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UNITED NATIONS EDUCATIONAL, SCIENTIFIC AND CULTURAL ORGANIZATION
INTERNATIONAL CENTRE FOR THEORETICAL PHYSICS
I.C.T.P., P.O. BOX 586, 34100 TRIESTE, ITALY, CABLE: CENTRATOM TRIESTE

H4-SMR 471/18

COLLEGE ON MEDICAL PHYSICS

10 - 28 SEPTEMBER 1990

PHYSICAL PRINCIPLES OF MRI - I

Lynn W. Jelinski

AT & T Bell Laboratories
Murry Hill, NJ
USA

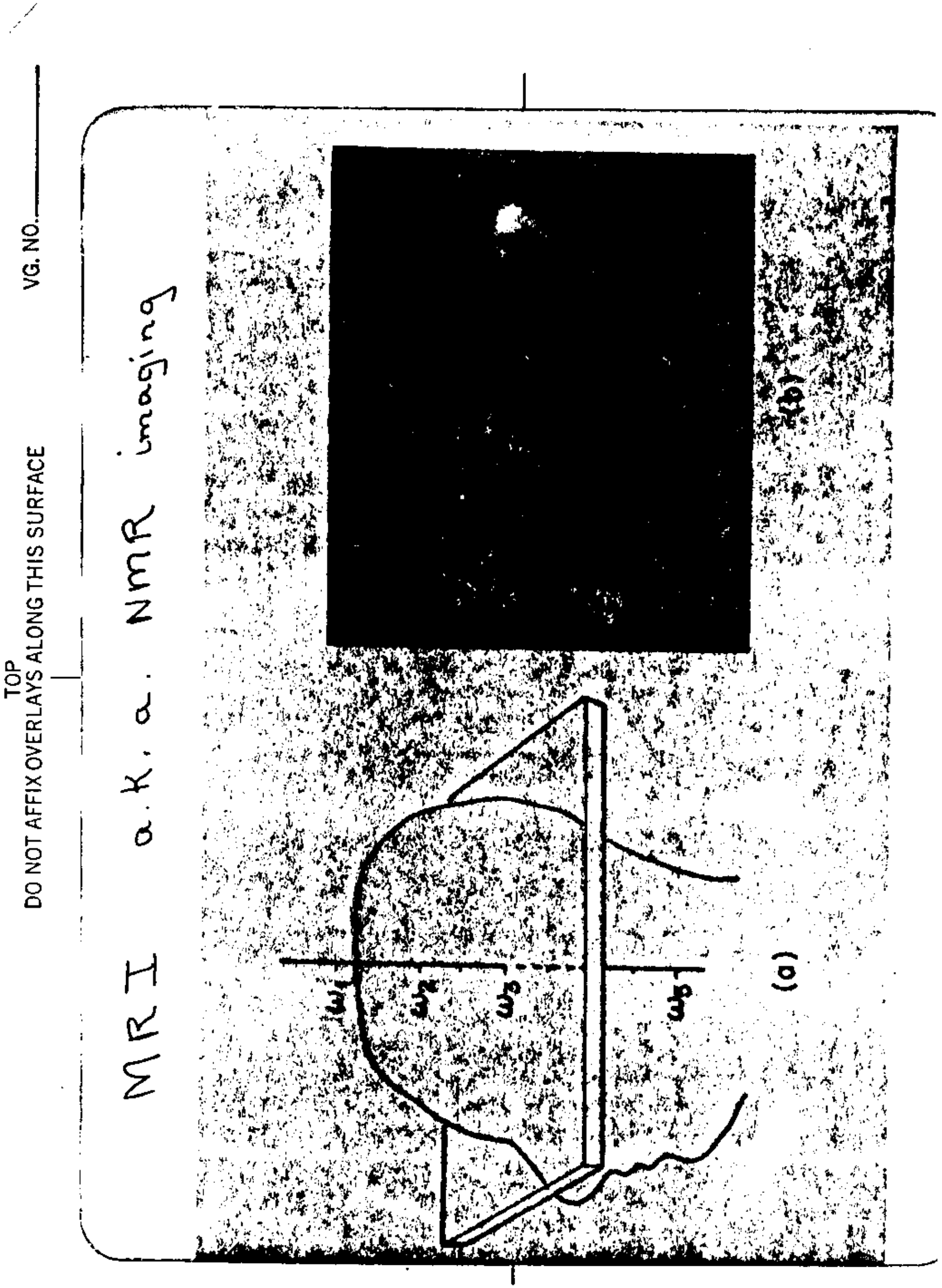
LYNN W. JELINSKI

AT&T BELL LABORATORIES
MURRAY HILL, NJ USA

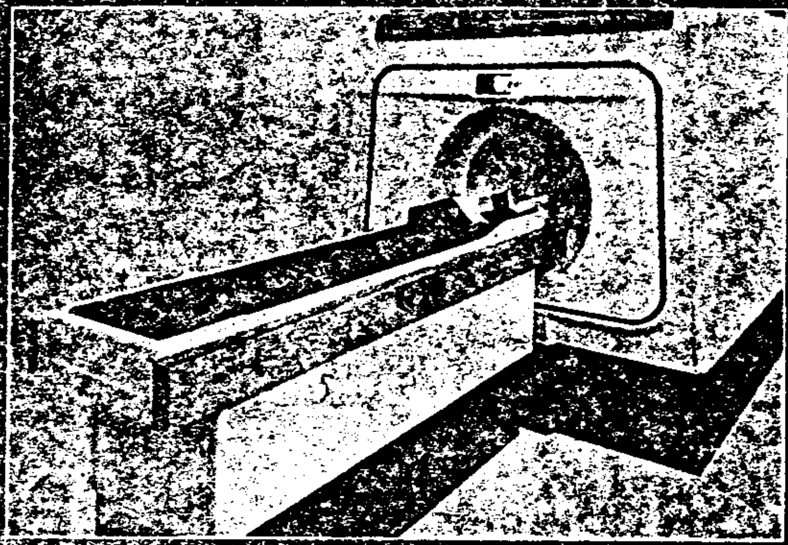
September, 1990

I. Physical Concepts of Magnetic Resonance Imaging and Applications to Measuring Arterial Stiffness

II. Arterial Stiffness, Blood Flow, and Ultraslow Flow and Anisotropic Diffusion



MAGNETIC RESONANCE IMAGING (MRI) MACHINE



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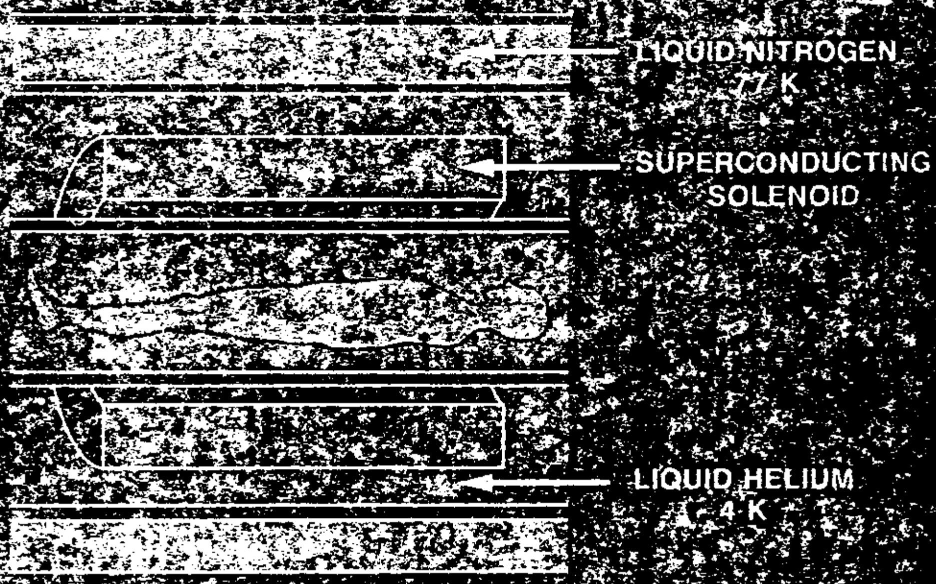
CROSS SECTION OF AN MRI MAGNET



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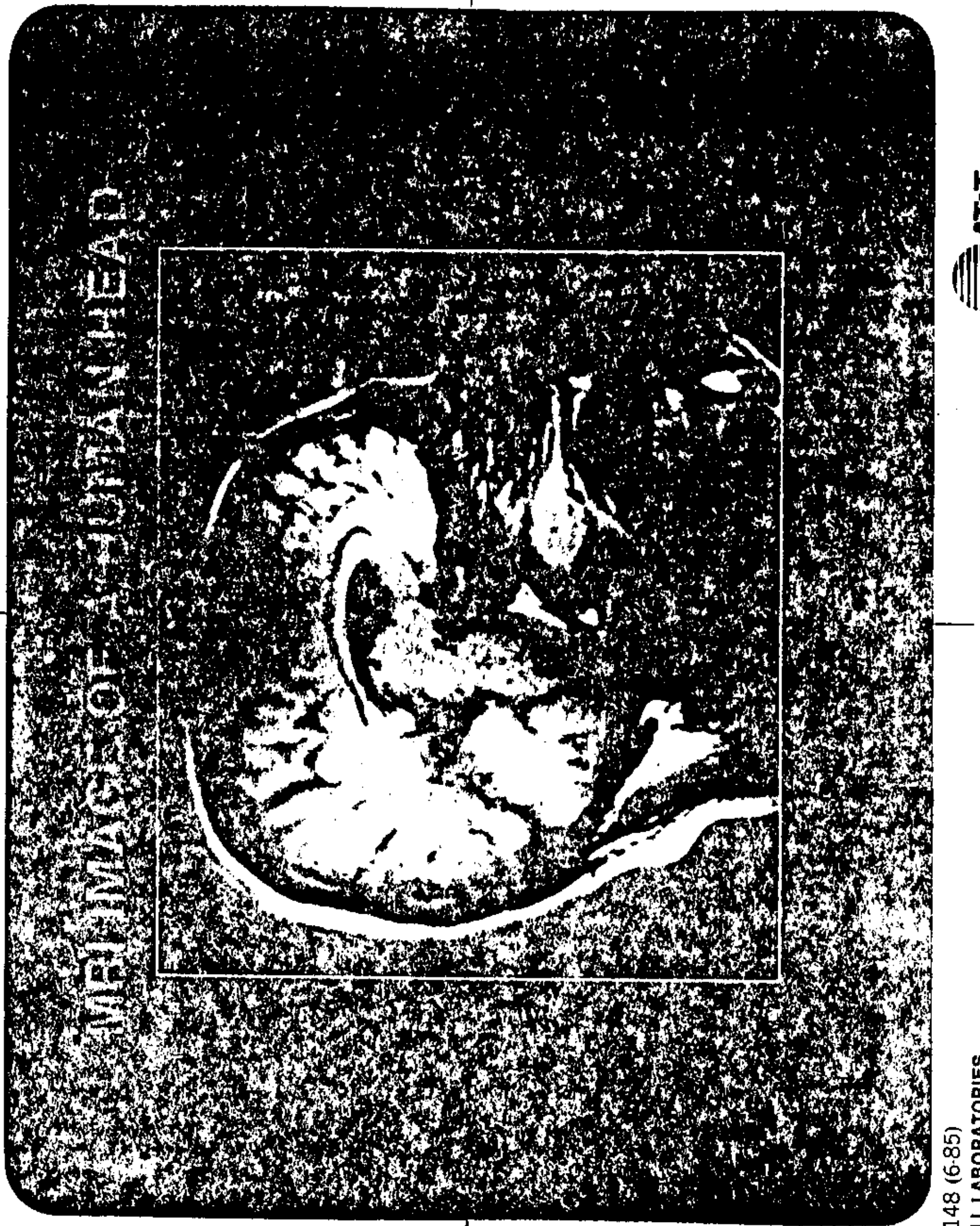

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losa), produced by the escape of blood from divided blood-vessels. In inflammation or great congestion of the brain these are very numerous and of a dark color. If the remaining portion of one hemisphere is slightly separated from the other, a broad band of white substance will be observed connecting them at the bottom of the longitudinal fissure; this is the *corpus callosum*. The margins of the hemispheres which overlap this portion of the brain are called the *labia cerebri*. Each labium is part of the convolution of the corpus callosum (*gyrus fornicatus*), and the space between it and the upper surface of the corpus callosum has been termed the *ventricle of the corpus callosum* (Fig. 446).

The hemispheres should now be sliced off to a level with the corpus callosum, when the white substance of that structure will be seen connecting the two hemispheres. The large expanse of medullary matter now exposed, surrounded by the convoluted margin of gray substance, is called the *centrum ovale majus* of Vieussens.

The **corpus callosum** (Figs. 442, 446) is a thick stratum of transverse fibres exposed at the bottom of the longitudinal fissure. It connects the two hemi-

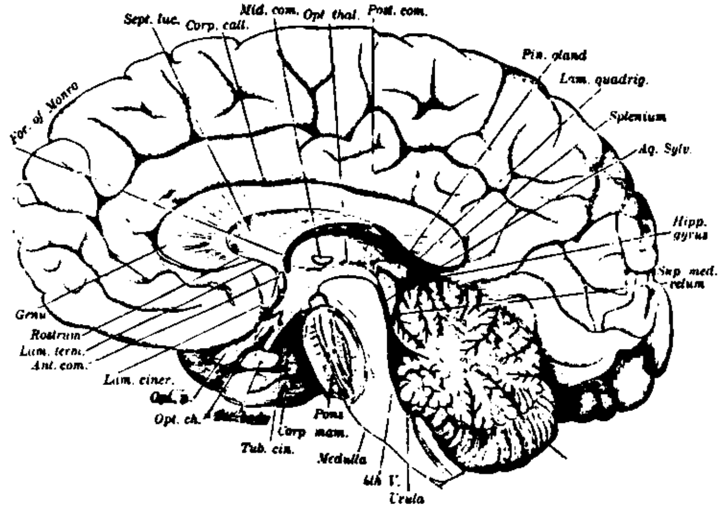

FIG. 446.—Antero-posterior median section of the brain. × ½. (Henle.)

spheres of the brain, forming their great transverse commissure, and forms the roof of the *lateral ventricles*. It is about four inches in length, extending to within an inch and a half of the anterior, and to within two inches and a half of the posterior, end of the hemispheres. It is somewhat broader behind than in front, and is thicker at either end than in its central part, being thickest behind. It presents a somewhat arched form (Fig. 446) from before backward, and terminates anteriorly by curving downward and backward between the frontal lobes. This distinct bend is named the *genu*, whence it is still continued downward and backward to the base of the brain, where it blends with the lamina cinerea. The reflected portion of the corpus callosum is called the *beak* or *rostrum*: it becomes gradually narrower as it passes backward, and is attached by its lateral margins to the frontal lobes. At its termination, besides blending with the lamina cinerea, the corpus callosum gives off two small bundles of white substance, which, diverging from one another, pass backward, across the corresponding anterior perforated space, to the entrance of the fissure of Sylvius, to enter the end of the temporal

7

AT&T Bell Laboratories
MRI Facility

8.4 T (360 MHz)
89 mm bore
35 mm accessible bore
Resolution$_{max}$ ~20μm

7.0 T (300 MHz)
180 mm bore
125 mm accessible bore
Resolution$_{max}$ ~50μm

"Unique"

→ Characterized by high field, high resolution, multi-nuclear capabilities

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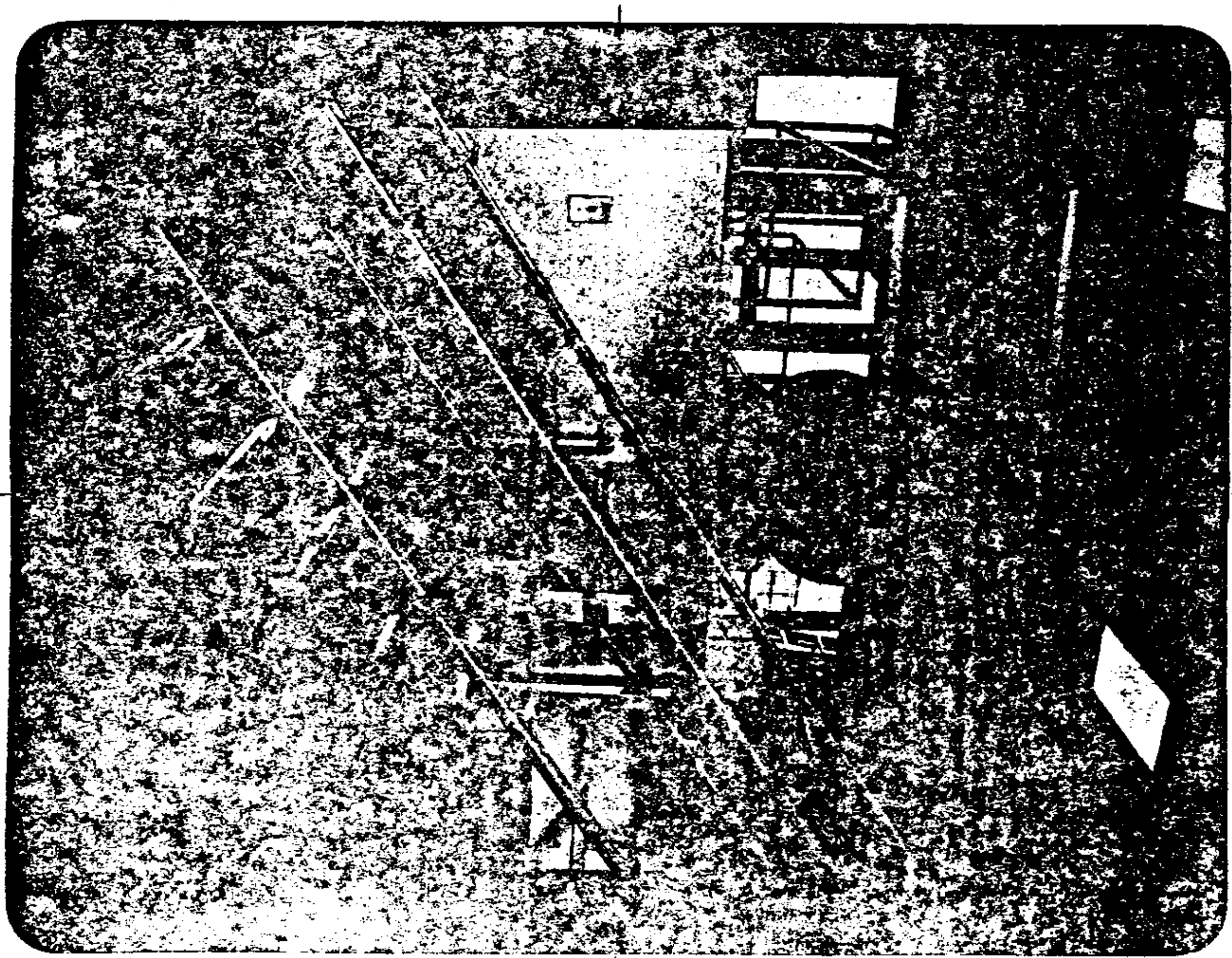

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Jim, FYI
Guy

THE NEW YORK TIMES, THURSDAY, JUNE 5, 1986

Man Hurt as Medical Magnet Attracts Forklift

By JAMES GLEICK

The powerful magnetism of a large, newly developed medical diagnostic scanner drew part of a fork lift into the device, seriously injuring a technician working inside, a medical journal re- rted today.

accident has alerted doctors to posed by the magnetic fields v the new devices, magnetic magers, which are being in- ny hospitals and mobile e nation.

was installing the rted semitrailer in a mobile diagnos- tic center. As he lay inside the machine, two steel tines, weighing as much as 80 pounds each, flew off an approaching forklift and knocked him 15 feet, seriously injuring him, doctors said.

