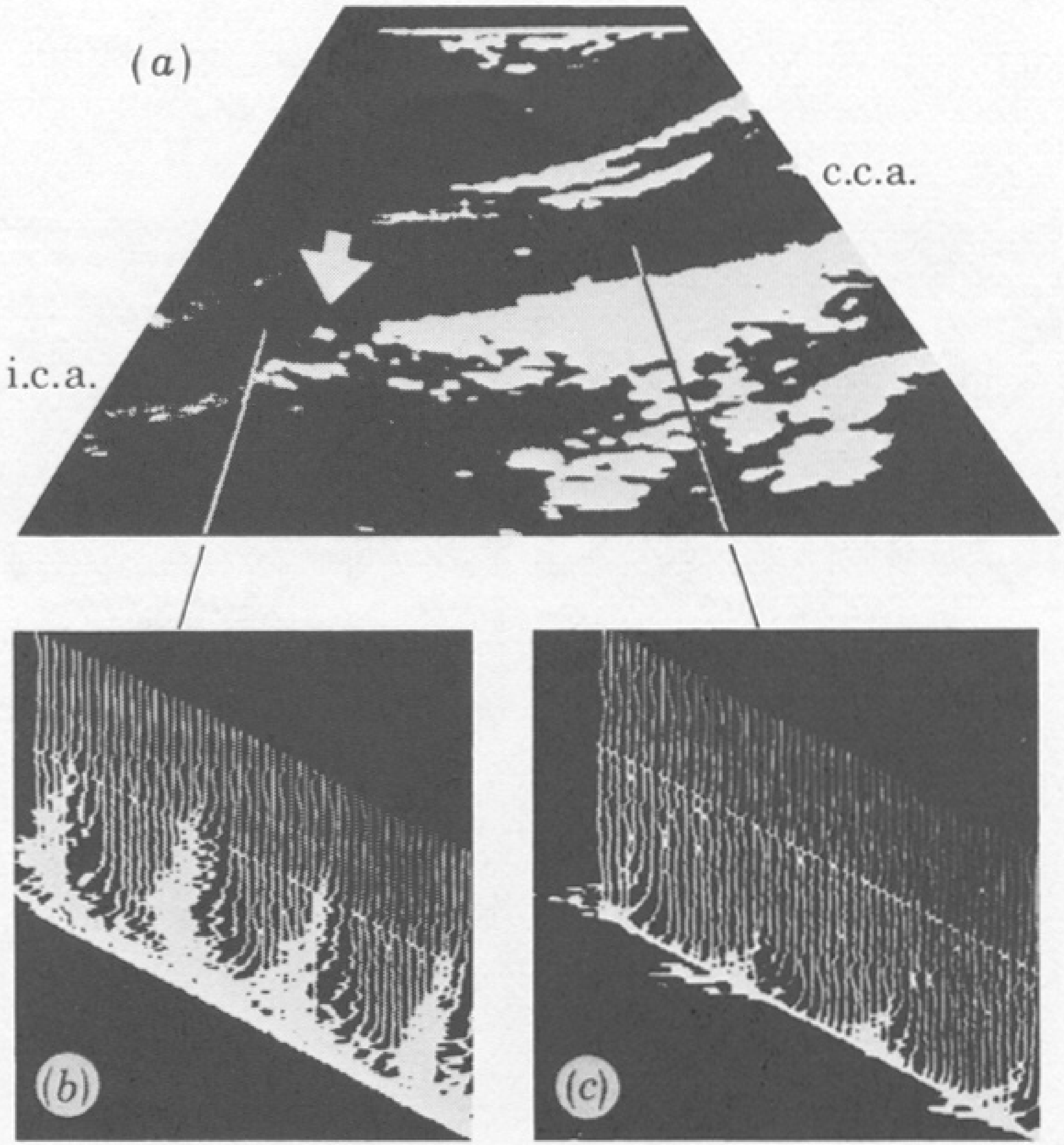

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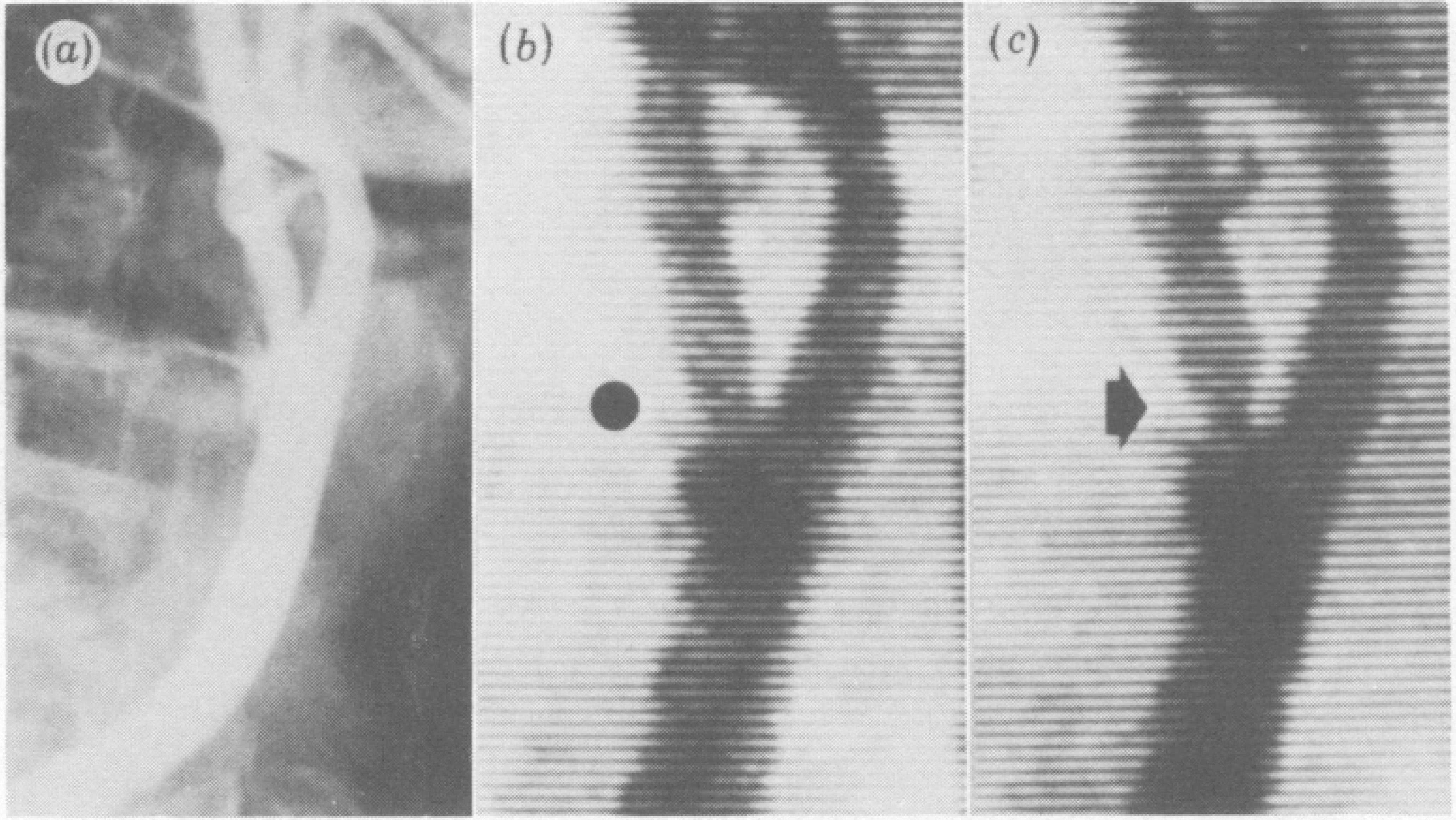

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