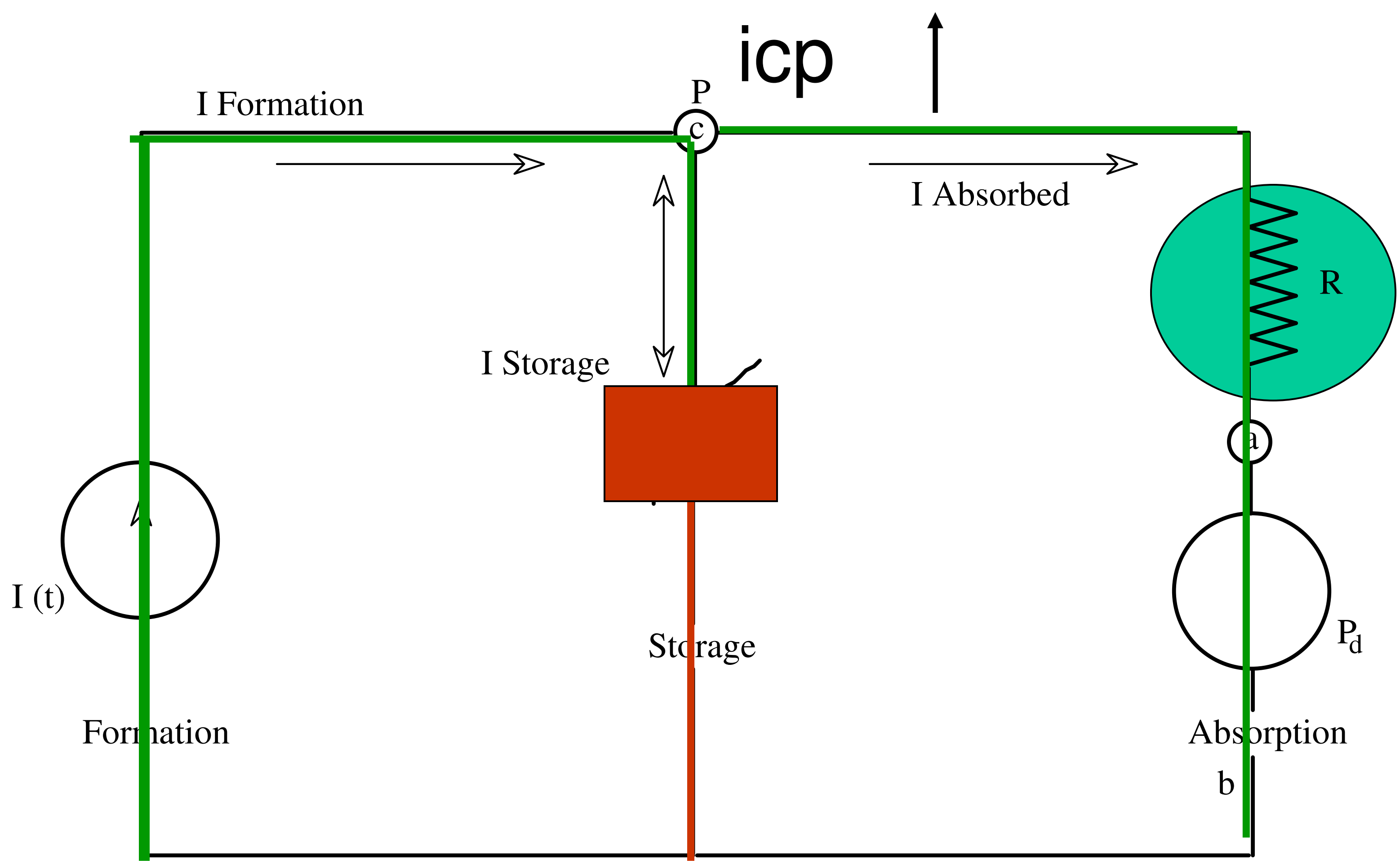

icp
P
c
I Formation
I Absorbed
R
I Storage
a
I (t)
Storage
P_d
Formation
Absorption
b