The magnetic field that caused the accident also complicated efforts to help the worker. A doctor had to remove his stethoscope before he could approach the victim, and when a paramedic tried to cut off the injured man's pants, the scissors flew out of his hand.

Magnetic resonance imagers are the newest products of a revolution in scanning devices that began in the 1970's with the CAT scanner and has become a multimillion-dollar business. Several hundred of the machines have gone into operation in the last two years.

In diagnosis by magnetic resonance, a patient lies on a motorized platform that carries him through a huge cylinder. With the help of advanced computer circuitry, the machine produces clear images of cross-sections of the patient's body, far clearer than anything an X-ray machine can produce.

Because the devices use such a powerful magnetic field, manufacturers and operators take extraordinary precautions, and the Cincinnati accident was the first serious injury reported in connection with a magnetic resonance imager.

In hospitals and mobile units where the imagers have been installed, prominent warning signs are generally posted, and specially made nonmagnetic tools are used.

The doctors said they were worried not about the day-to-day operation of the machines but about unwary personnel who might be called to the scene in an emergency. "It's not uncommon to have medical emergencies while they're being scanned," said Dr. Scott A. Syverud, who treated the victim at the scene. "You have metal IV needles and metal things on your person, and standard medical equipment contain a lot that is attracted to magnets."

The accident took place De- technicians were completing lation of a mobile unit for a major distributor of

make final adjustments, they had turned on the magnet, cooled by liquid helium to increase its conductiv-

One technician lay on his back the cylinder, where the pat- Another approached As the heavy tines of near, the magnet cylinder.

Dr. Syverud by helicopte slow to re all me pro

10

The Fourth Dimension of MRI

→ Biological Function ←

- How MRI works
- Research results
  - Arterial elasticity
  - Blood flow
  - Anisotropic diffusion
  - PET-like information from MRI

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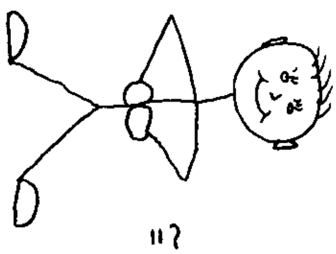
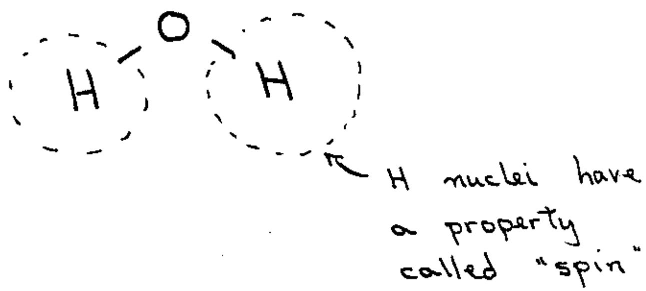
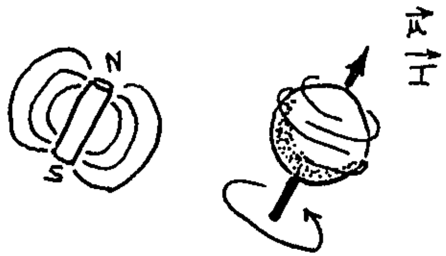
Water, water,
everywhere !!