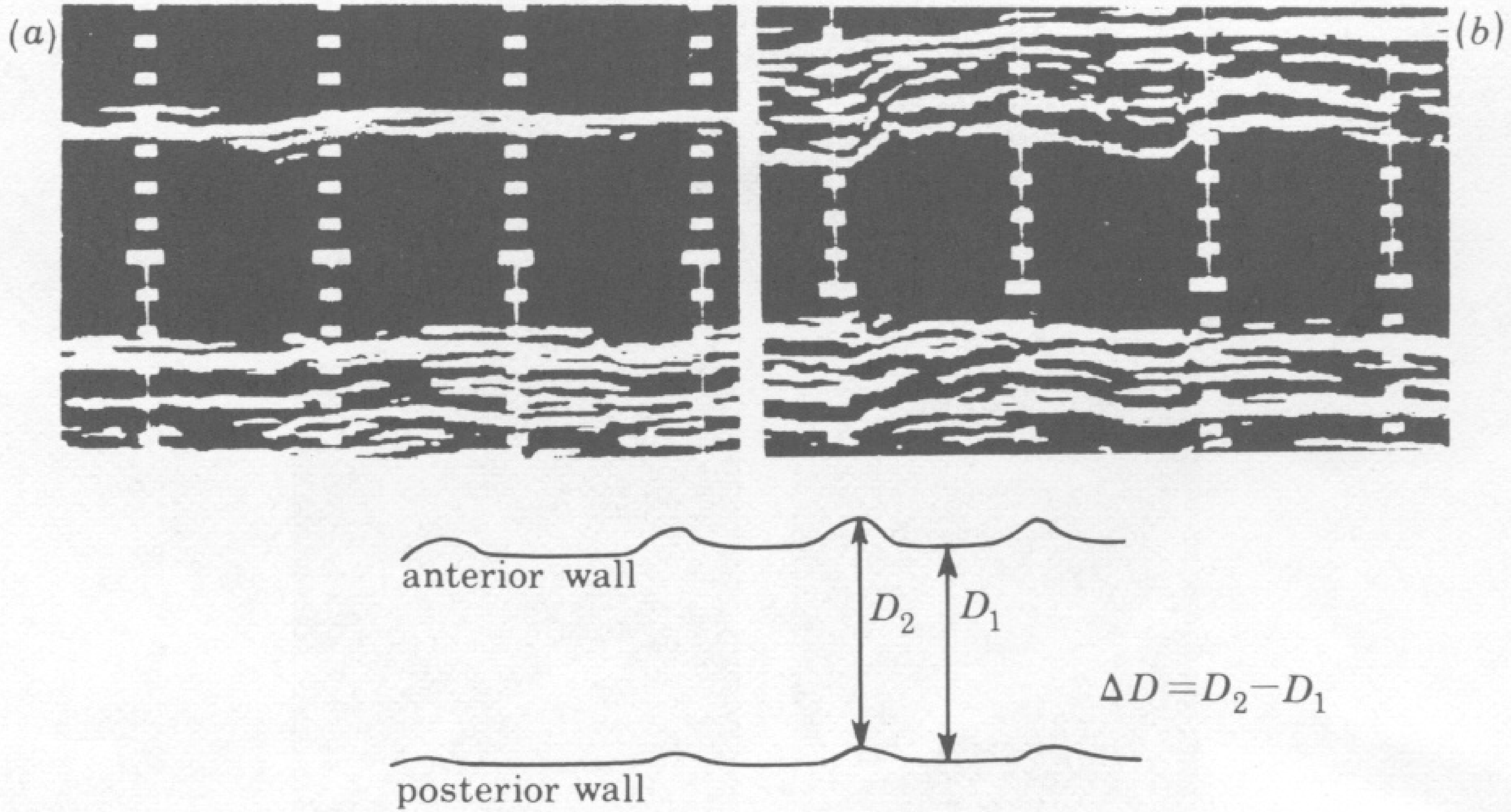

Figure 6. M-mode distensibility showing the movement in anterior and posterior walls of the carotid artery: (*a*) c.c.a.; (*b*) origin of i.c.a. An increase in percentage distensibility ($100\,\Delta D/D_1$) is noted at the origin of the internal carotid artery.