$$ICP = I_f R_o + P_v$$

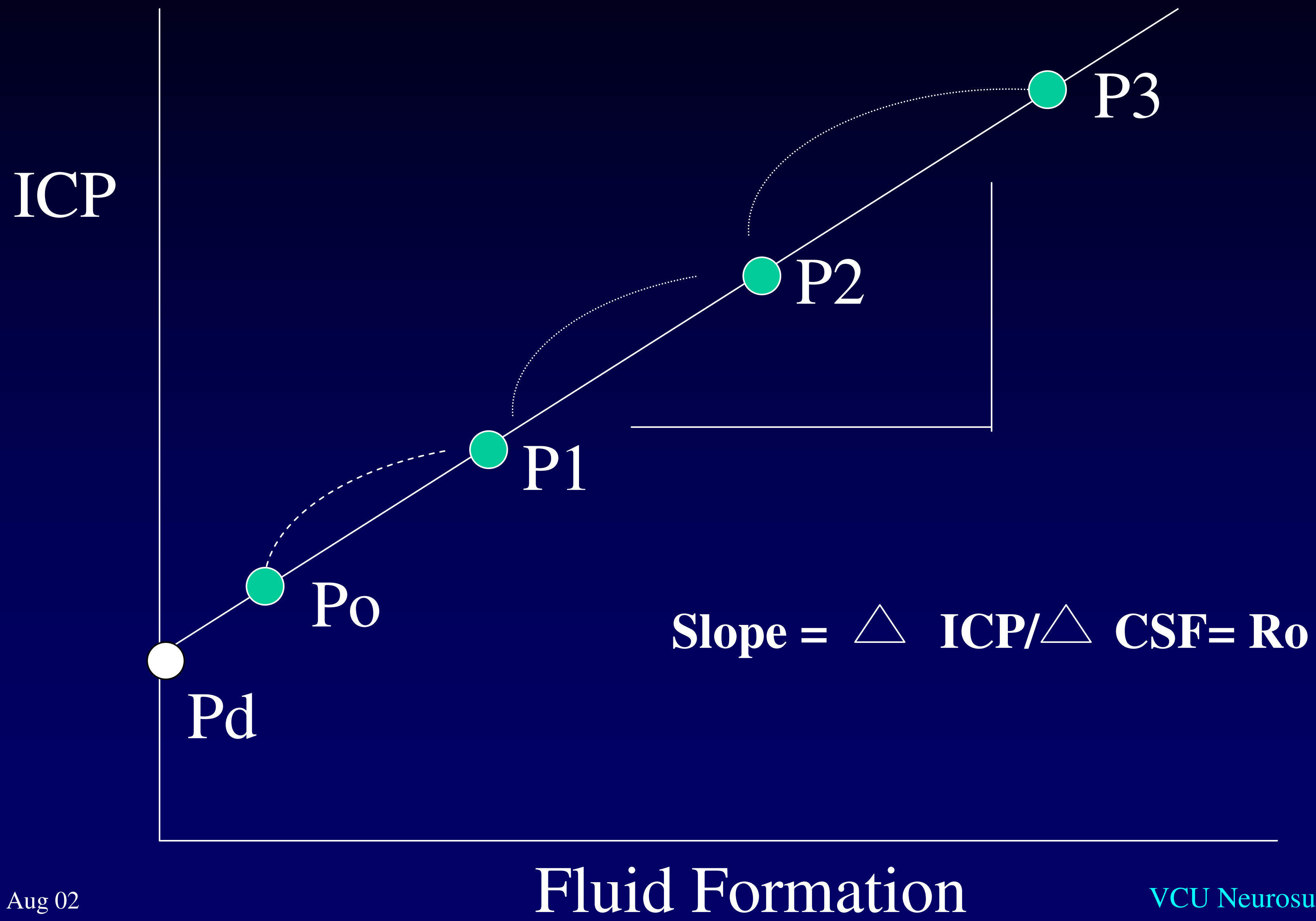
ICP = Intracranial Pressure

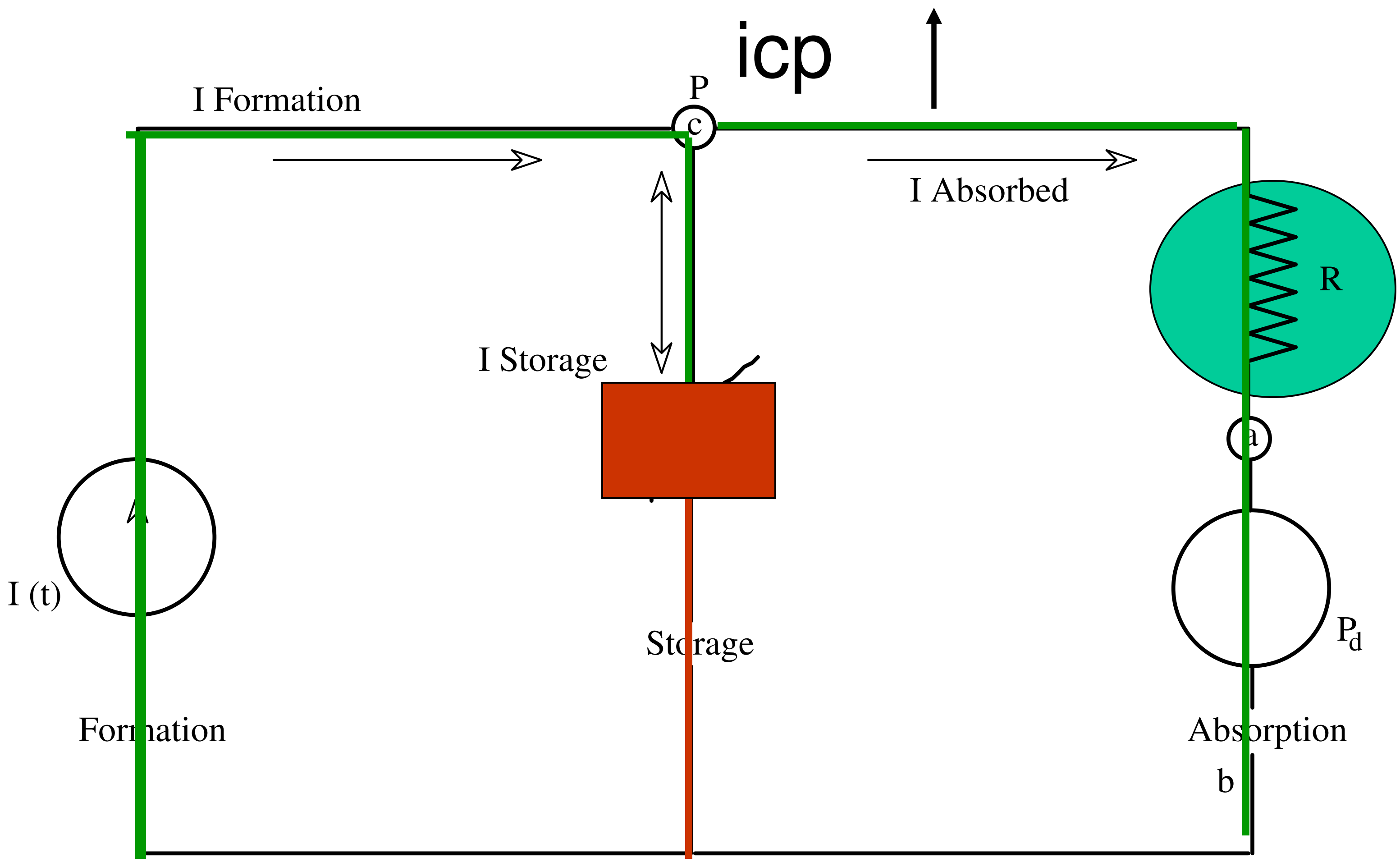
I_f = CSF rate of formation

R_o = Outflow resistance

P_v = Dural Sinus Pressure

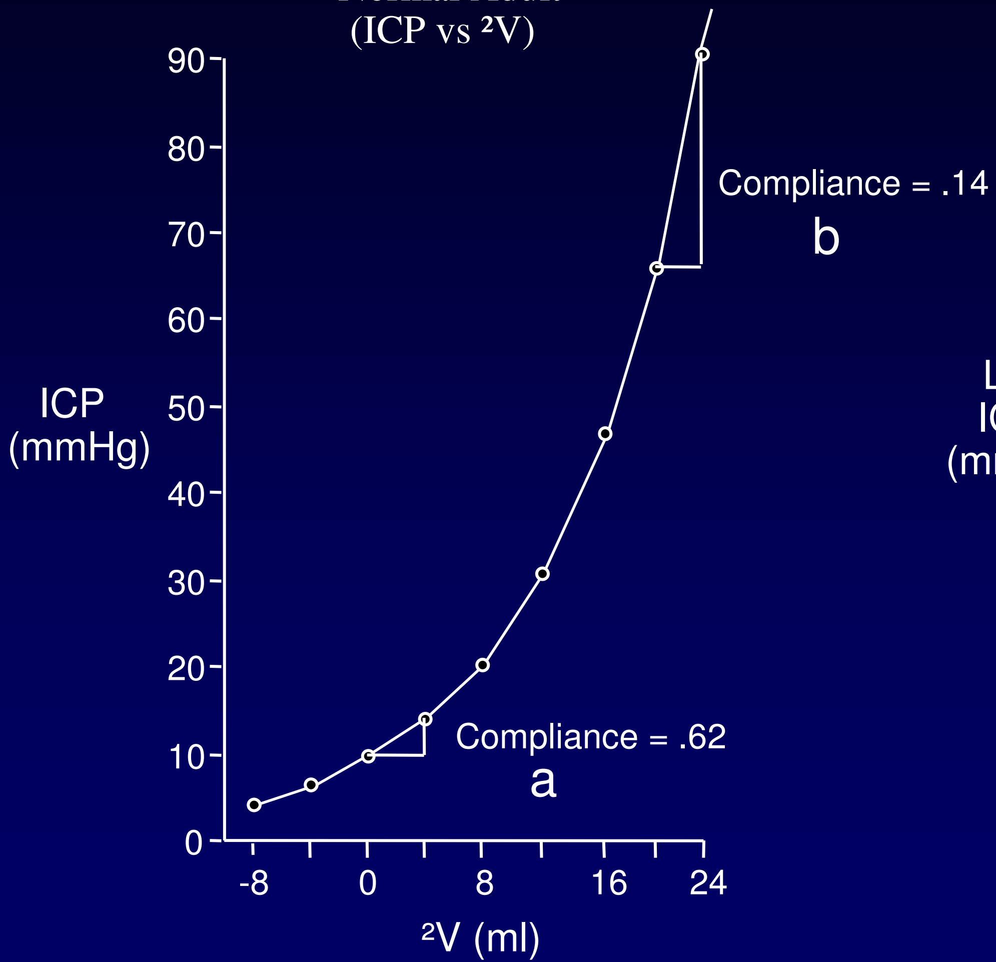
Measurement of CSF Resistance




icp
P
I Formation
c
I Absorbed
R
I Storage
a
I (t)
Storage
Pd
Formation
Absorption
b

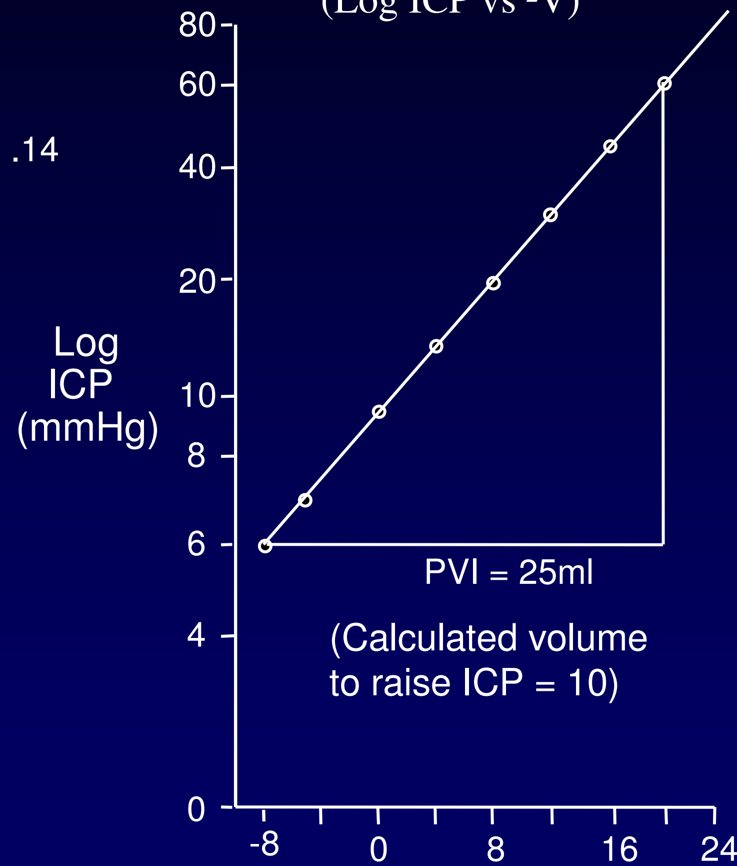
[A] Pressure Volume Curve

Normal Adult
(ICP vs ²V)