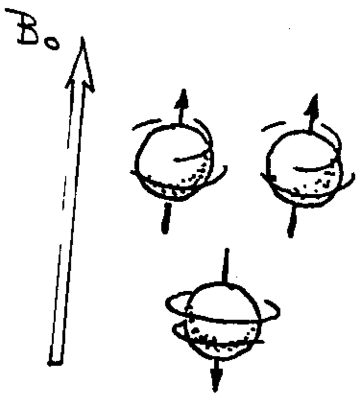
≈ 80% H_2O

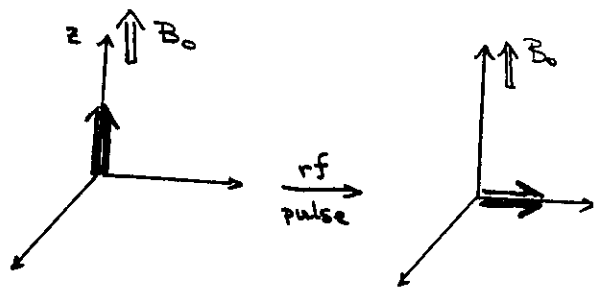




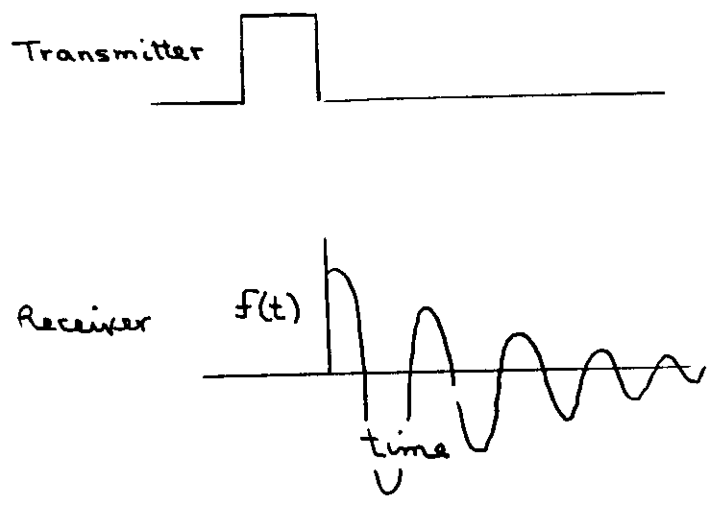
bar magnet nuclear spin

$\omega_0 = \gamma B_0$

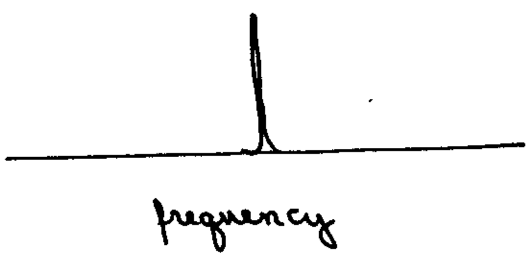


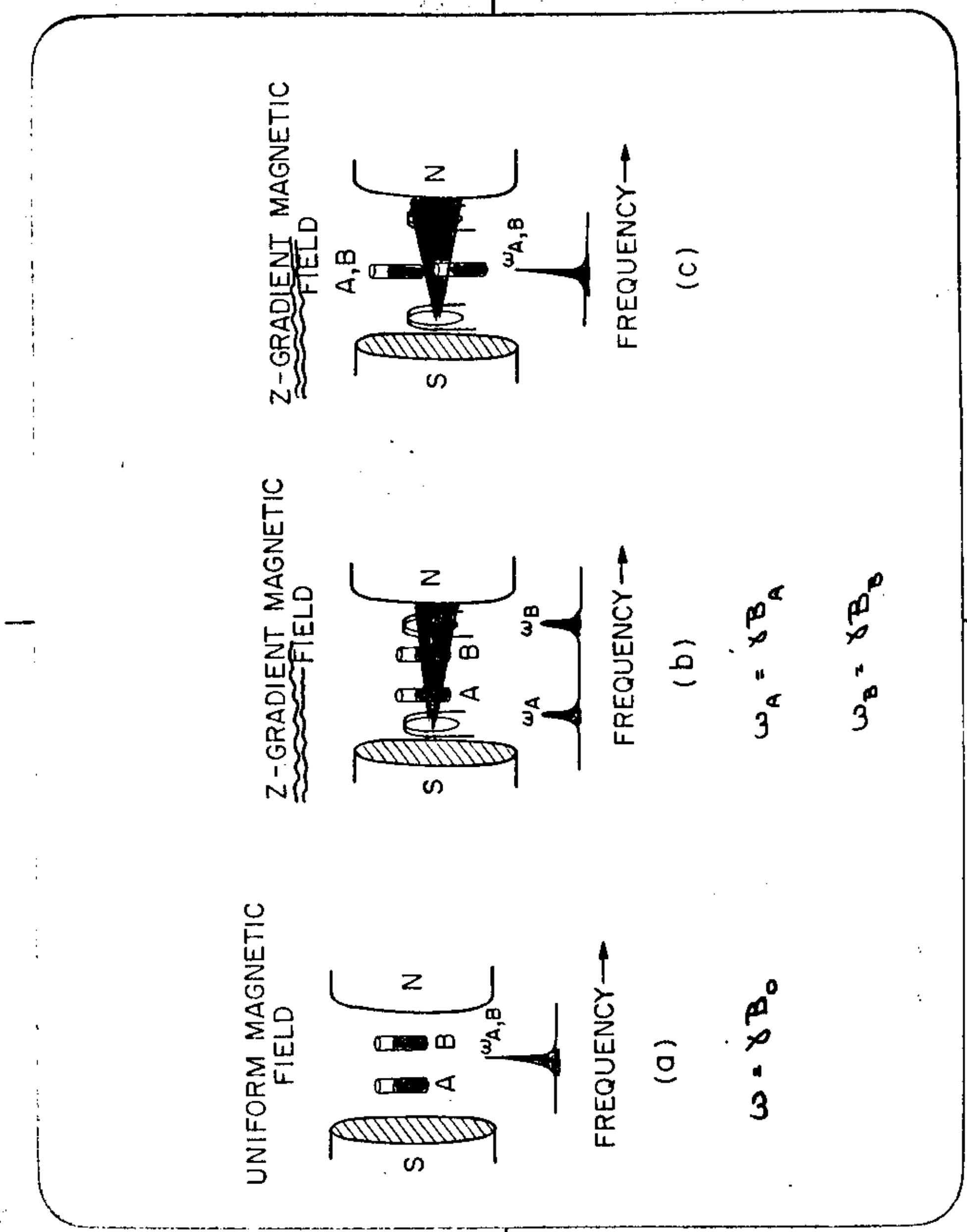


equilibrium non-equilibrium



$$F(\omega) = \int_{-\infty}^{\infty} f(t)\, e^{-i\omega t}\, dt$$





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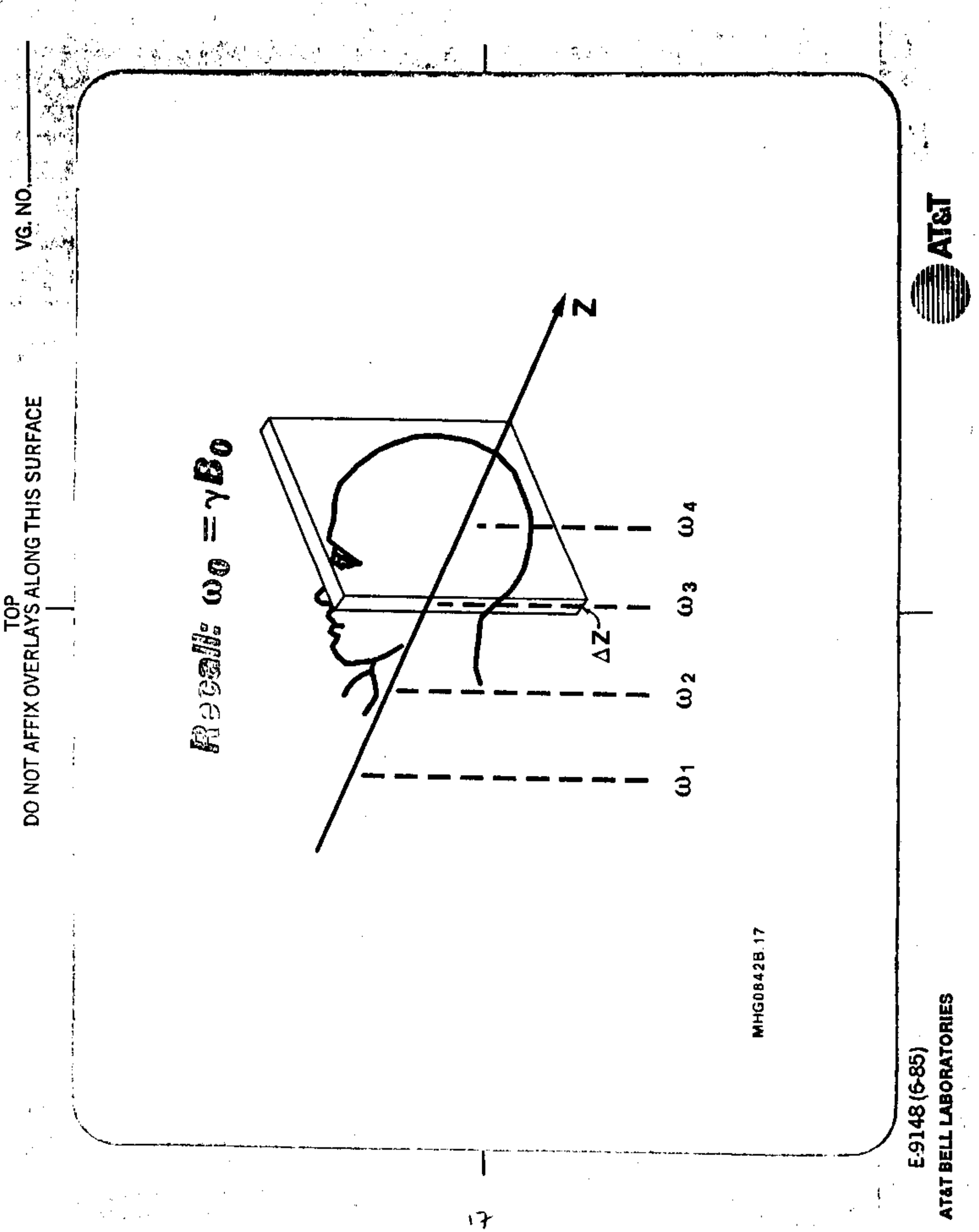
VG. NO.
TOP
DO NOT AFFIX OVERLAYS ALONG THIS SURFACE
Recall: $\omega_0 = \gamma B_0$
Z
ΔZ
ω_1
ω_2
ω_3
ω_4
MHG0842B.17
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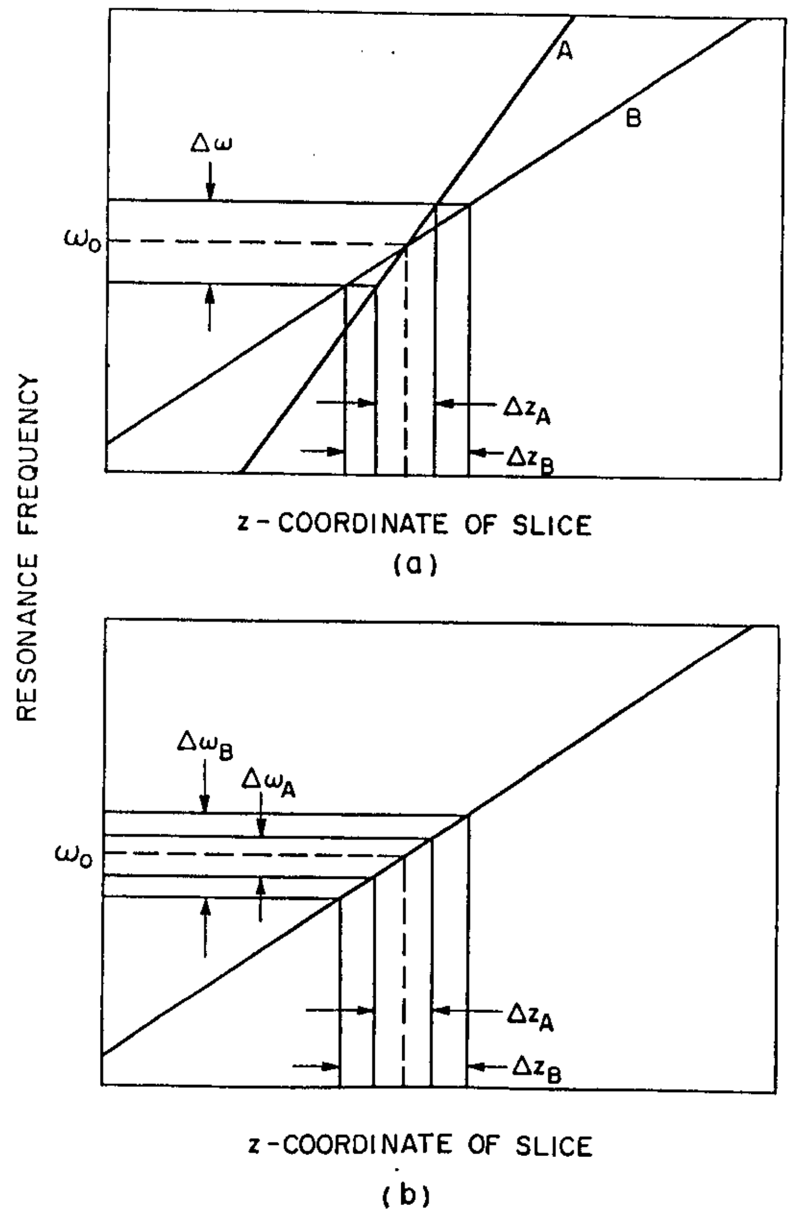
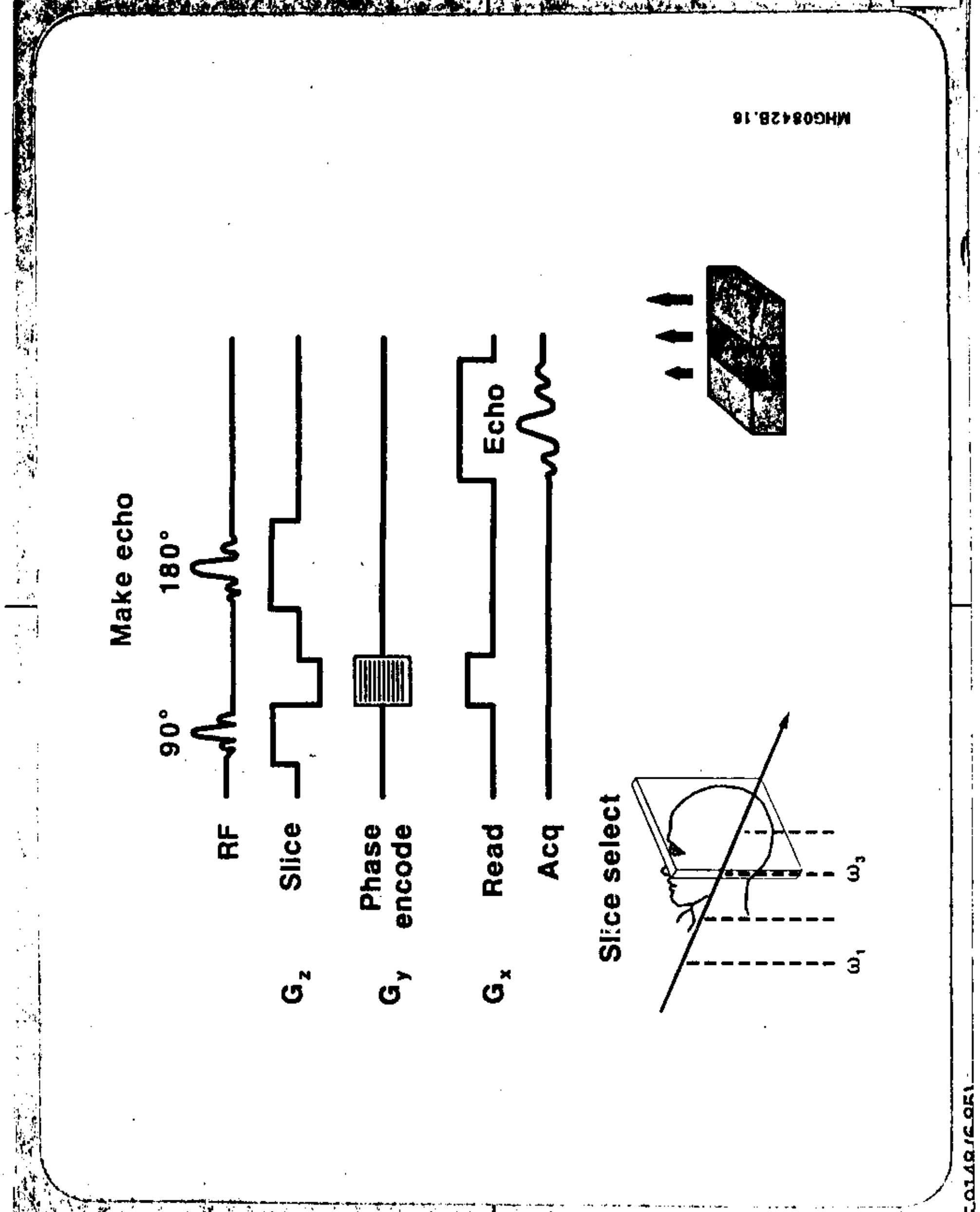
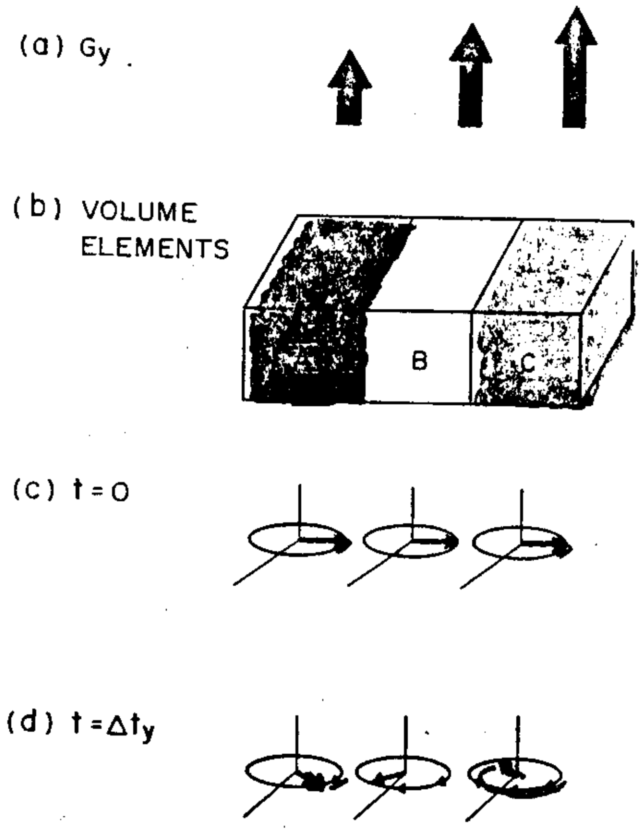

RESONANCE FREQUENCY
A
B
Δω
ω_0
Δz_A
Δz_B
z - COORDINATE OF SLICE
(a)
$\Delta\omega_B$
$\Delta\omega_A$
ω_0
Δz_A
Δz_B
z - COORDINATE OF SLICE
(b)


Make echo
90°
180°
RF
G_z Slice
G_y Phase encode
G_x Read
Acq
Echo
Slice select
ω_1
ω_3


(a) G_y
(b) VOLUME ELEMENTS
B
C
(c) t = 0
(d) t = Δt_y

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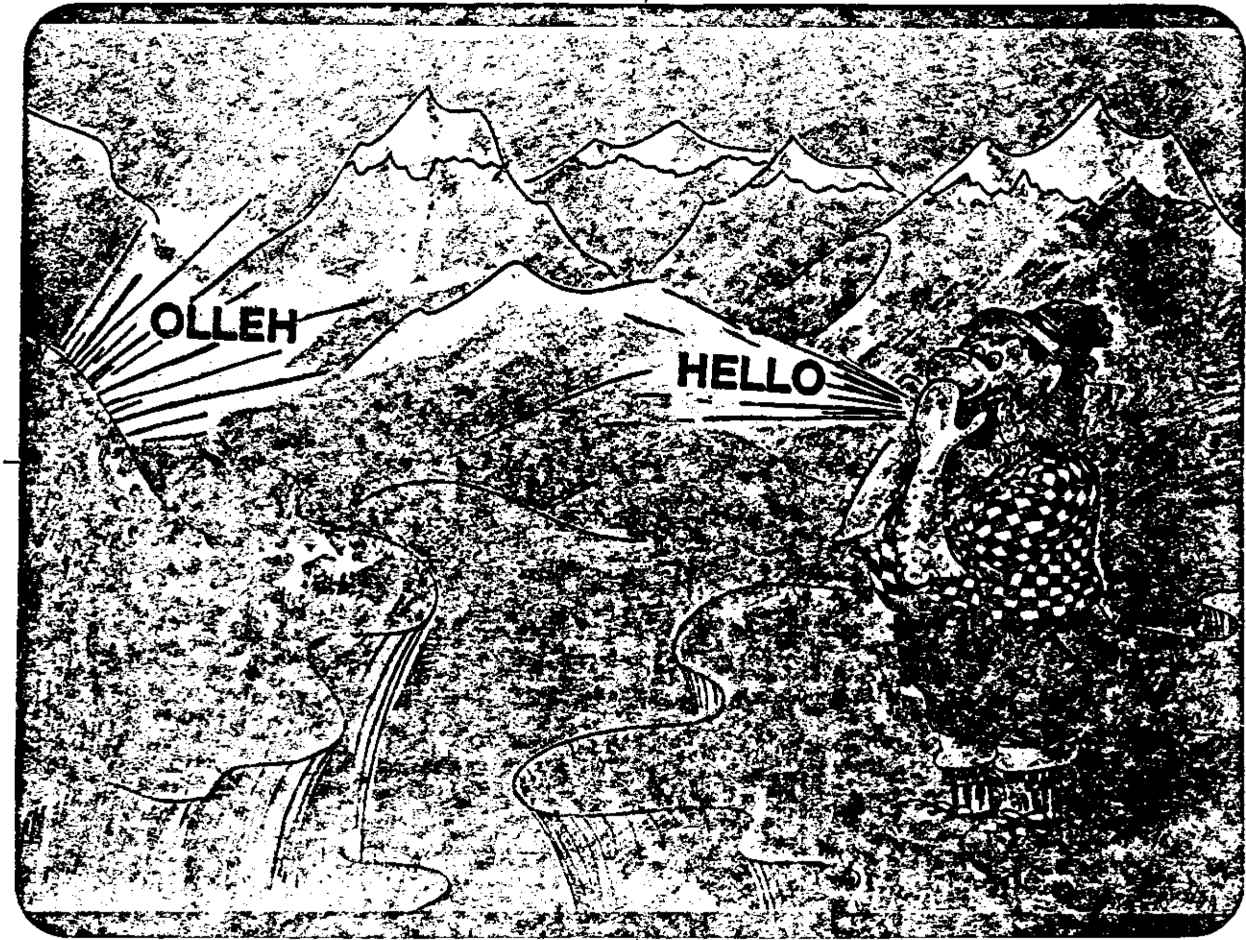

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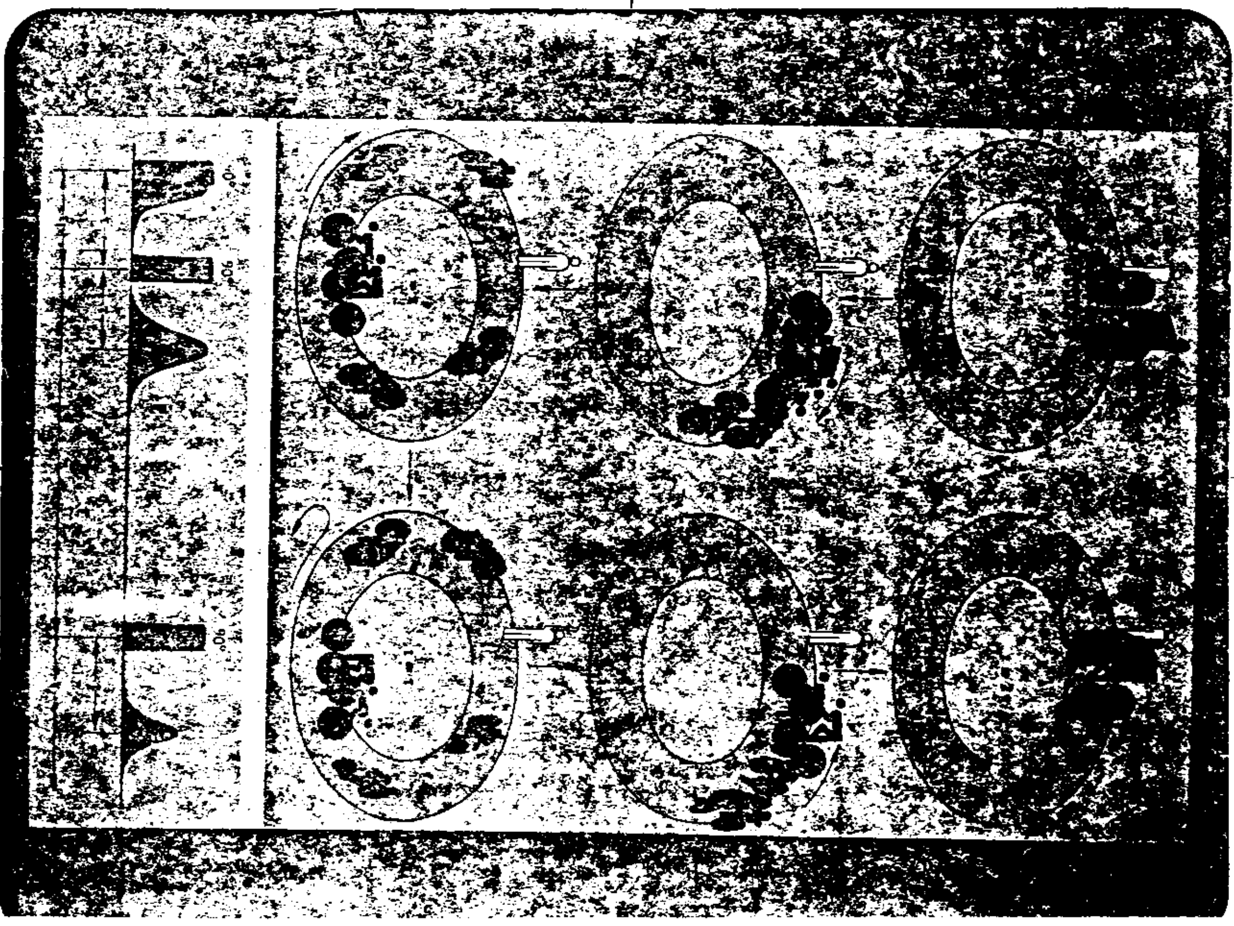
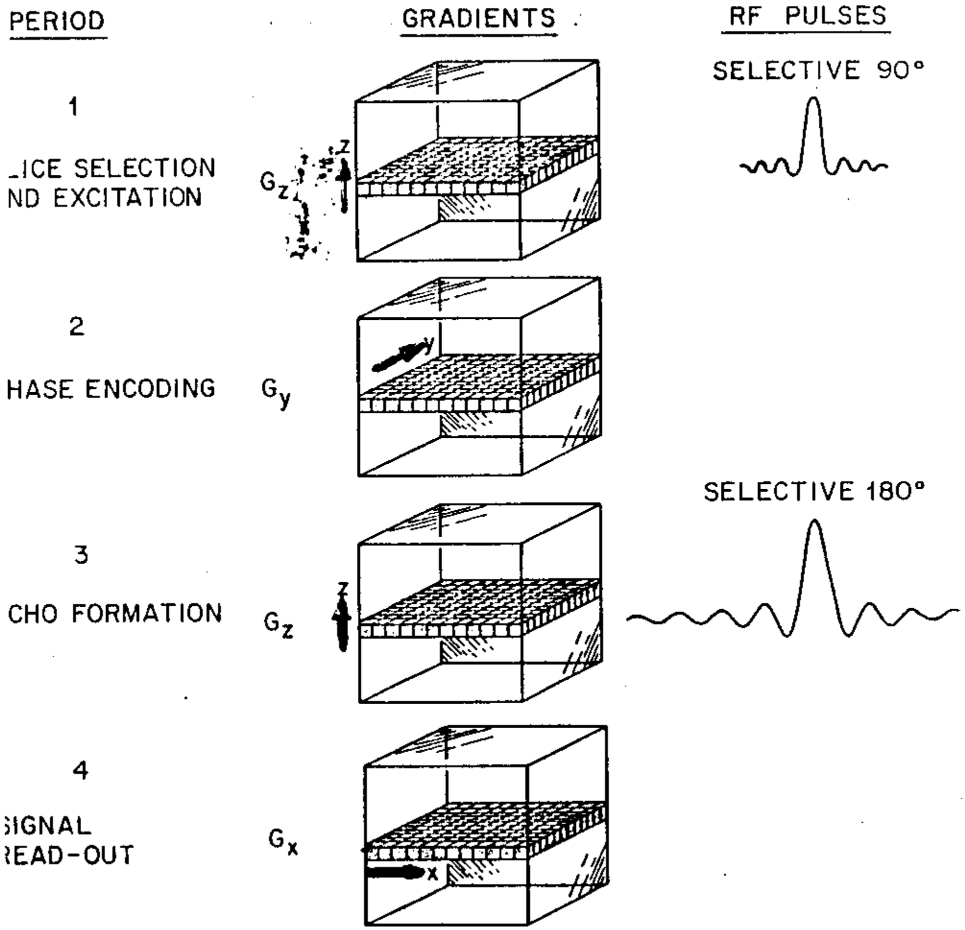
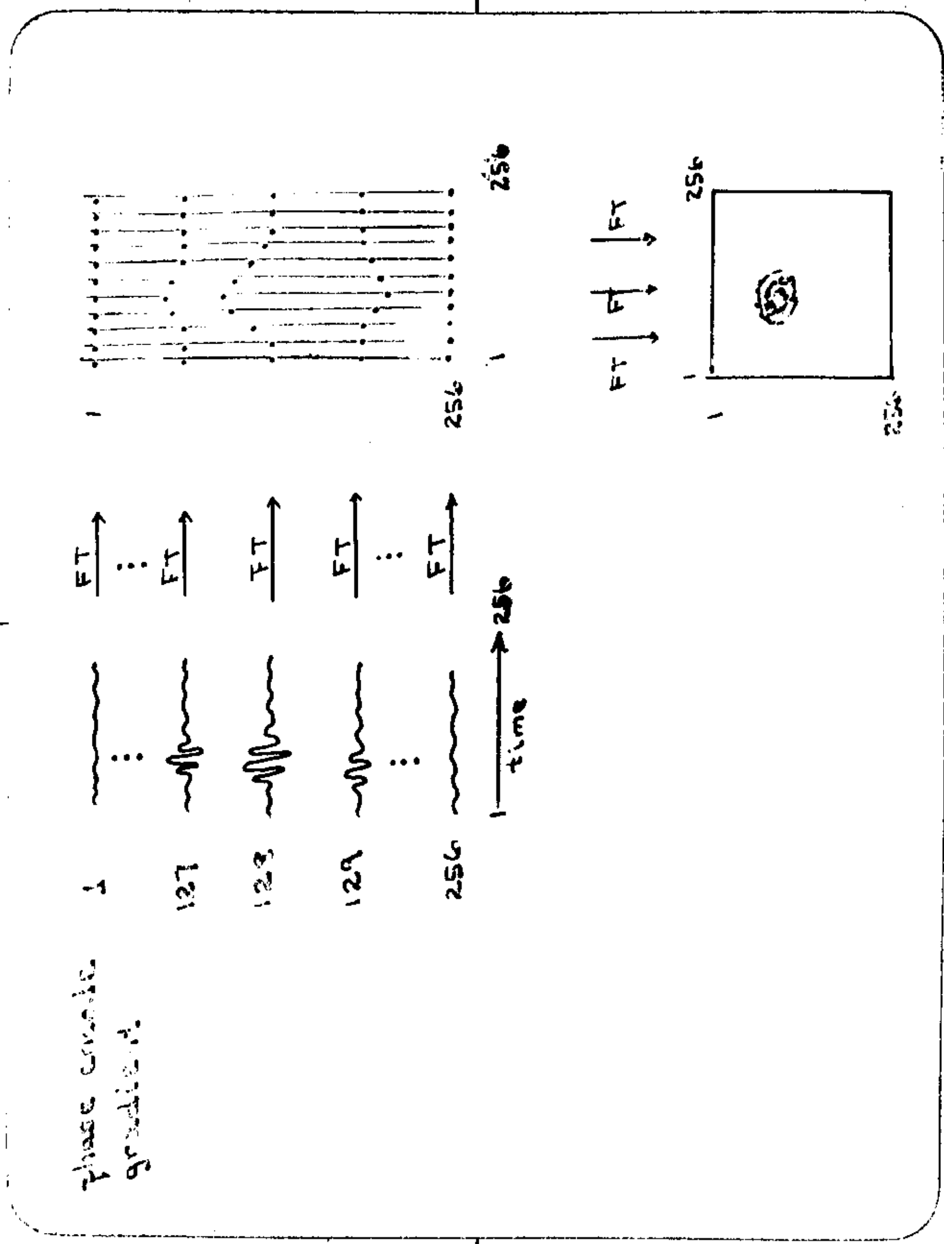



PERIOD
GRADIENTS
RF PULSES
SELECTIVE 90°
1
LICE SELECTION
ND EXCITATION
G_z
z
2
HASE ENCODING
G_y
y
SELECTIVE 180°
3
CHO FORMATION
G_z
z
4
SIGNAL
READ-OUT
G_x
x

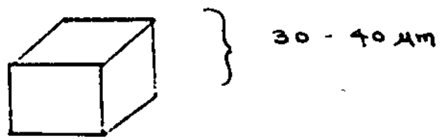

FT
256
time
127
128
129

What is the very best resolution you could "ever" get?

Assume: can detect 10^{16} spins

Assume: density = 1 g/cm^3

Assume: f [illegible] 14 g/mole - repeat unit



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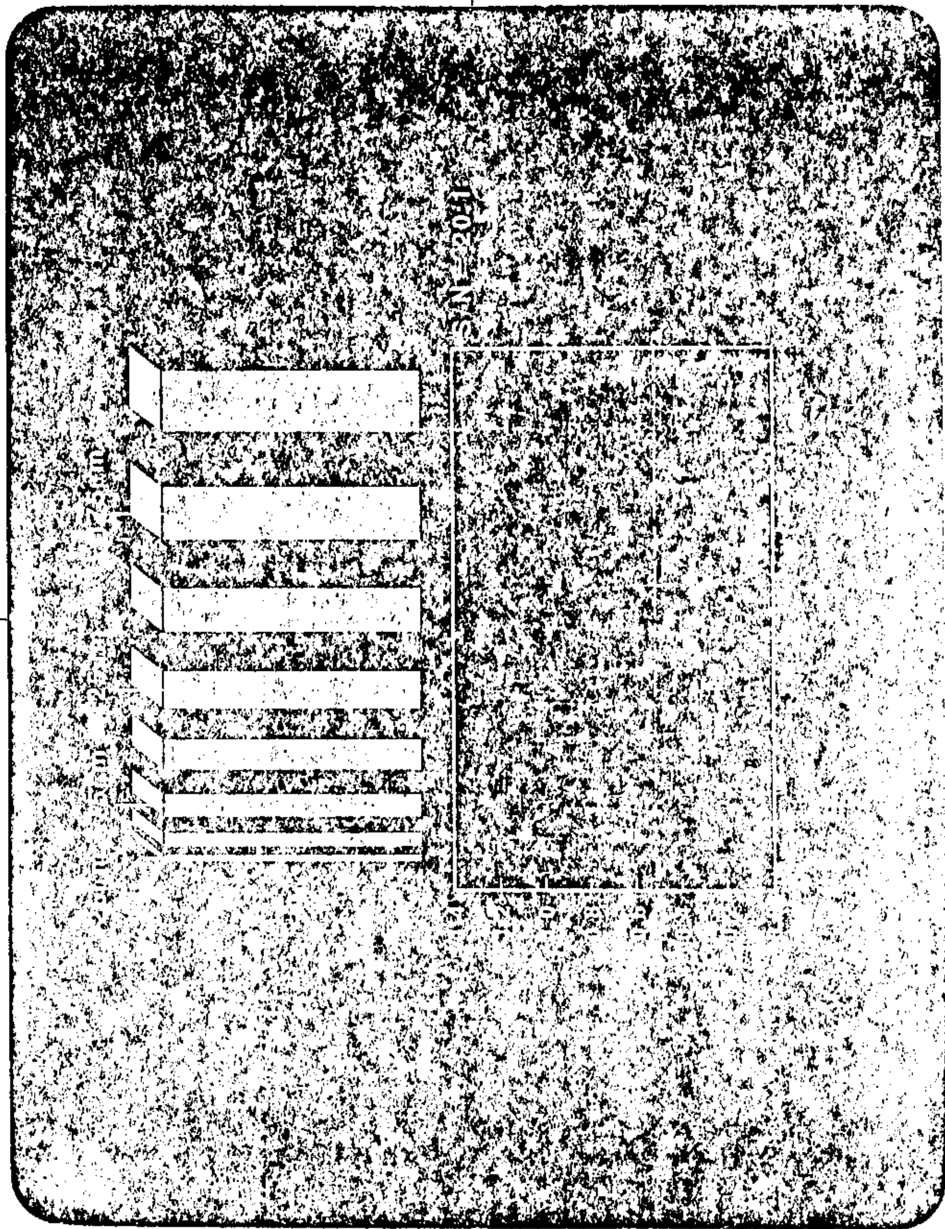
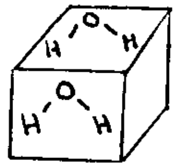
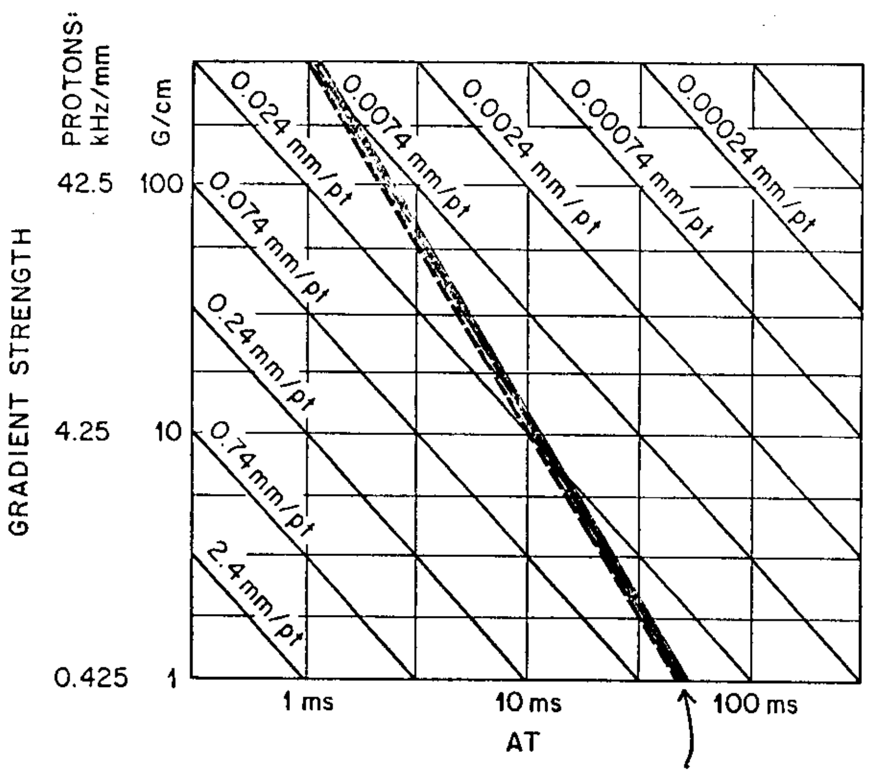




$$D = 2.5 \times 10^{-5}\ cm^2/sec$$



15% intensity loss because of water diffusion

- adapted from J. M. Listerud, S. W. Sinton, G. P. Drobny, Anal. Chem. 61, 358A (1989).

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Measuring Young's Modulus Of The Carotid Artery — Non-Invasively

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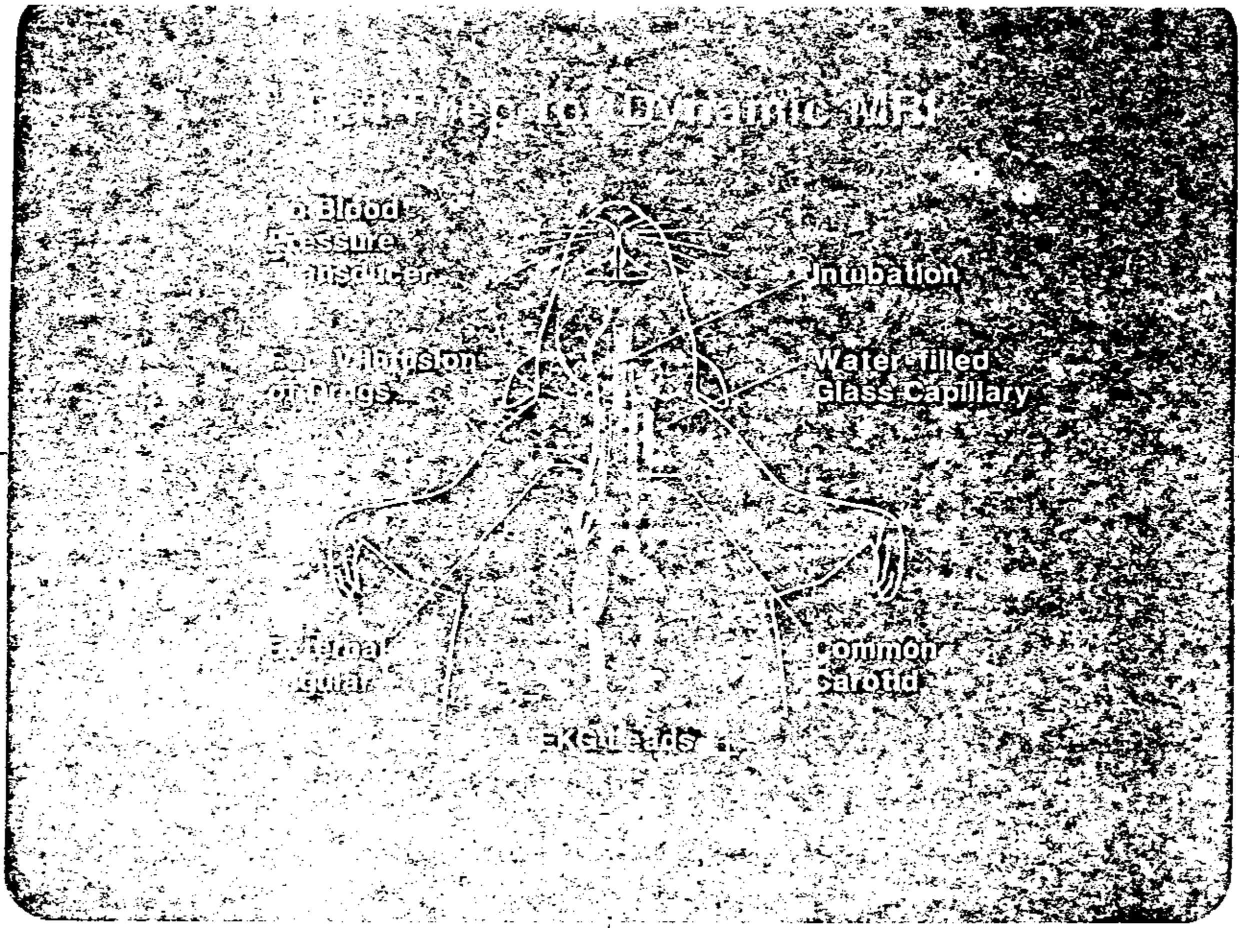
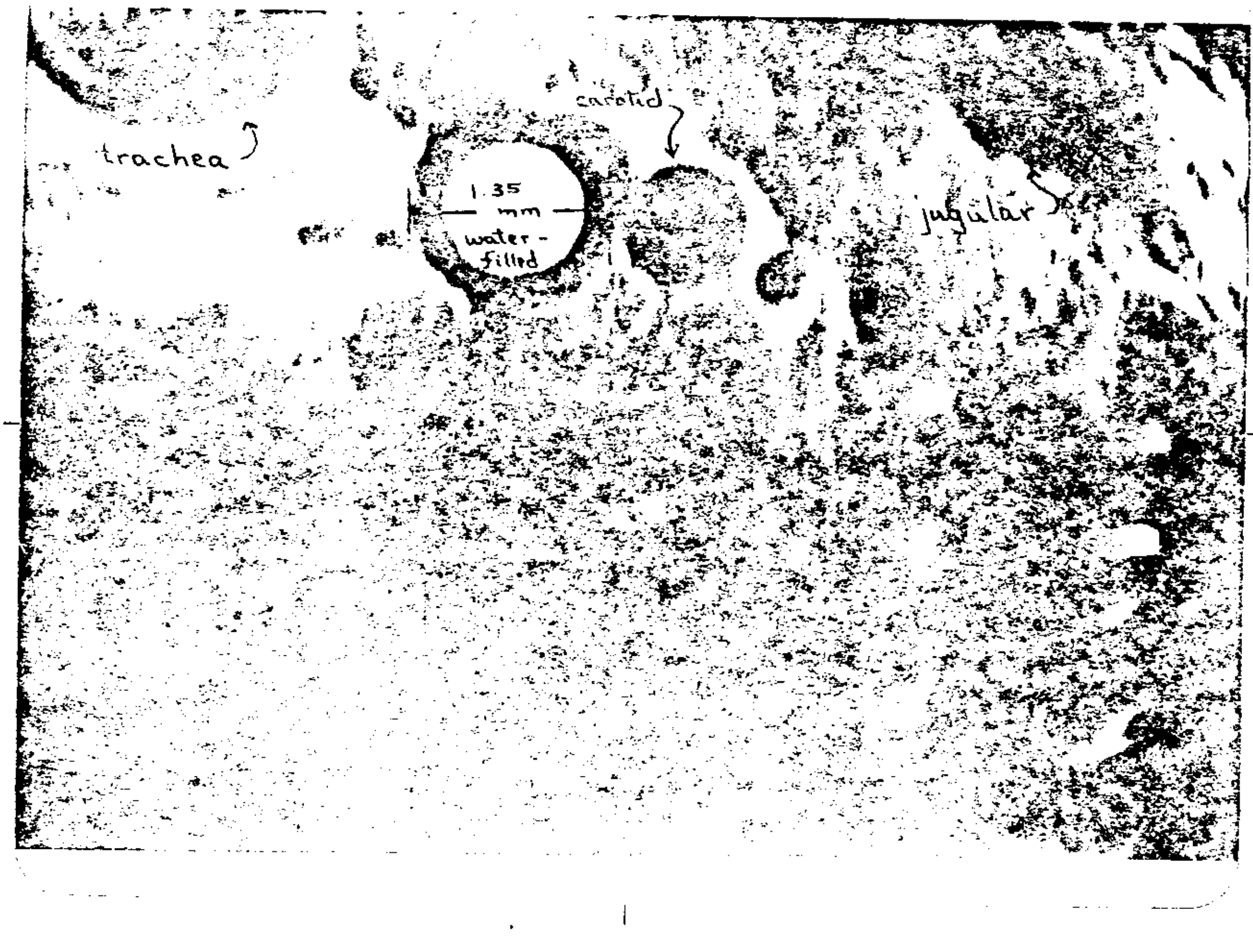
31