[B] Pressure Volume Index (PVI)

Normal Adult
(Log ICP vs ²V)



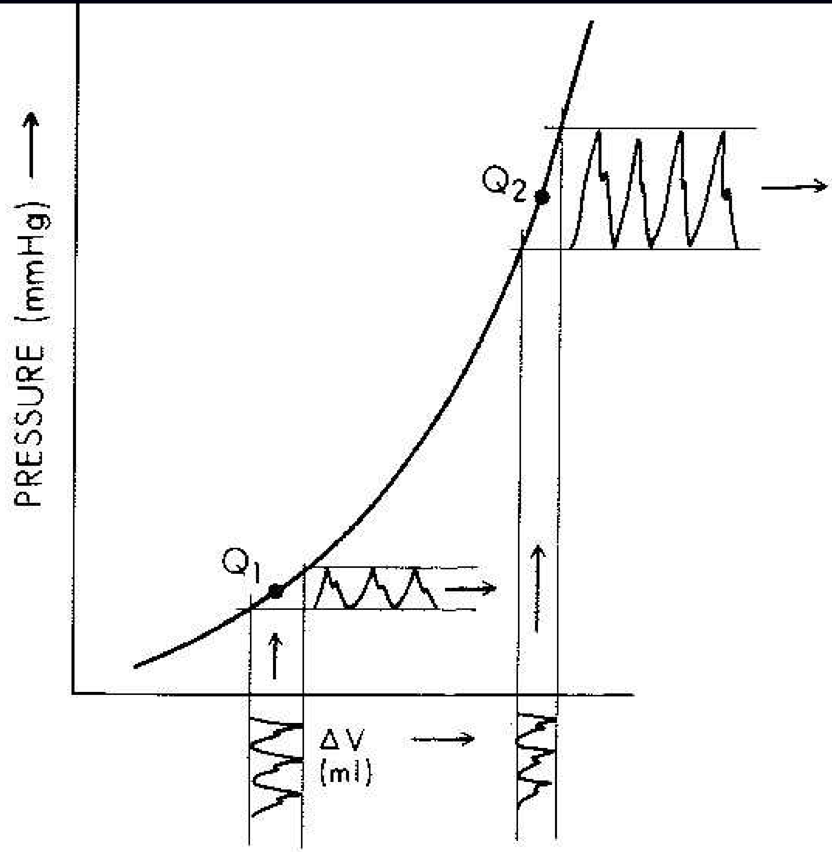


FIG. 2. The initial resting pressure level represents a stable point (Q_1) positioned on the volume-pressure curve. The magnitude of pulsatile pressure for pulsations in volume will be determined by the slope at point Q_1. An increase of steady-state pressure represents a permanent shift to a new operating point (Q_2). Pulsatile components will increase in magnitude because of the reduced compliance.

First Order Non-Linear Equation

$$\frac{dP}{dt} + P^2 \frac{K}{Ro} - P\,I(t) = 0$$

Where

P = Intracranial Pressure

K = f (slope of the Pressure Volume Curve)

R = Resistance to CSF absorption

I(t) = CSF formation rate

Solution of the First Order Non-Linear Equation

Let $P = \dfrac{1}{X}$

Then

$$P(t) = \frac{\Psi(\tau)}{1/Po + K/Ra \displaystyle\int_{to}^{t} \Psi(\tau)\, d\tau}$$

Where

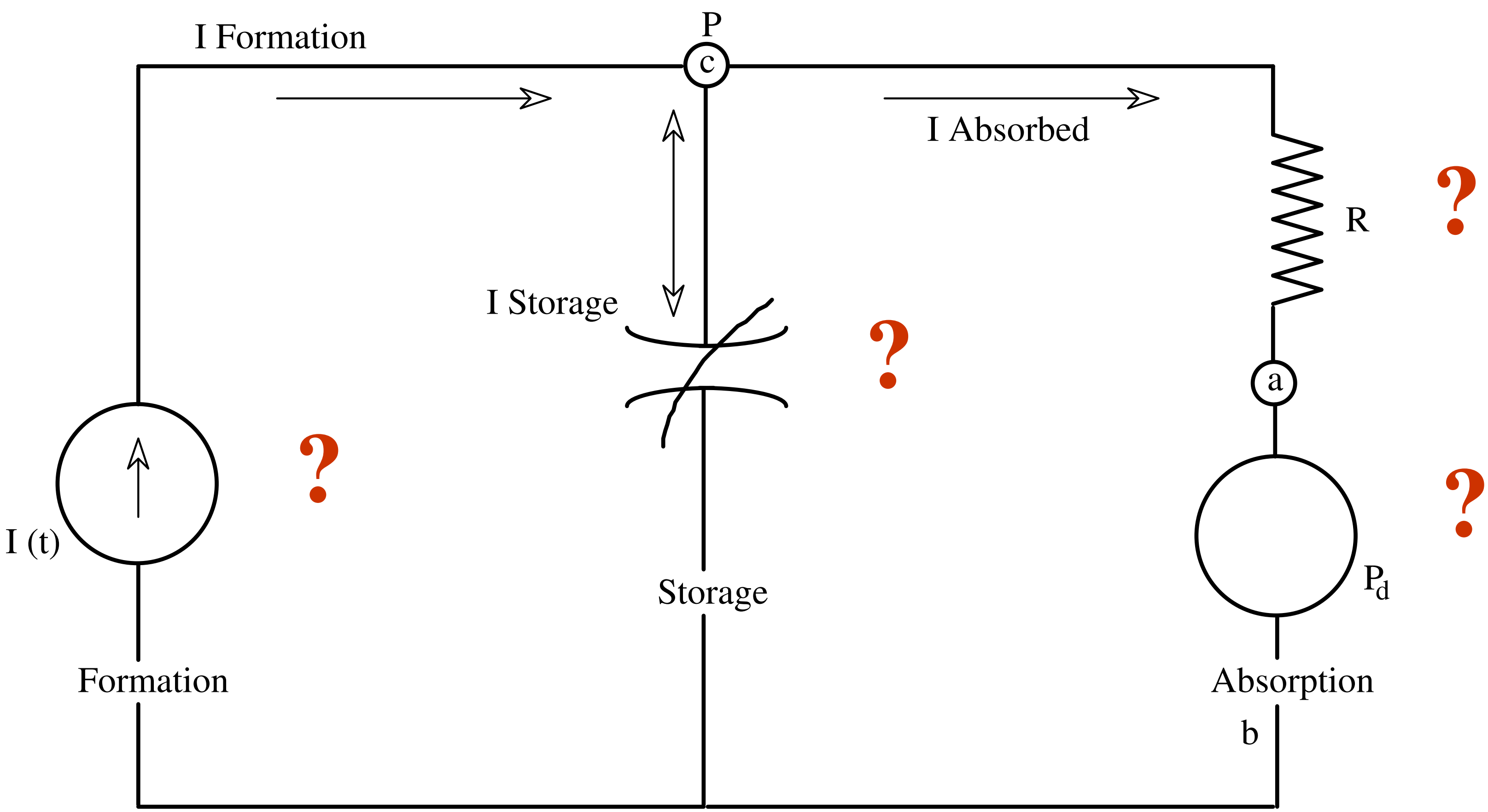
$$\Psi(\tau) = e^{K \int_{to}^{t} I(\tau)\, d\tau}$$

Why Solve it ??