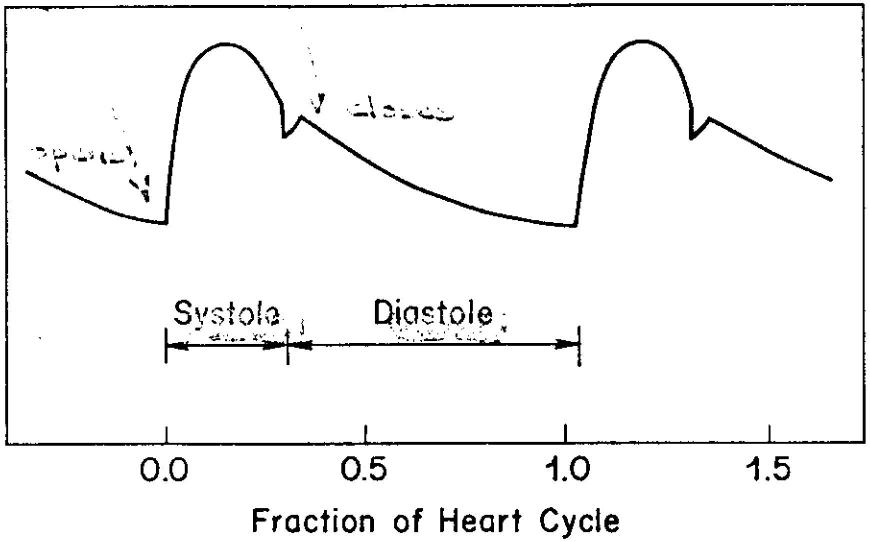
Dynamic MRI
Blood
Intubation
of Drugs
Water-filled
Glass Capillary
Common
Carotid

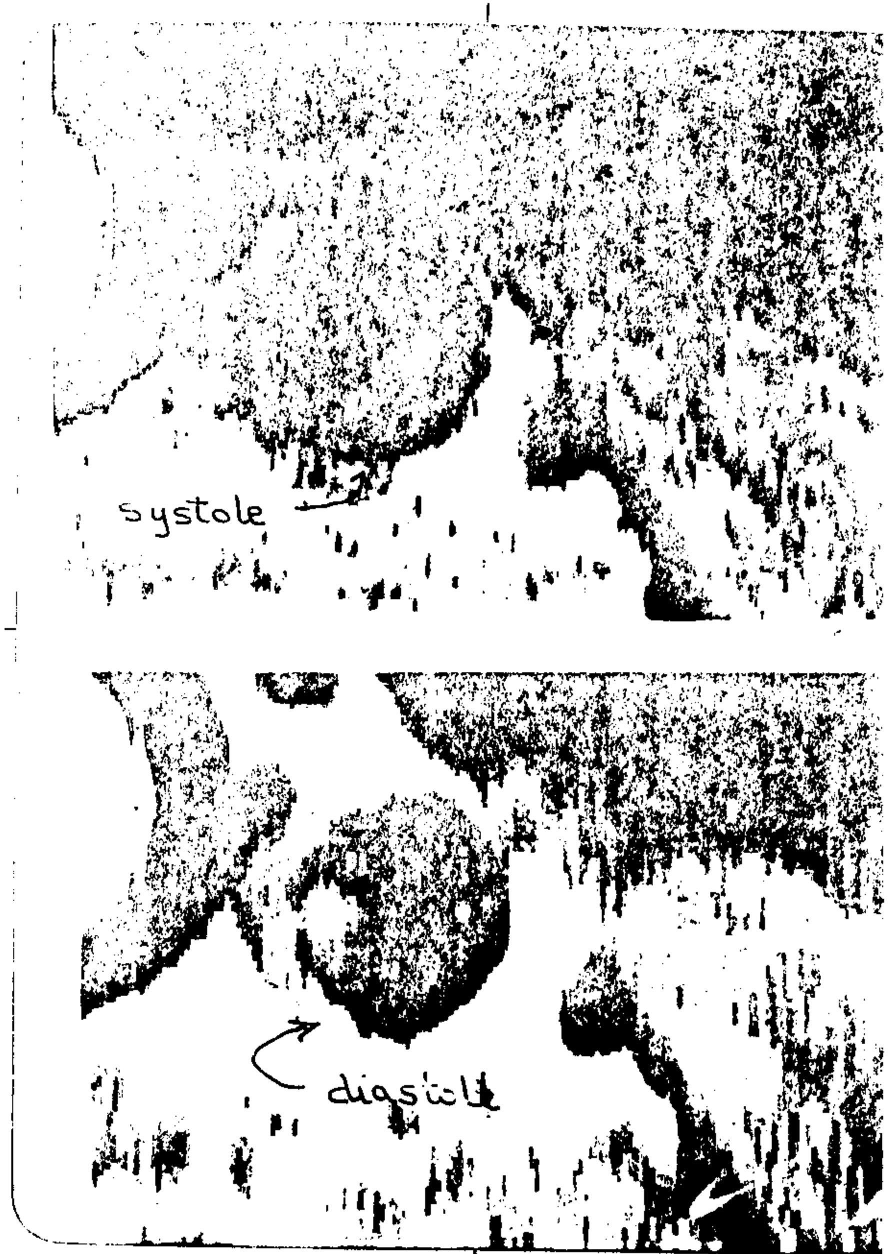
32



trachea
carotid
1.35 mm
water-filled
jugular

Blood Pressure Wave Form





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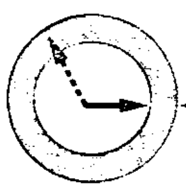
Young's Modulus:

a measure of stiffness

$$E = \frac{2\pi r_0}{t_0} K$$

r_0 = non-extended radius



t_0 = thickness

K is related to the pressure change

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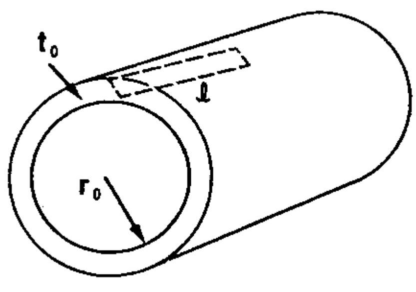

Young's modulus

$$E = \frac{2\pi r_0}{t_0} K$$

$$\text{Force} = Pr\ell = K\ell(2\pi[r - r_0])$$

Integrate:

$$P_2 - P_1 = 2\pi K \ell n (r_2/r_1)$$

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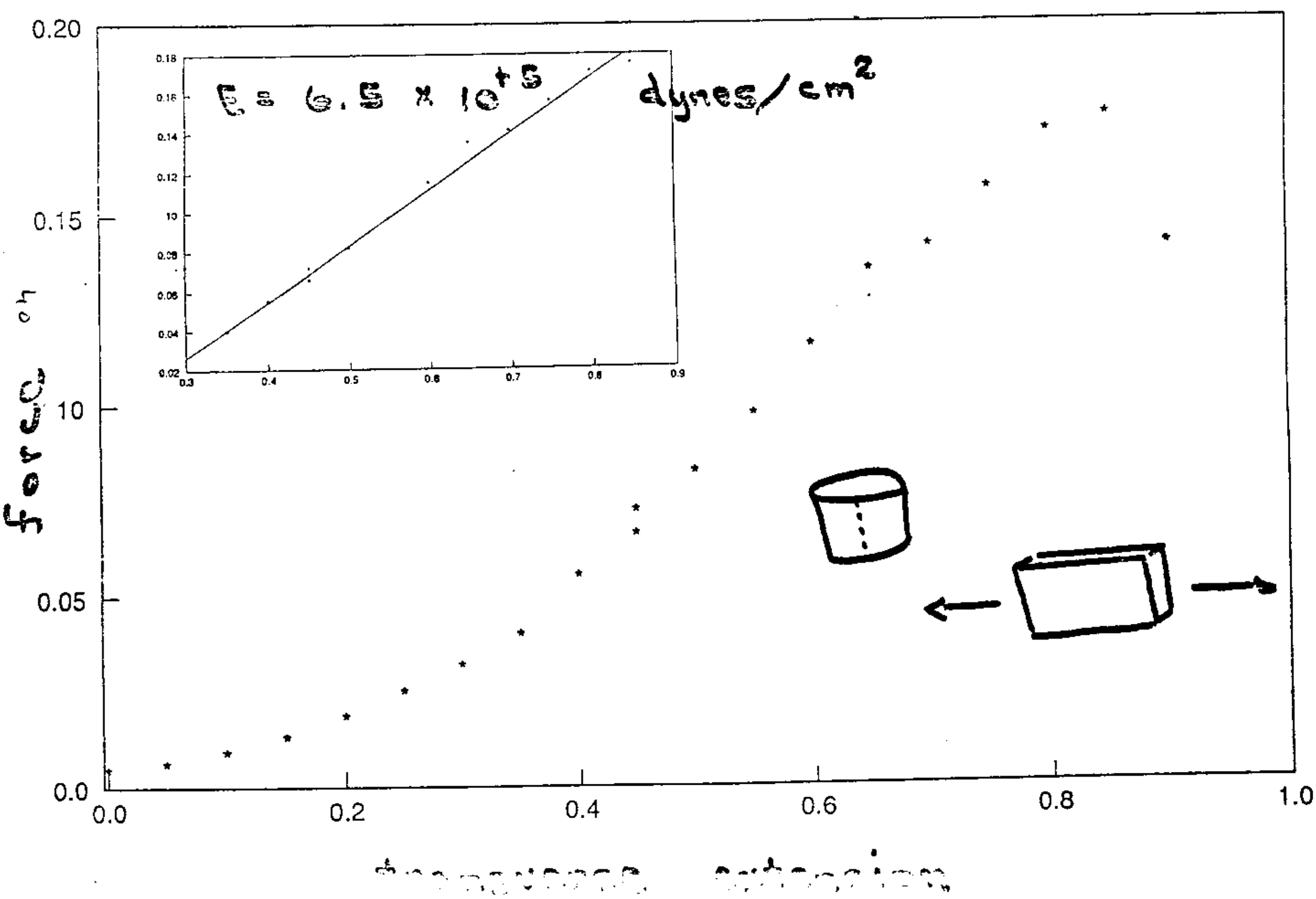
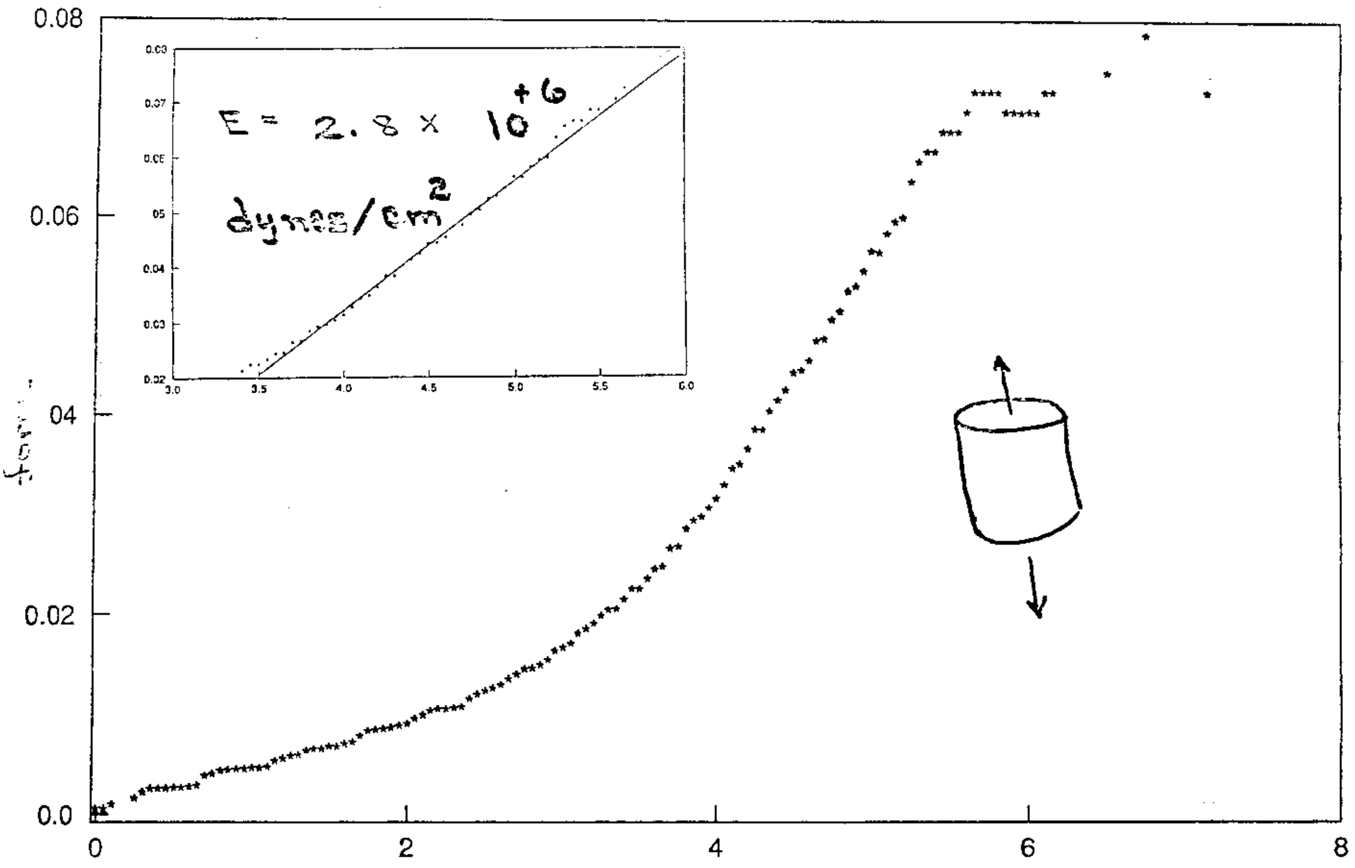
$E_{NMR} = 7 \times 10^{+3}$ dynes/cm^2





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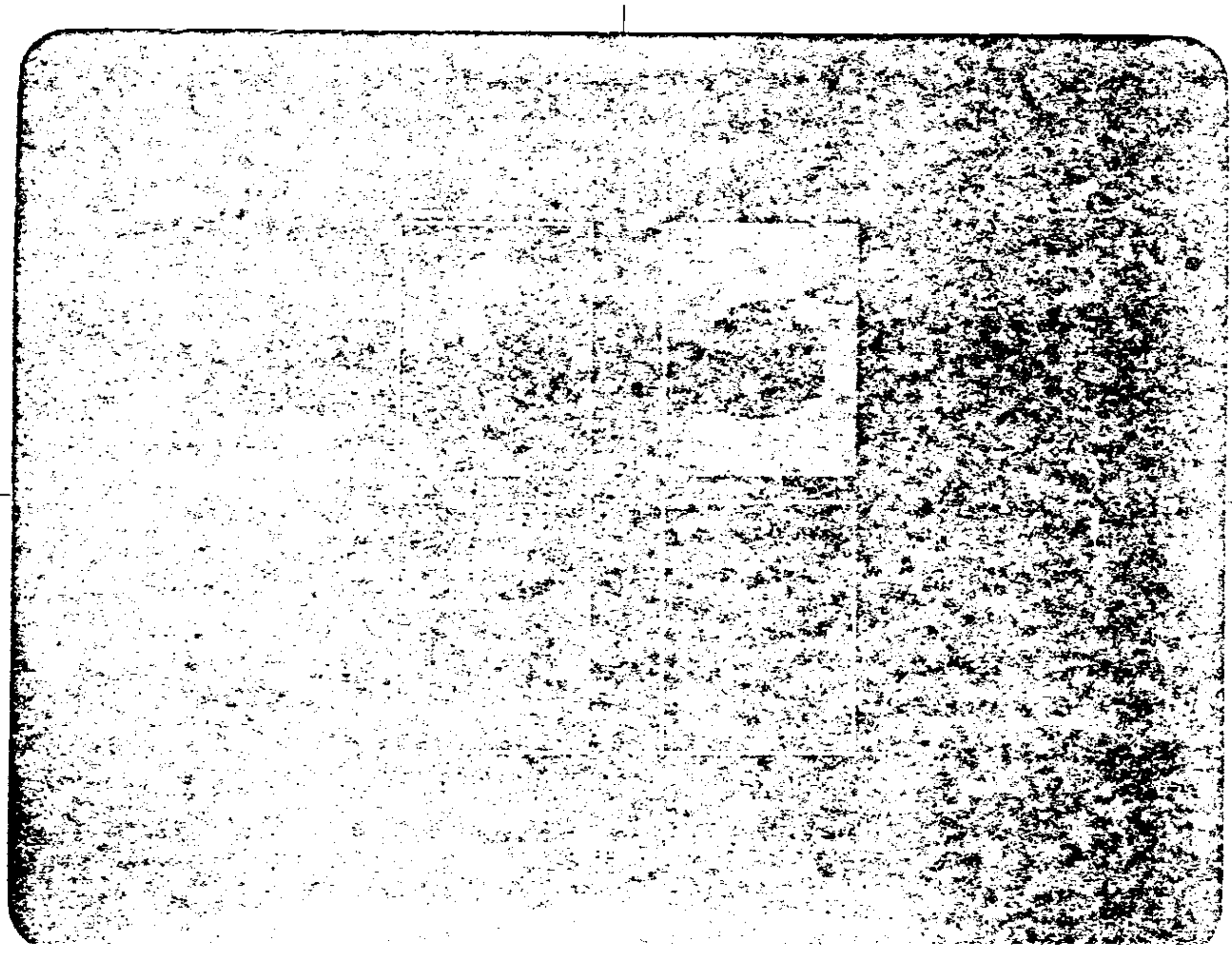

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44

Carotid Elasticity - Conclusions

- Developed a method to measure local arterial stiffness
- Mapped the entire cardiac cycle
- Directly observed effects of vasoconstrictors and vasodilators

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MRI Can Provide Vector Fields Of Fluid Flow -- Blood

MHG35428.03

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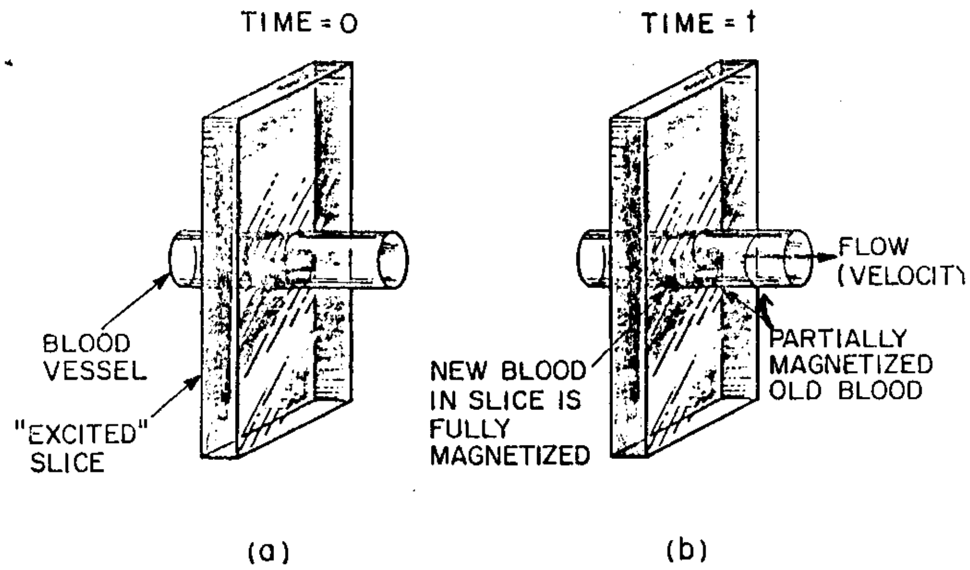

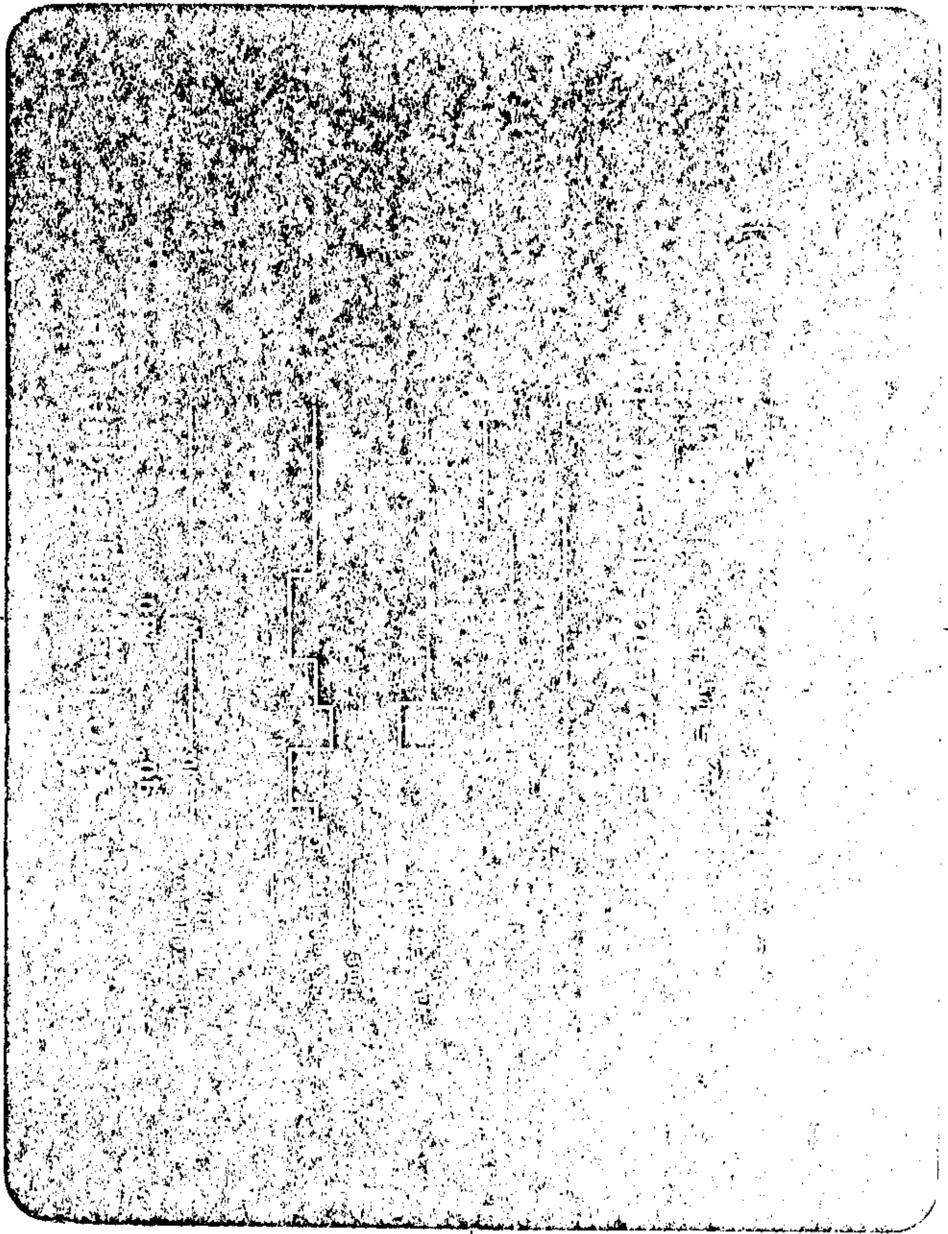

for example:

$$\Phi_1 = G_z \int_0^{\tau_1} (z_0 + V_z t)\, dt$$

$$\Phi_1 = G_z z_0 \tau_1 + \frac{1}{2} G_z V_z \tau_1^2$$

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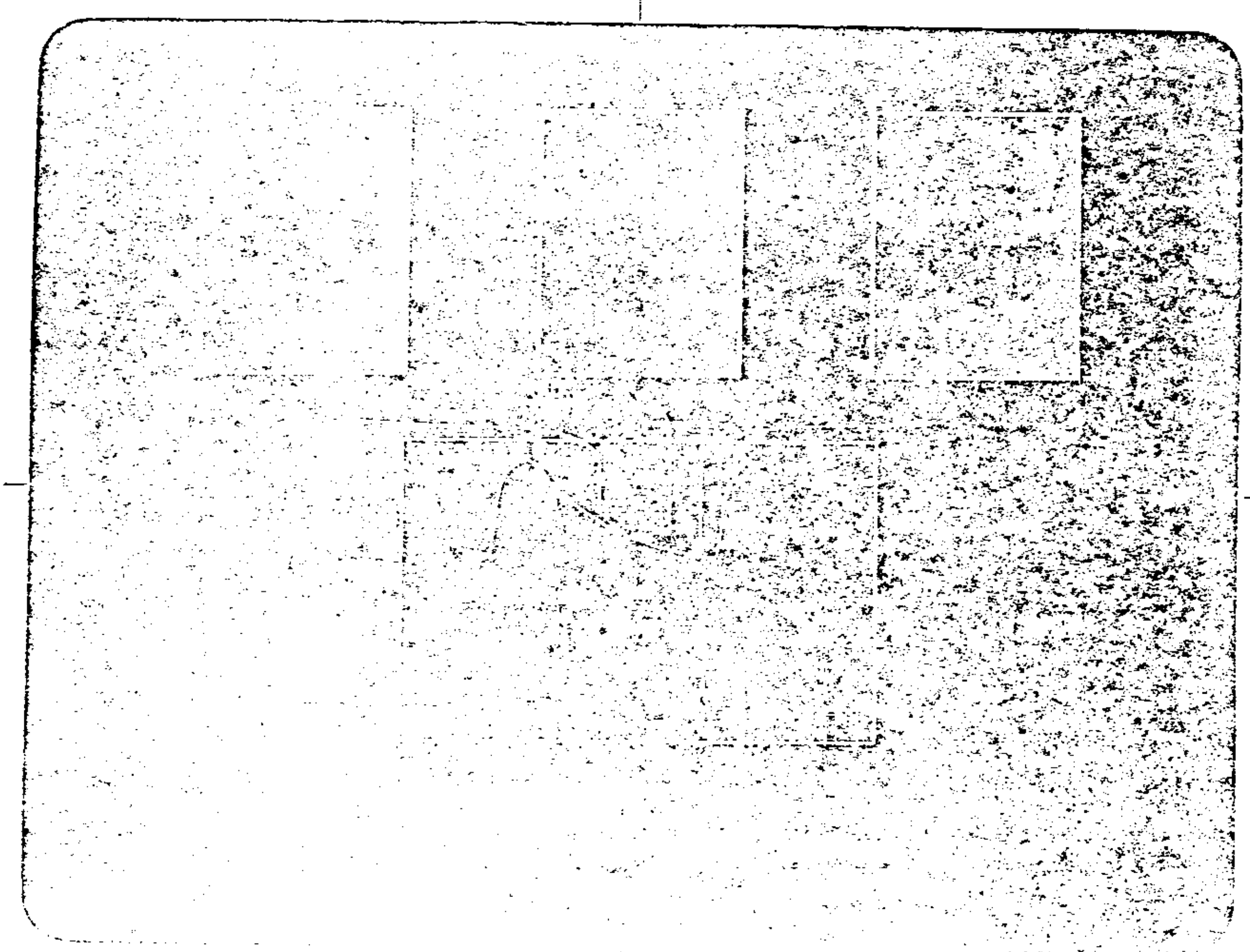
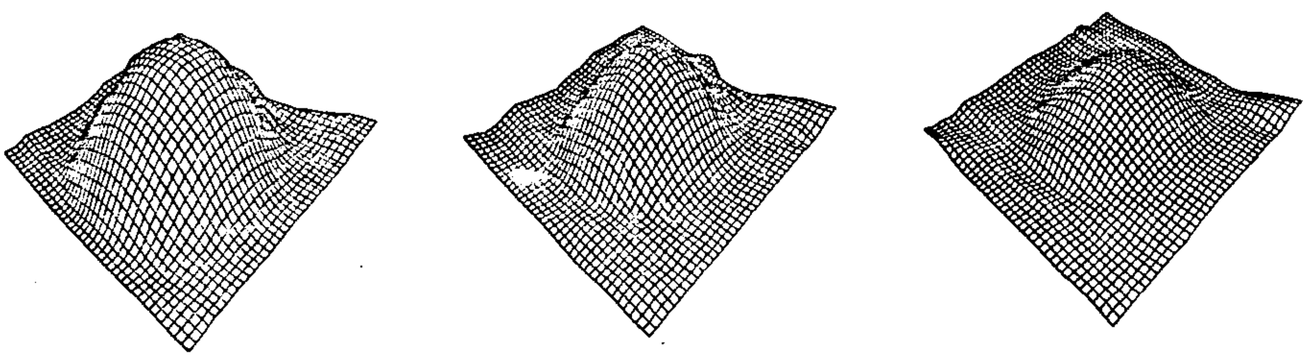


E-9143 (6-85)

49

Fraction of Heart Cycle



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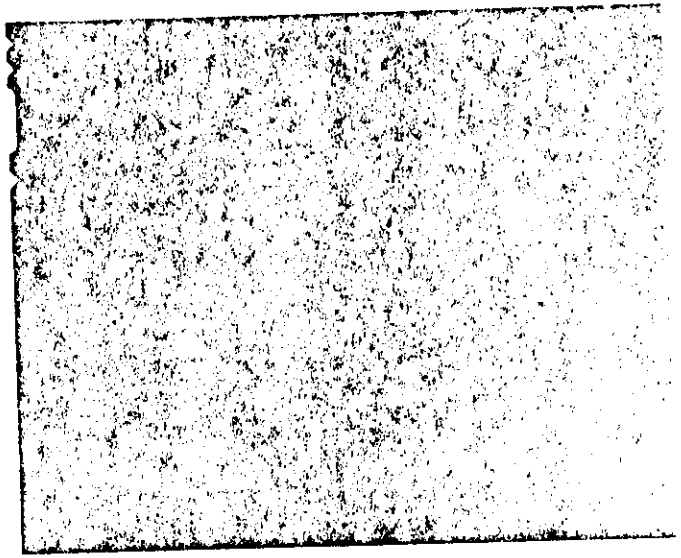