Solution of the General Equation allows one to predict the change of ICP for any volume change

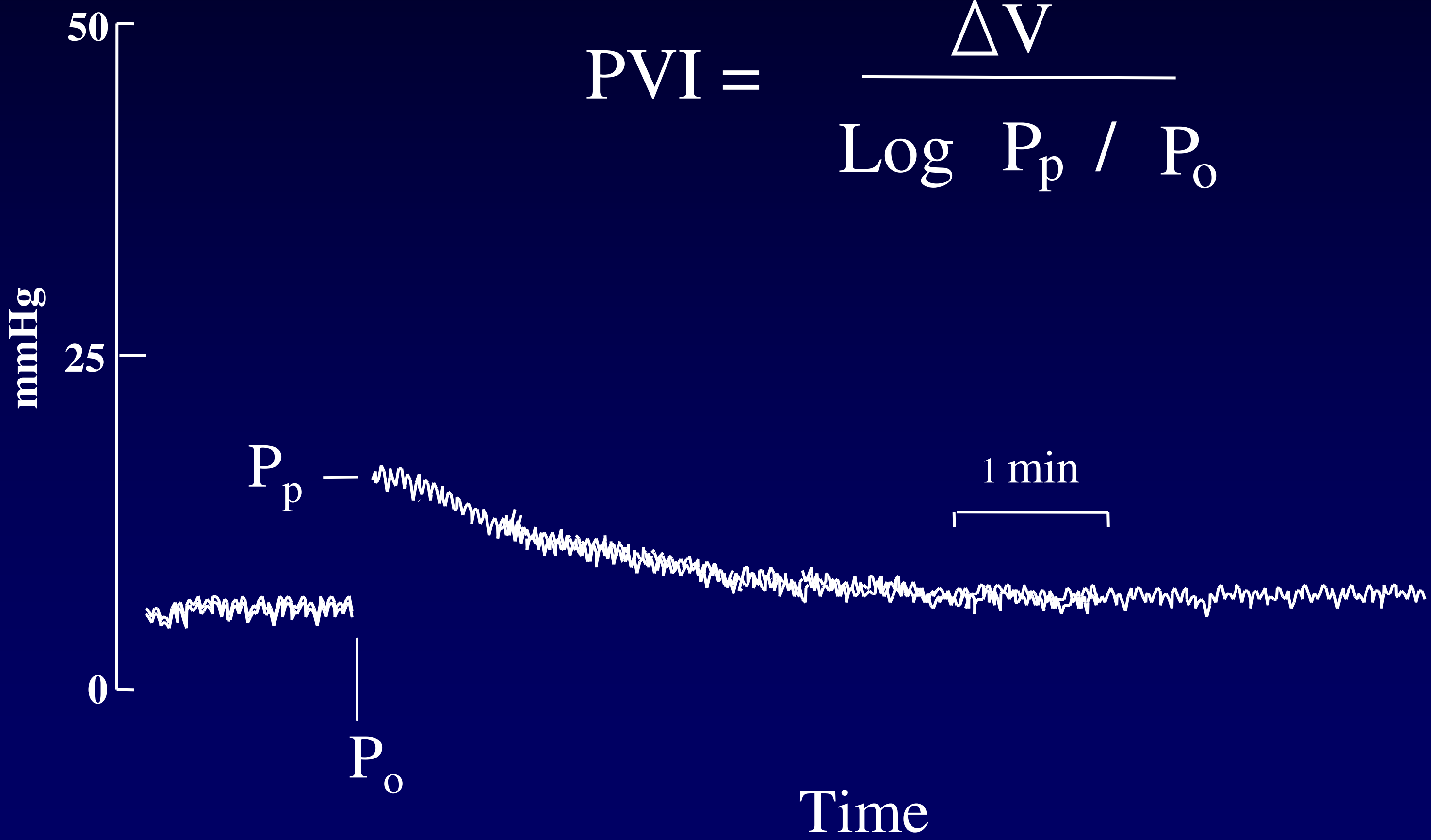
OR the Reverse

Given the pressure change to a volume disturbance, one can work backward and compute the Resistance to CSF production and the Pressure Volume Index

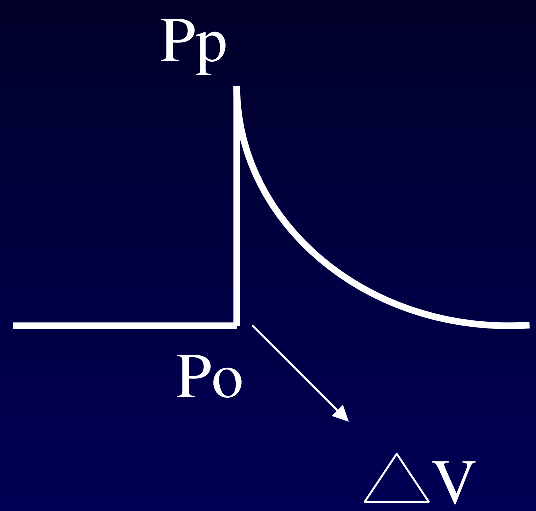


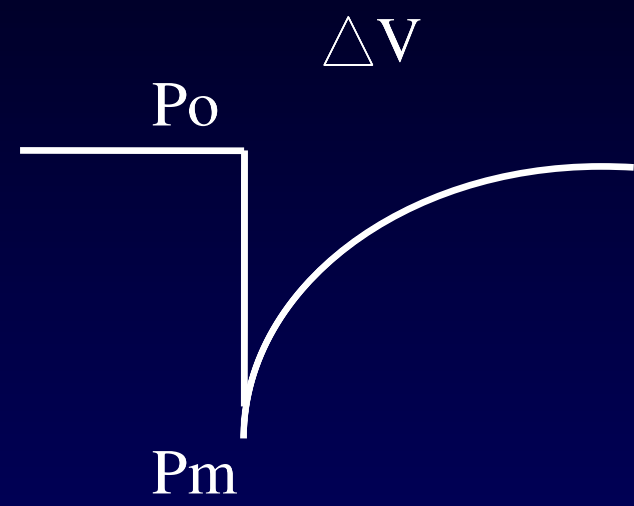
I Formation
P
c
I Absorbed
R
?
I Storage
?
a
?
?
I (t)
Storage
Pd
Formation
Absorption
b

$$PVI = \frac{\Delta V}{\text{Log } P_p / P_o}$$



Calculation of Pressure Volume Index (PVI) ml





PVI = ΔV/Log (Pp - Po)

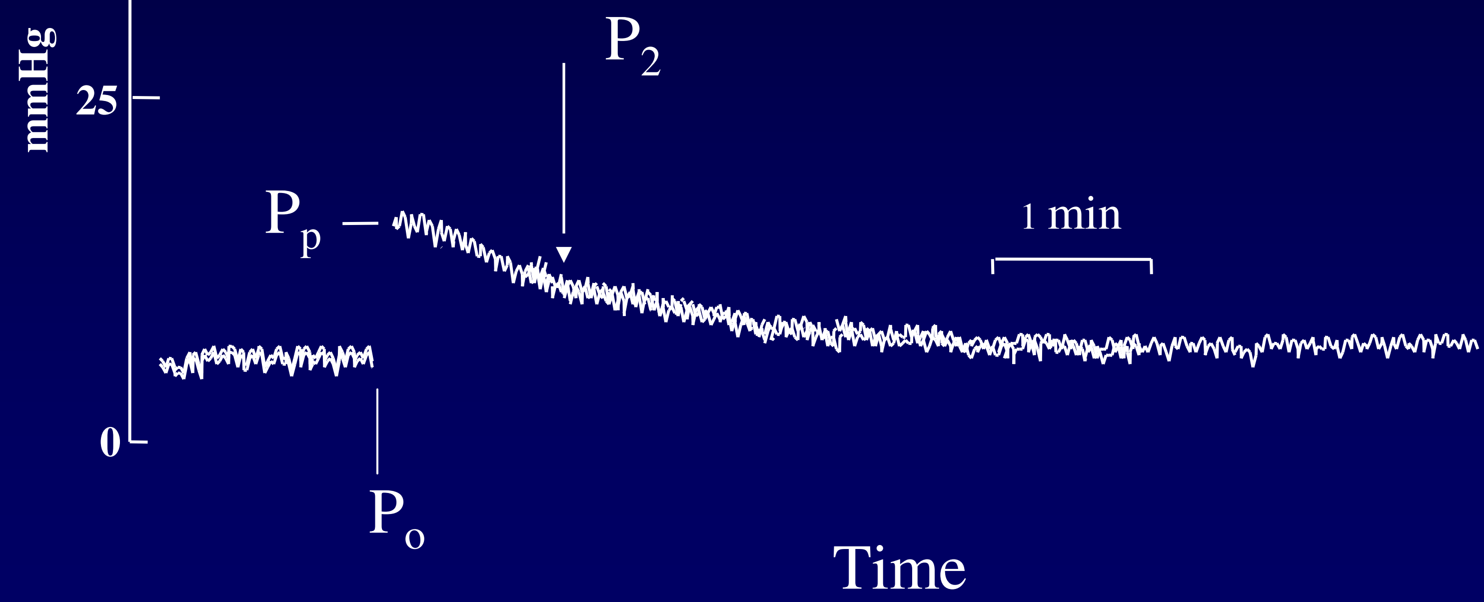
Bolus Addition

PVI = ΔV/Log (Po - Pm)