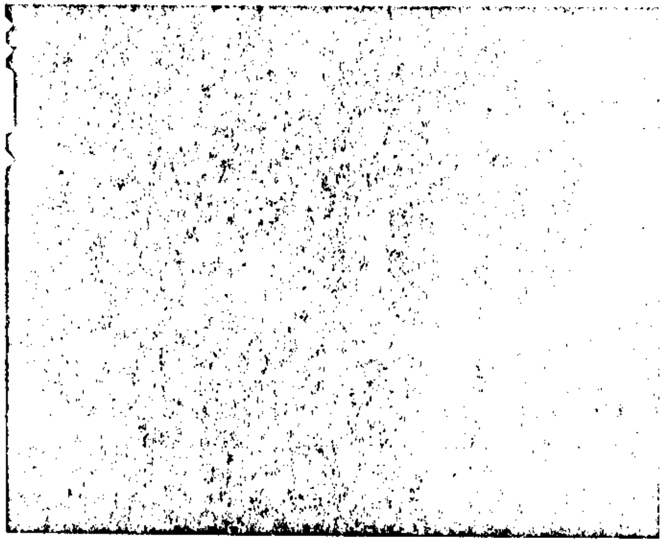

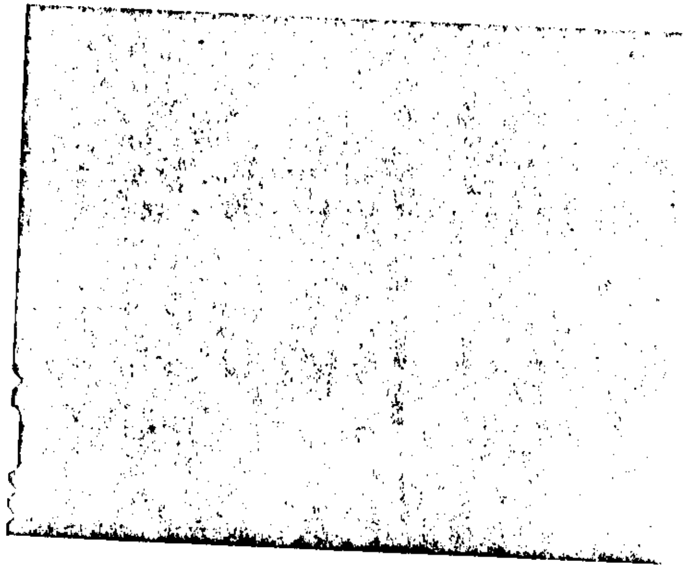

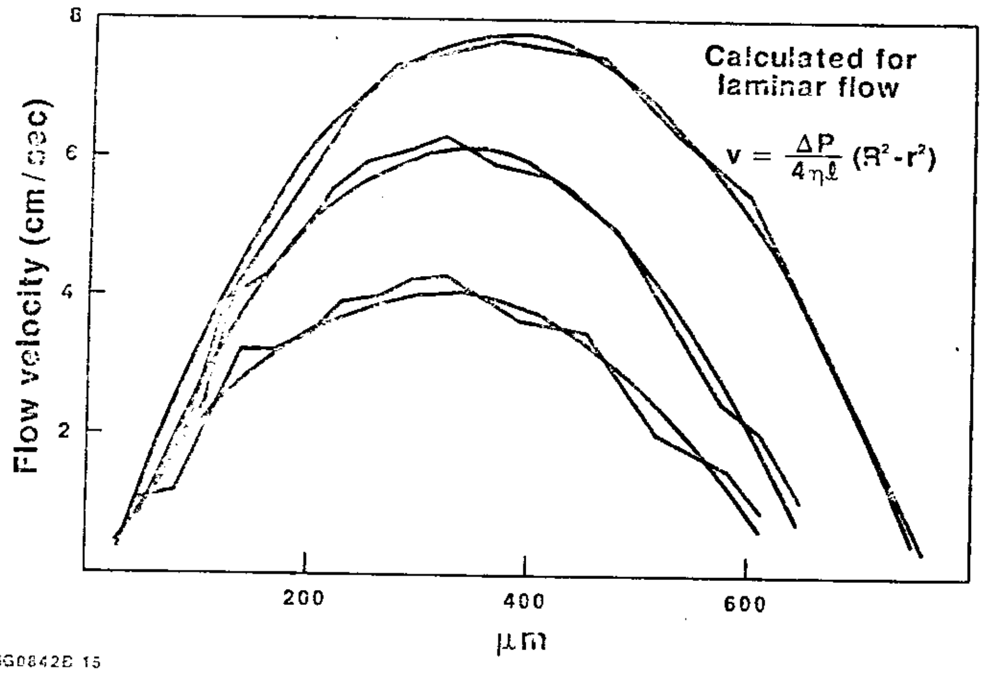

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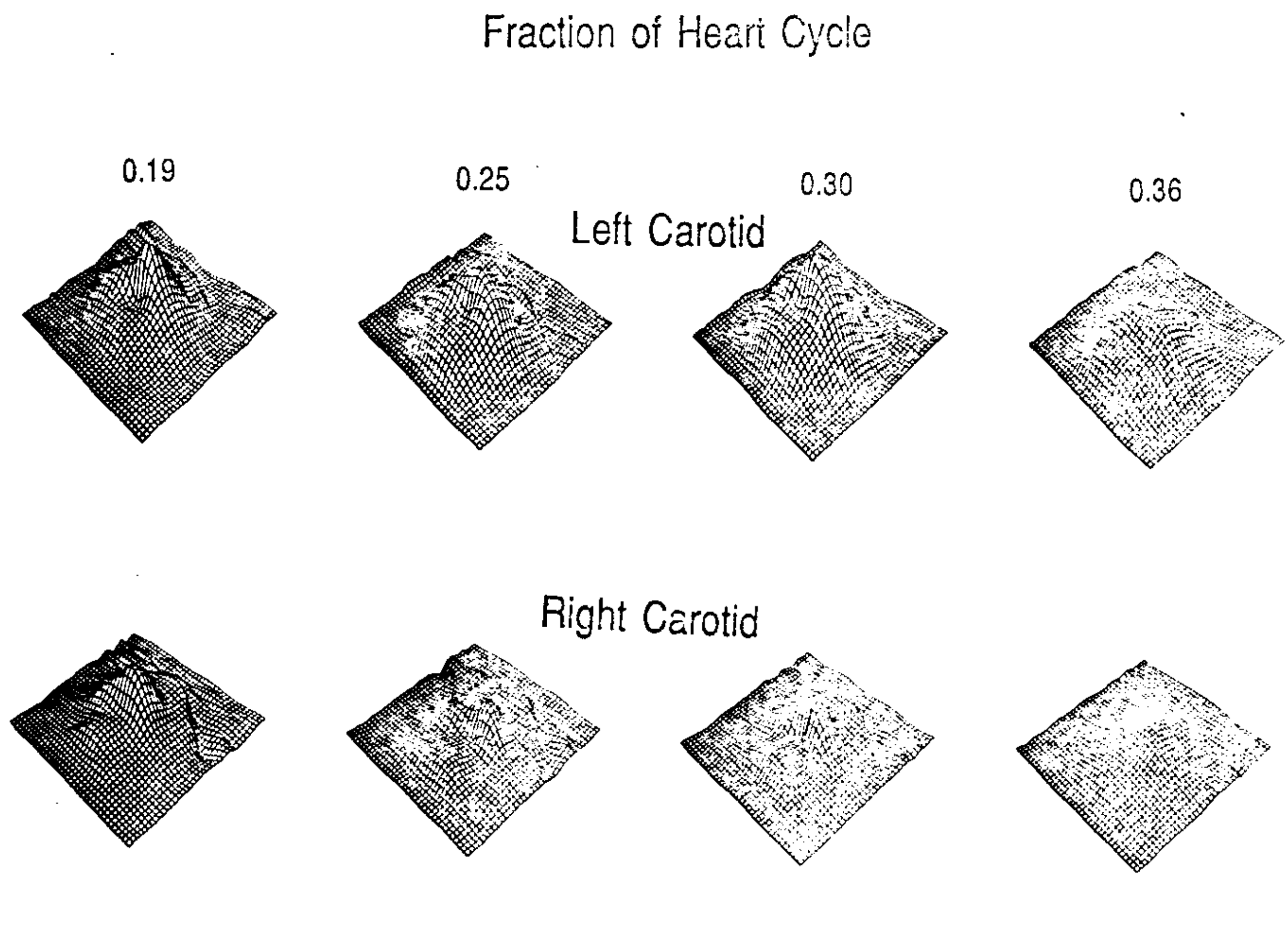
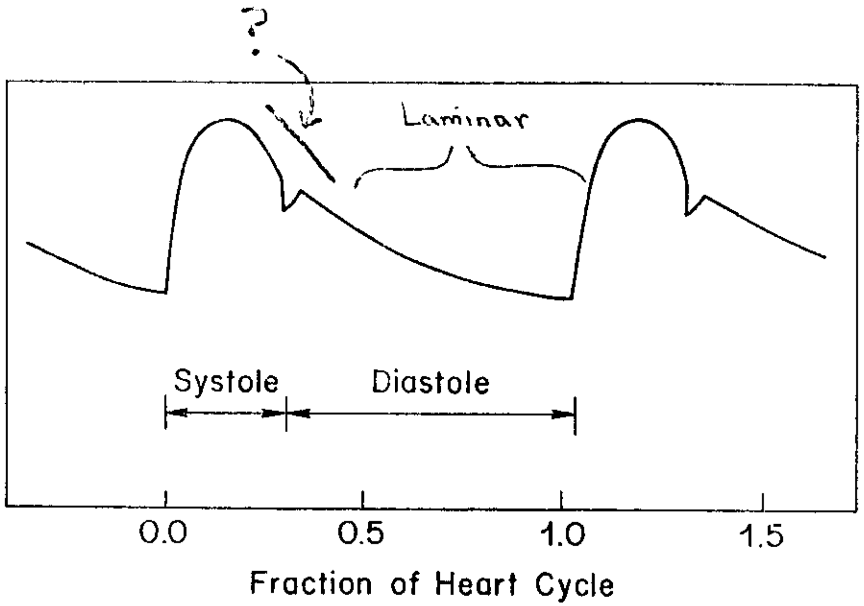
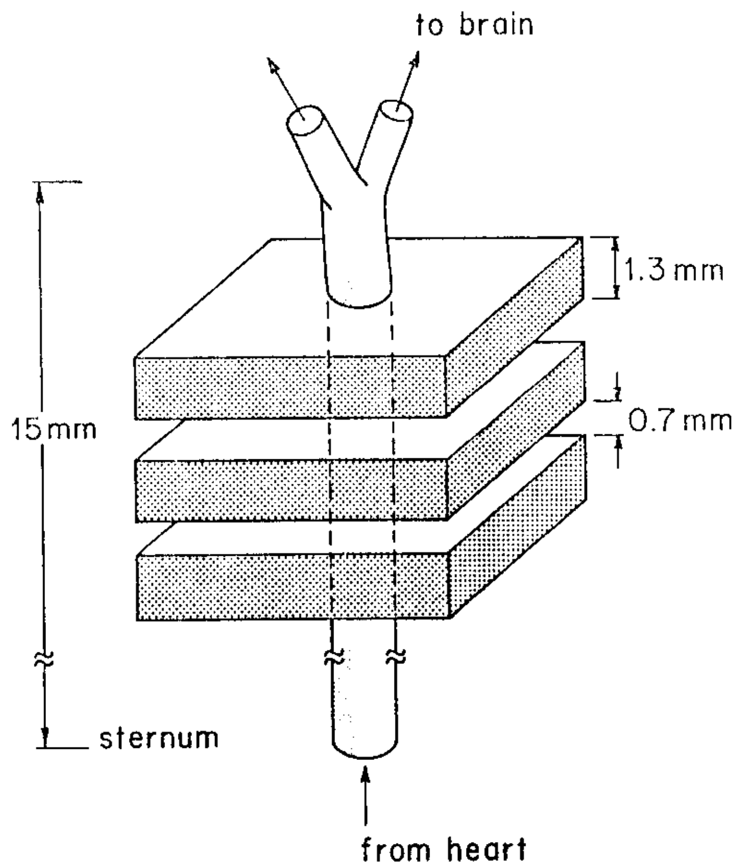



?
Laminar
Systole
Diastole
0.0
0.5
1.0
1.5
Fraction of Heart Cycle


to brain
1.3 mm
15 mm
0.7 mm
sternum
from heart

VG. NO.

Arterial Blood Flow - Conclusions

- Phase angle images provide velocity fields of fluid flow throughout heart cycle
  - Laminar during diastole
  - Complex during deceleration period of systole
- Flow observed simultaneously through both arteries - - - peaks first in left carotid
- Body compensates by increasing flow to head when artery is blocked or stenosed
- These velocity fields provide data otherwise unobtainable for hemodynamics modelling

MHG0842B.04

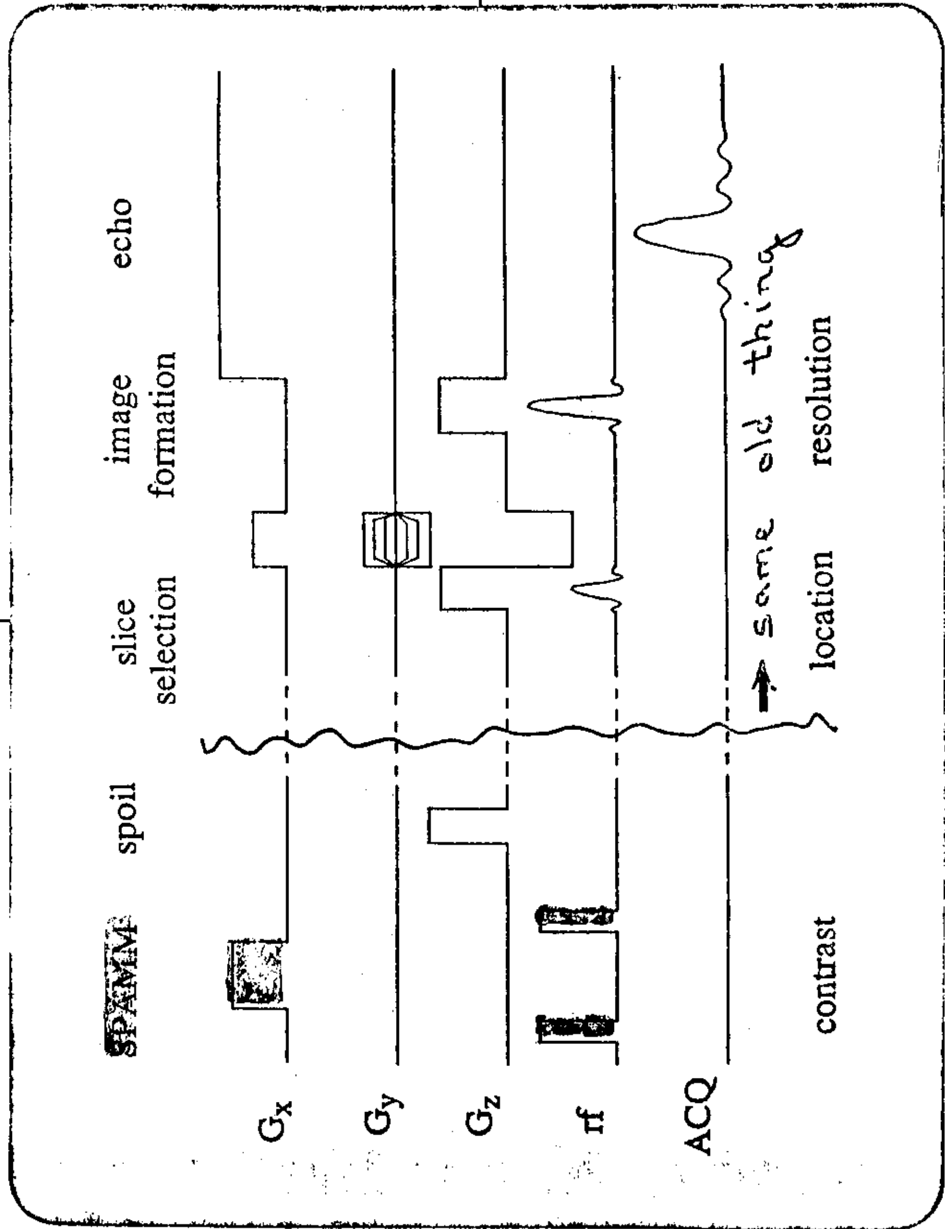
VG. NO.

SPAtially Modulated Magnetization

(SPAMM) can measure ultra-slow flow

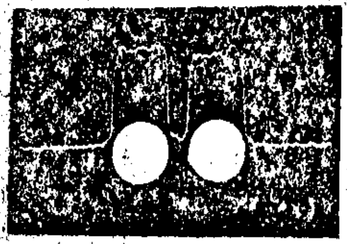
MHG0842B.07

How slow can
you go ??

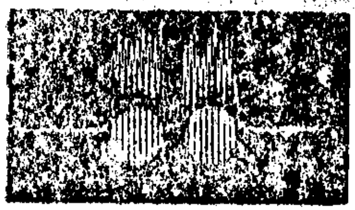


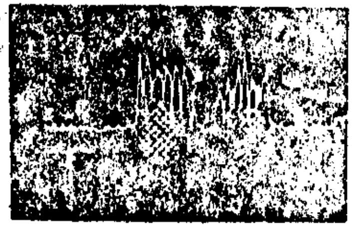
SPAMM on a Phantom

spin echo control

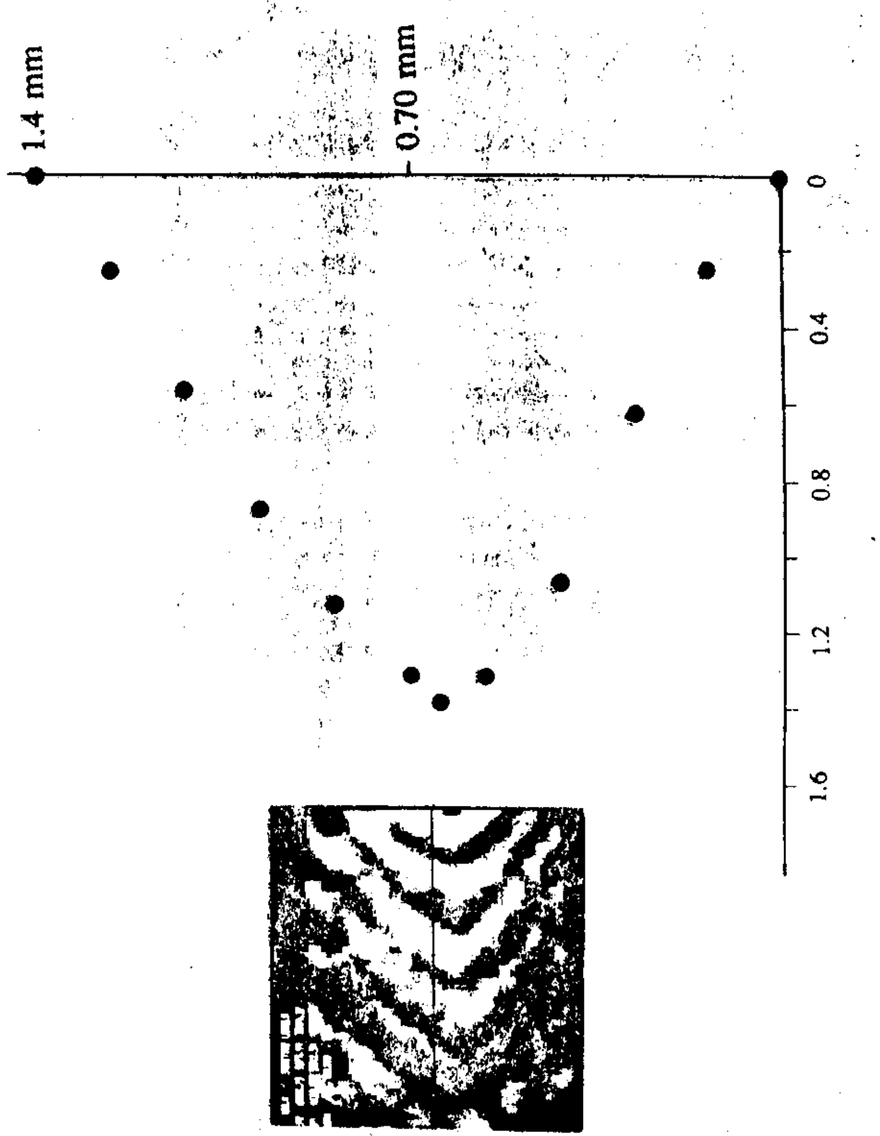


1D transverse 2D





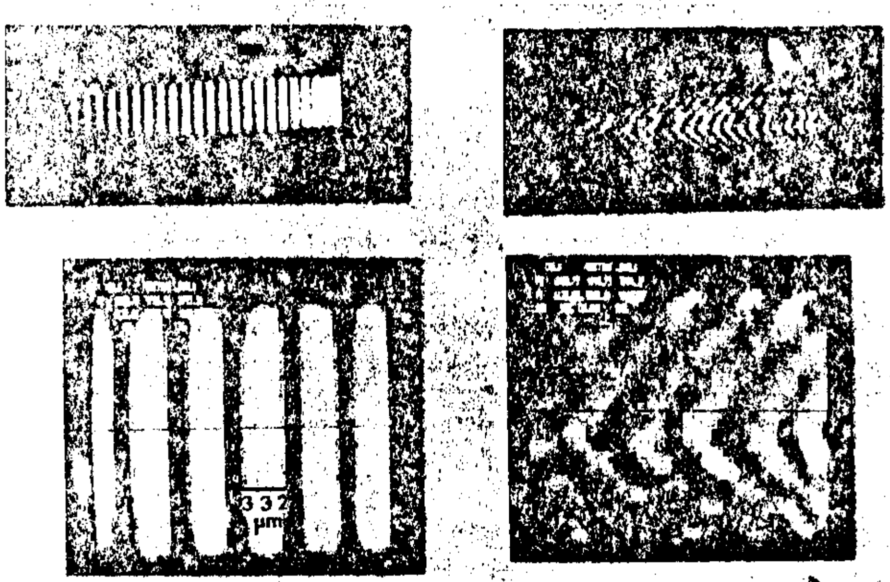
1D longitudinal



SPAMM on a Phantom

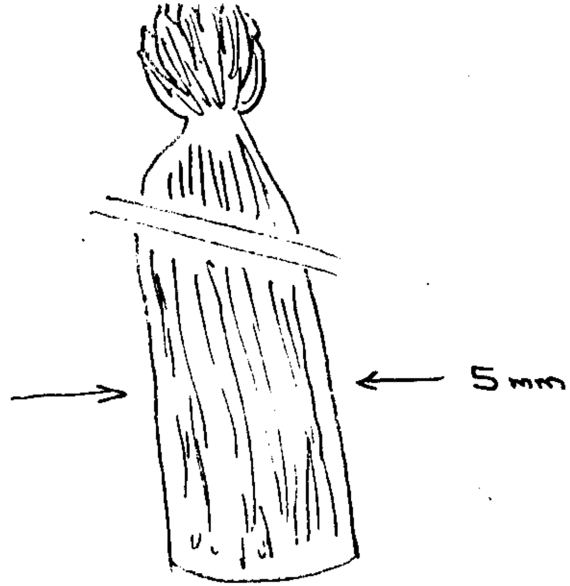
Longitudinal Section

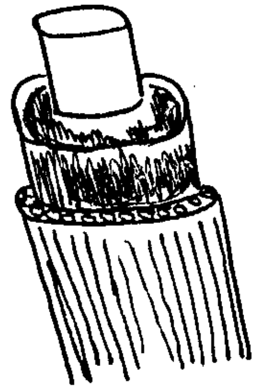
1.4 mm ID Tube
Doped Water



[redacted]