Bolus Removal

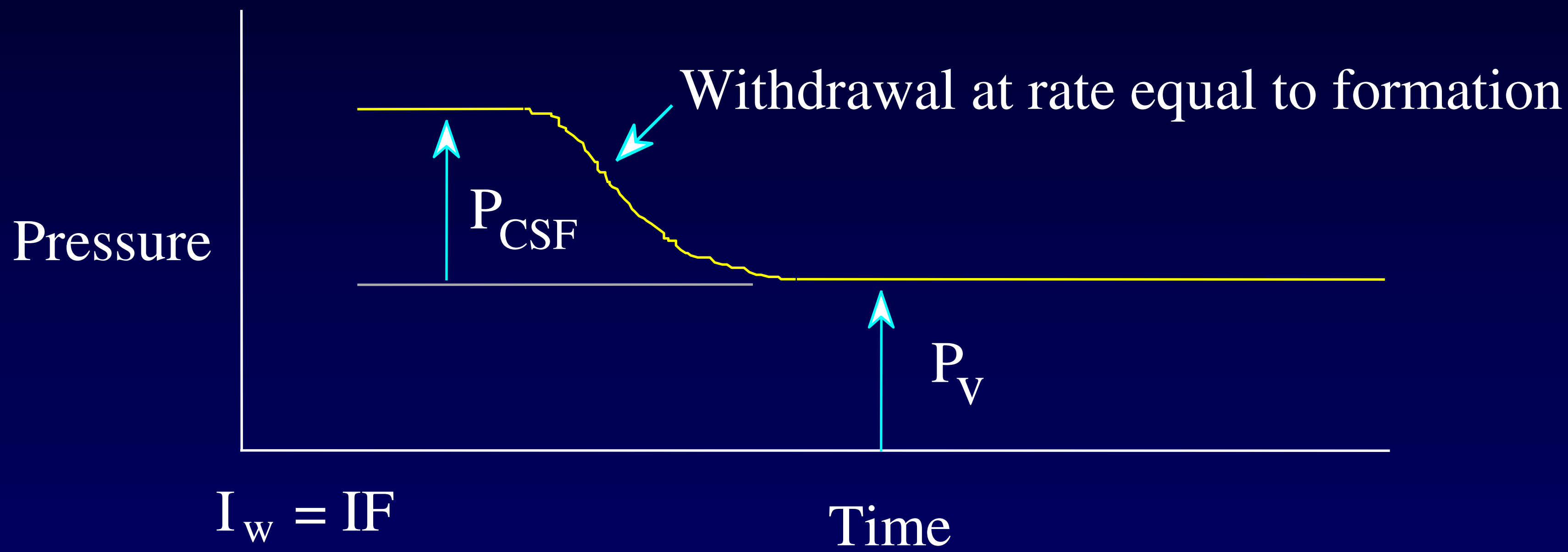
$$R_o = t_2 P_o / (PVI_i) \text{Log} [(P_2/P_p)(P_p/P_o) / P_2 - P_o]$$

$$PVI = \frac{\Delta V}{\text{Log } P_p / P_o}$$



Estimate of Vascular Pressure Contribution to ICP

$$ICP = I_f \bullet R_o + P_v$$



$I_w = IF$

$ICP \simeq P$

$t = 15$ min

Must venous pressure rise ?

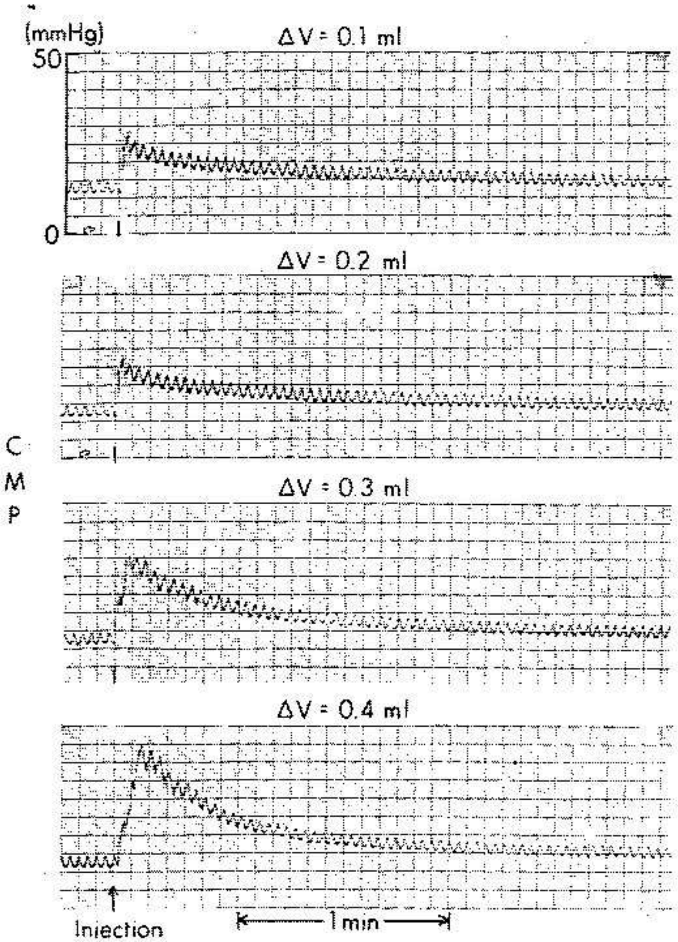
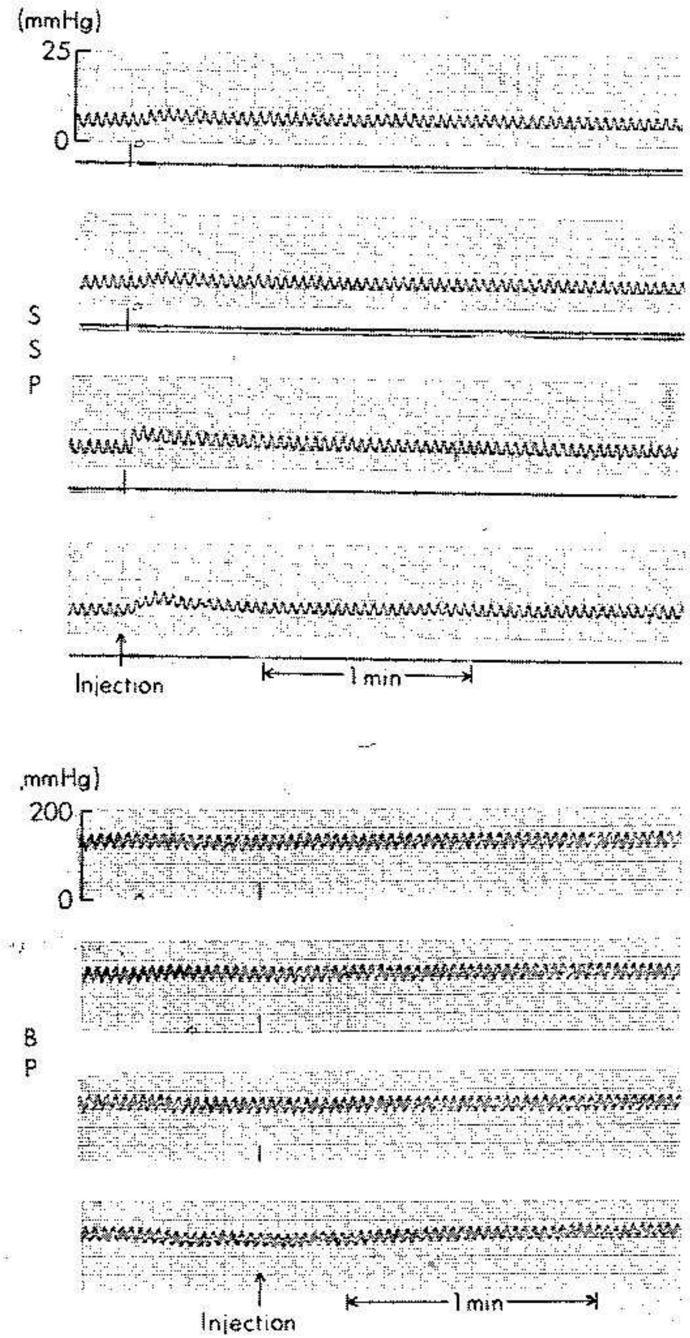


FIG. 3. The pressure-volume curve was obtained by injecting small increments of volume into the CSF compartment and recording the rise of cisterna magna pressure (CMP) *(upper left)*. Sufficient time was allotted for pressure to return to equilibrium levels. The small rise (4 mm Hg) observed in sagittal sinus pressure (SSP) is insignificant *(upper right)*. Blood pressure (BP) remains stable during the injection intervals (0.05 to 0.1 ml/sec) *(lower right)*.



Application to Head Injury

- What is the cause of ICP rise in the severely head injured patient ?

ICP = [CSF Formation x Resistance to Outflow] + Dural Sinus pressure

$$ICP = [If \times Ro] + Pd$$

Resistance component

Vascular component

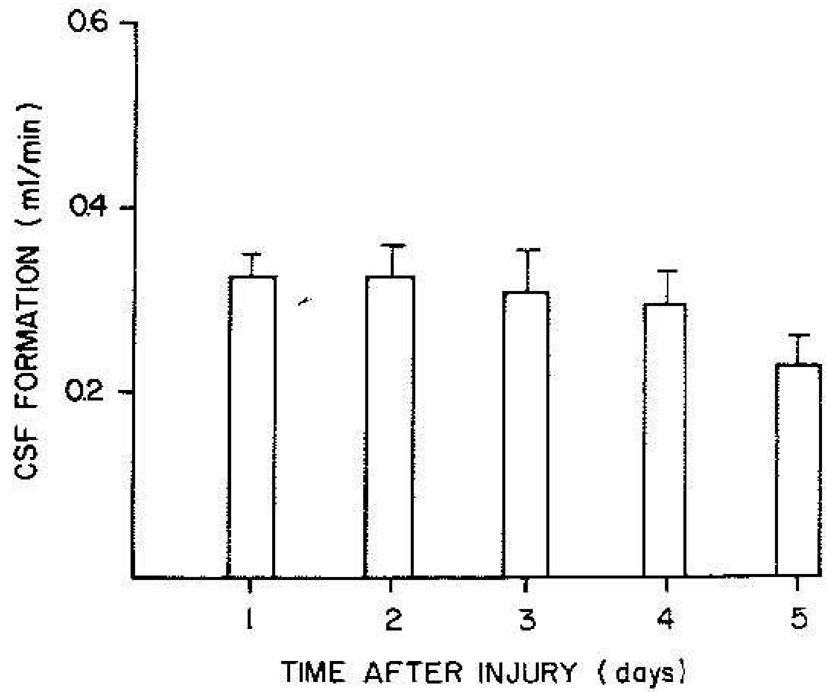


FIG. 1. Graph showing the rate of cerebrospinal fluid (CSF) formation determined from daily measurements using the bolus withdrawal technique and substituting the response of intracranial pressure (ICP) in the equation: If = PVI[log Po/Pm]/t2. Approximately 2 cc was removed for each study. The measured rates of formation averaged 0.326 ml/min, which is equivalent to 469 cc/day and is within the normal range. The number of patients studied decreased as time progressed (21 patients on Day 1 and five on Day 5), and thus the patients studied on Day 5 represent those in whom we had greater difficulty in managing ICP. The CSF formation rate on Day 5 showed a statistically significant decrease from that on Day 1; however the reduction of CSF formation compared with ICP was not statistically significant (see Fig. 2).

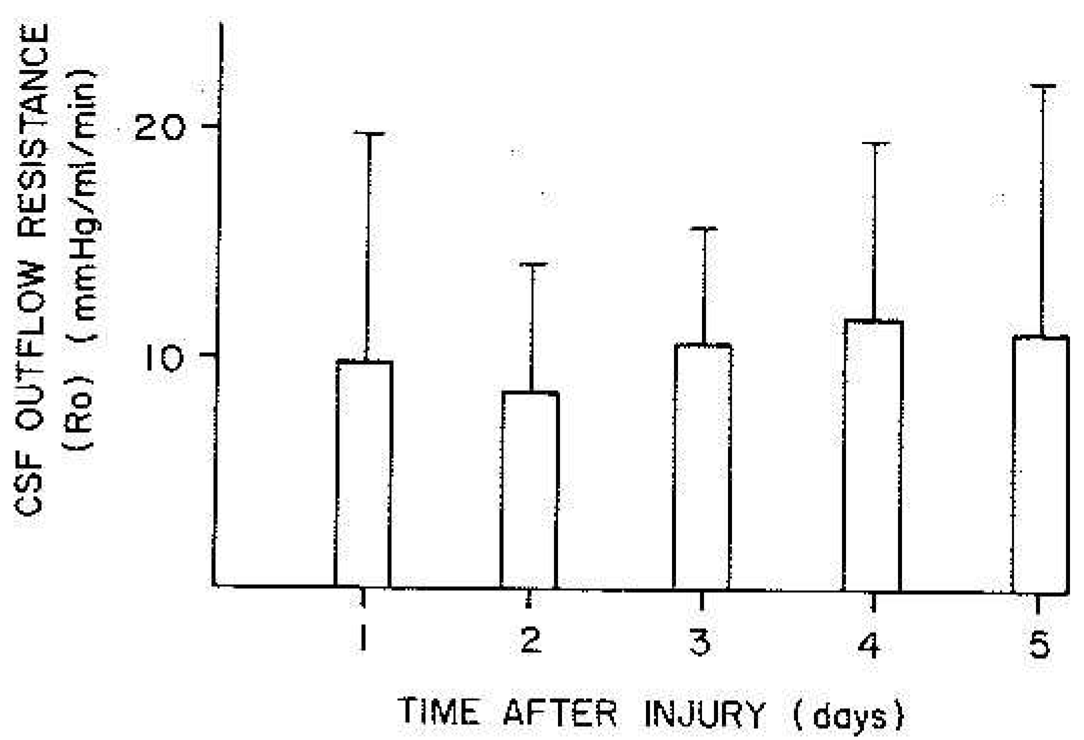
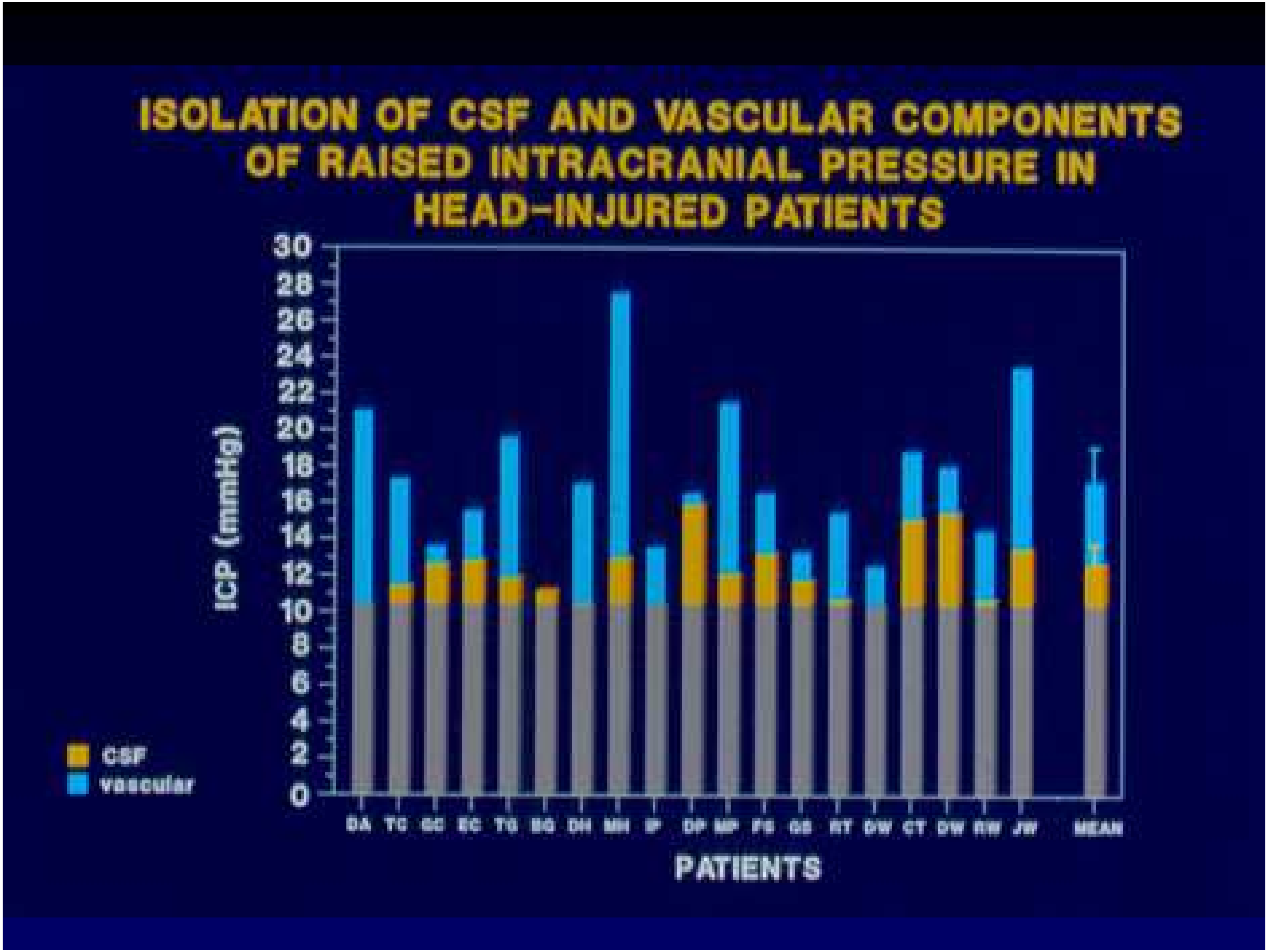