average [redacted]
6.8×10^{-1} cm/s





TOP
DO NOT AFFIX OVERLAYS ALONG THIS SURFACE

VG. NO.________

65

SPAMM - Conclusions

- Resolution: 15 μm pixels; 81 μm stripes
- SPAMM accurately measures ultra-slow flow; limit $\simeq 1 \times 10^{-3}$ cm/s
- Applications? Transpiration; lymph; capillary flow; Ions rushing to lesions

MHG0842B.06

E-9148 (6-85)
AT&T BELL LABORATORIES

AT&T

TOP
DO NOT AFFIX OVERLAYS ALONG THIS SURFACE

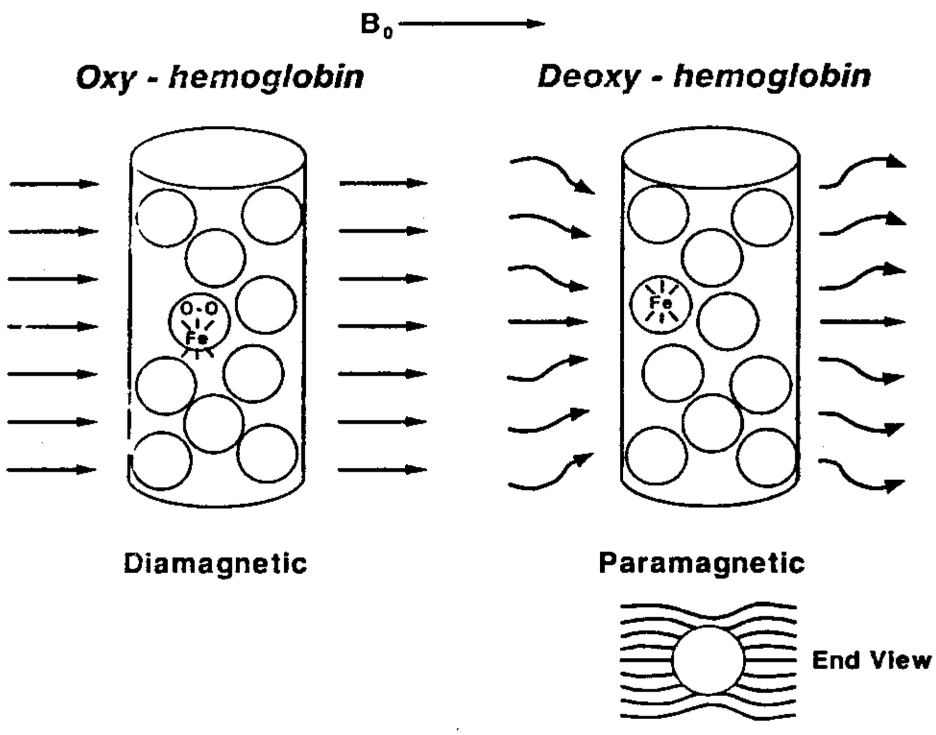
VG. NO.________

66

Blood Oxygenation Level Dependent

(BOLD) **image contrast provides PET-like images of biological function**

MHG0842B.02



MHG0842B.14

E-9148 (6-85)
AT&T BELL LABORATORIES

AT&T

TOP
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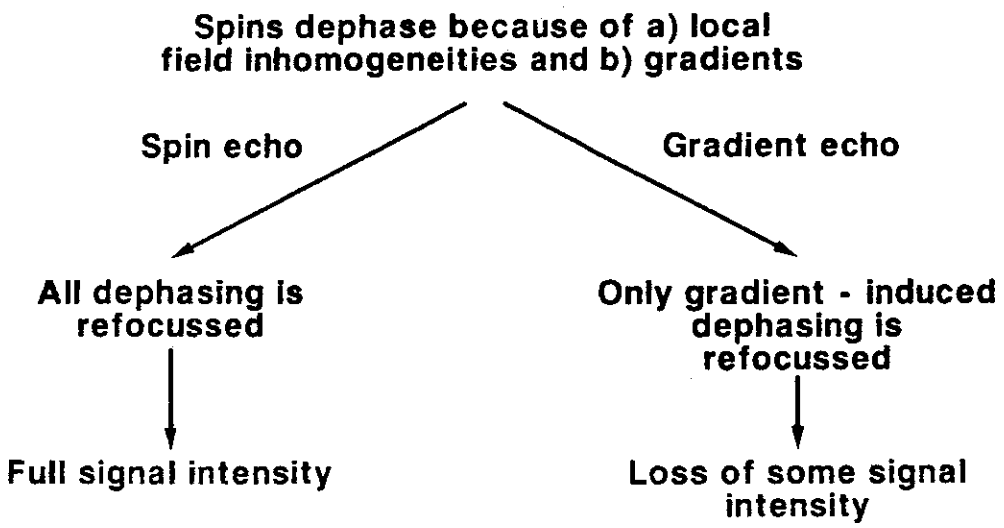
VG. NO.________



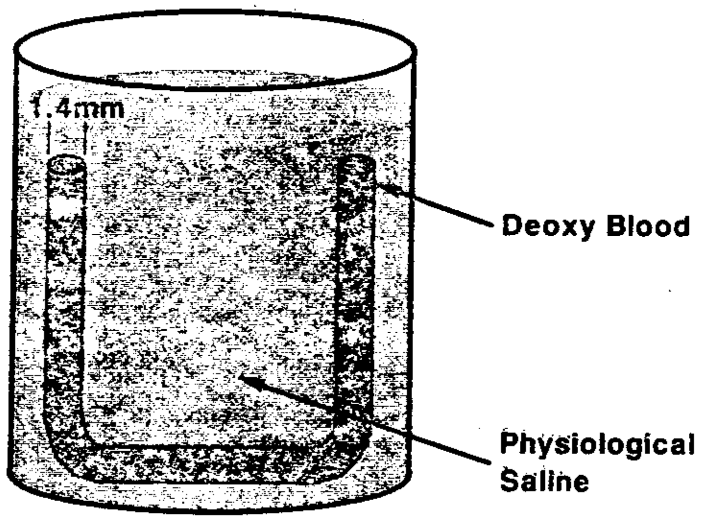
MHG0842B.12

E-9148 (6-85)
AT&T BELL LABORATORIES

AT&T

TOP
DO NOT AFFIX OVERLAYS ALONG THIS SURFACE

VG. NO.______



MHG0842B.13

E-9148 (6-85)
AT&T BELL LABORATORIES

AT&T

TOP
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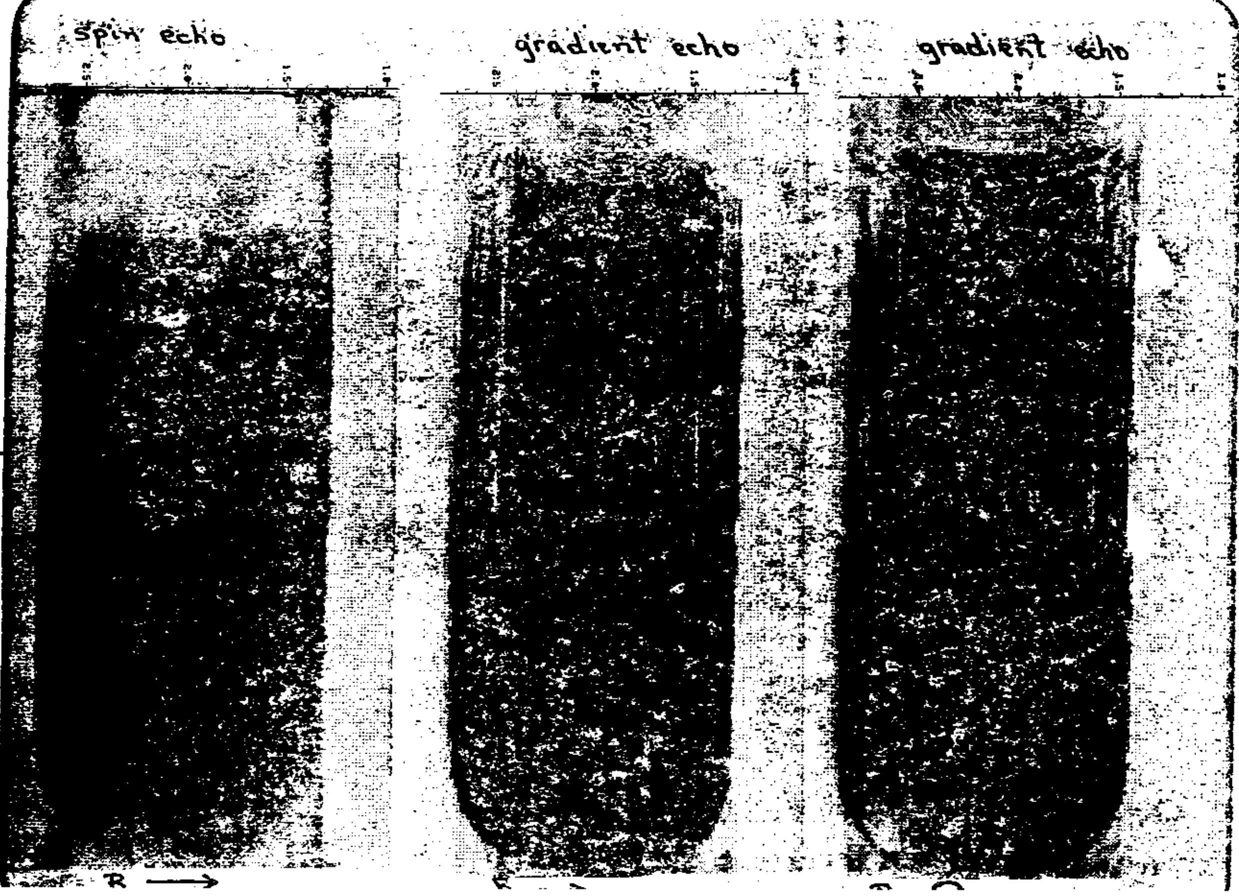
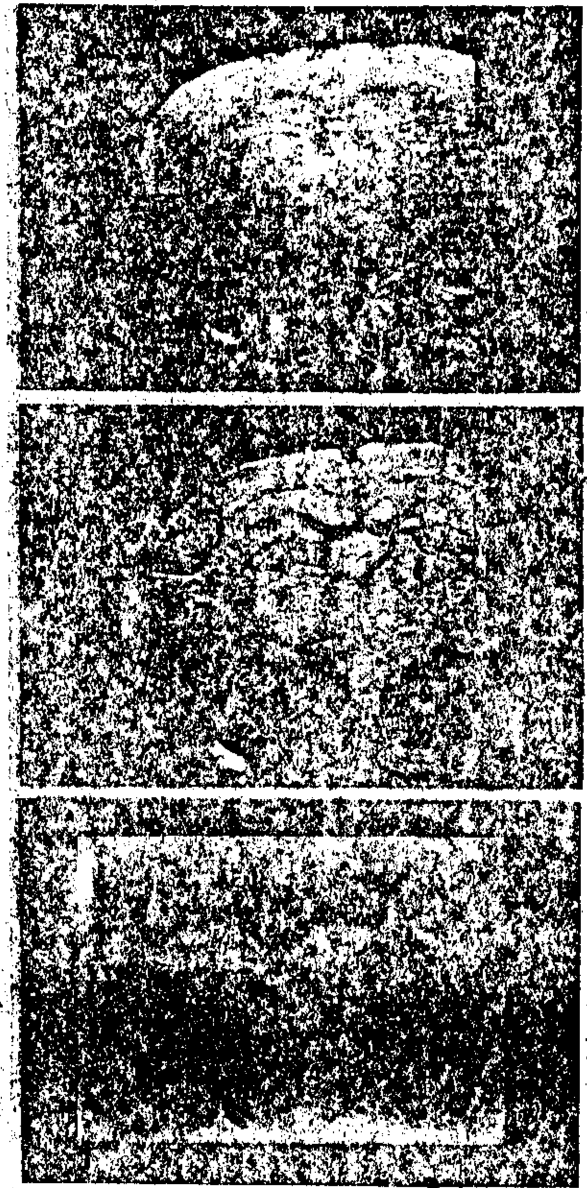
VG. NO.______



can see
corresponding
~~in~~ blood
Vessels

Anaesthe[illegible]

100% O_2



a

20% O_2

← Note large intensity losses

b

histo-logical section

c

E-9148 (6-85)
AT&T BELL LABORATORIES

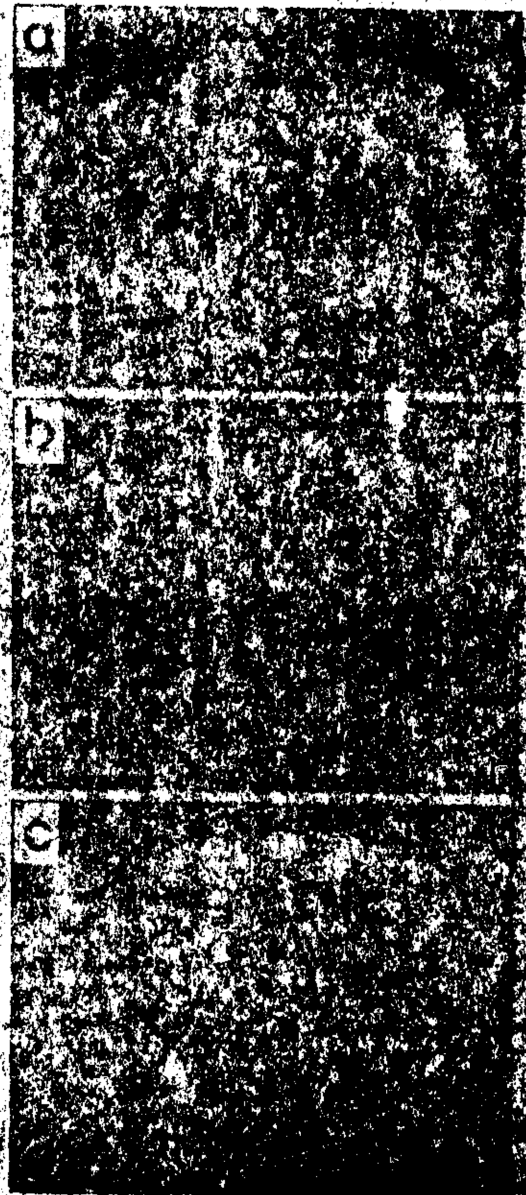
AT&T BELL LABORATORIES
E-9148 (6-85)

sagittal sinus flow in (c) is faster than (b) by a factor of 4

stimulation → local O_2 use → flow goes up

want may cause 20% change in flow

Valium 100% O_2



Urethane 100% O_2

Urethane 90% O_2 10% CO_2 causes increased blood flow

Valium + EtOH cause 10% inten. change

DO NOT AFFIX OVERLAYS ALONG THIS SURFACE

TOP

VG. NO.

BOLD Contrast - Conclusions

- Magnetic susceptibility effect due to paramagnetic deoxyhemoglobin
- Sensitive to
  - 50-90% blood oxygenation
  - Vessels ⊥ to B_o
  - Vessels >50 μm
- Provides PET-like information without radioactive injections
- Takes advantage of Nature's own contrast agent

MHG0842B.08

AT&T

E-9148 (6-85)
AT&T BELL LABORATORIES

- Measuring Young's modulus "on the fly"
- Producing vector flow fields of a non-Newtonian fluid
- Characterizing ultra-slow flow and anisotropic diffusion