FIG. 3. Graph showing outflow resistance (Ro) to cerebrospinal fluid (CSF) determined by daily measurements of the intracranial pressure response to bolus addition of fluid (1 to 3 cc) and calculating the Ro according to Equation 5. In all 22 studies in the 22 patients evaluated, pressure returned to the predisturbance level within minutes. Normal Ro, as assessed by the bolus injection technique, is approximately 3.0 mm Hg/ml/min.

CONTRIBUTION OF CSF AND VASCULAR FACTORS TO RAISED ICP IN HEAD INJURED PATIENTS WITH INDEPENDENT MEASURES OF IF AND RO

	ICP (mmHg)	ICP RISE (mmHg)	IF (ml/min)	RO (ml/min/Hg)	% ICP (csf)
pediatric					
mean	17.06	7.06	0.322	7.56	24.85
SD	6.85	6.85	0.216	6.84	30.08
adult					
mean	16.99	6.99	0.286	10.05	29.30
SD	3.81	3.81	0.102	7.09	23.47

NEUROSURGERY


ISOLATION OF CSF AND VASCULAR COMPONENTS OF RAISED INTRACRANIAL PRESSURE IN HEAD-INJURED PATIENTS
ICP (mmHg)
PATIENTS
CSF
vascular

ICP = [CSF Formation x Resistance to Outflow] + Dural Sinus pressure

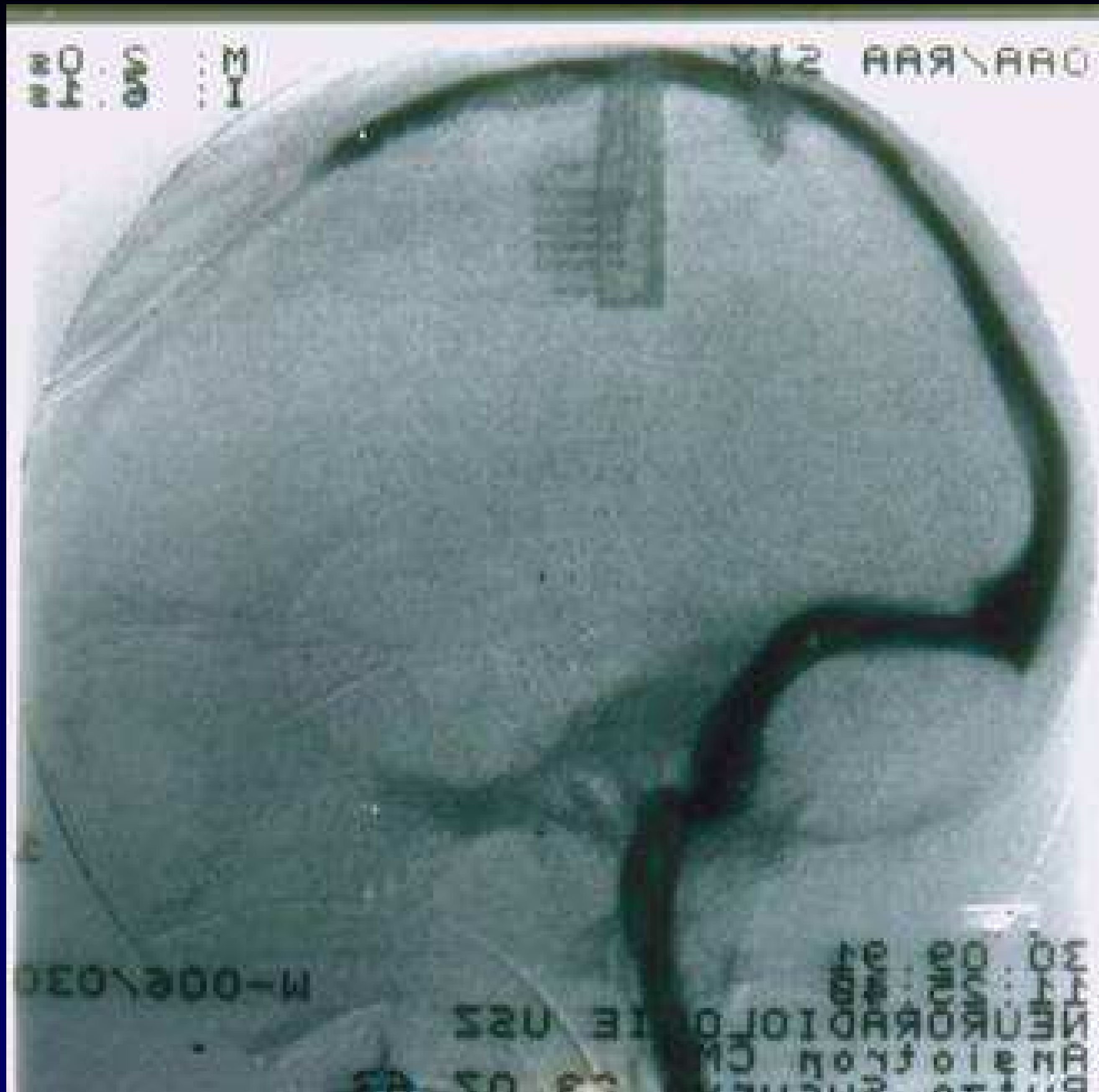
$$ICP = [I_f \times R_o] + P_d$$

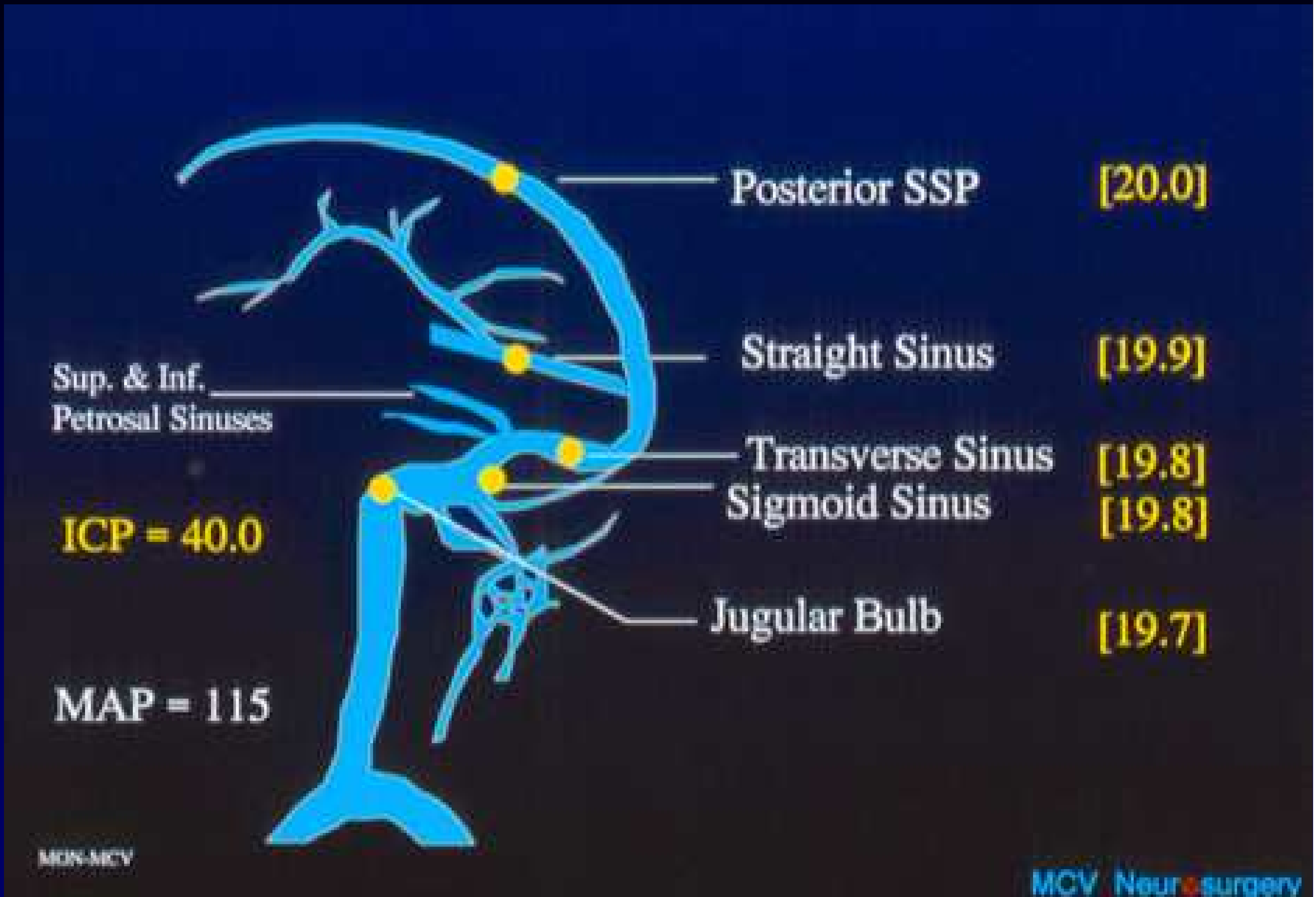
Resistance component

Vascular component

Summary: Head Injury

With exception of subarachnoid hemmorhage where Ro is significantly elevated, the predominant component of ICP rise in TBI is vascular

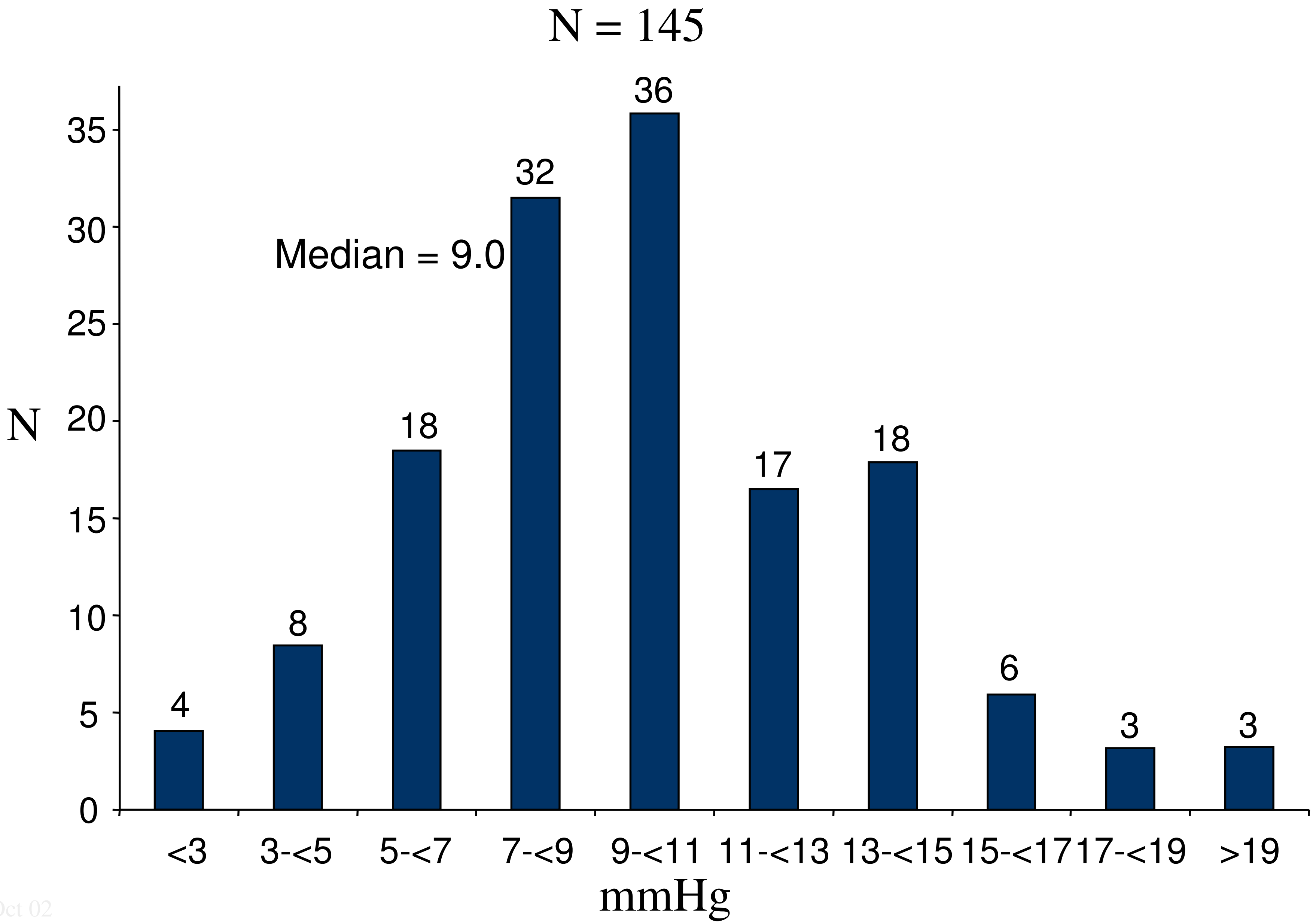



Posterior SSP
[20.0]
Straight Sinus
[19.9]
Sup. & Inf.
Petrosal Sinuses
Transverse Sinus
[19.8]
Sigmoid Sinus
[19.8]
ICP = 40.0
Jugular Bulb
[19.7]
MAP = 115
MCV Neurosurgery

Application to NPH

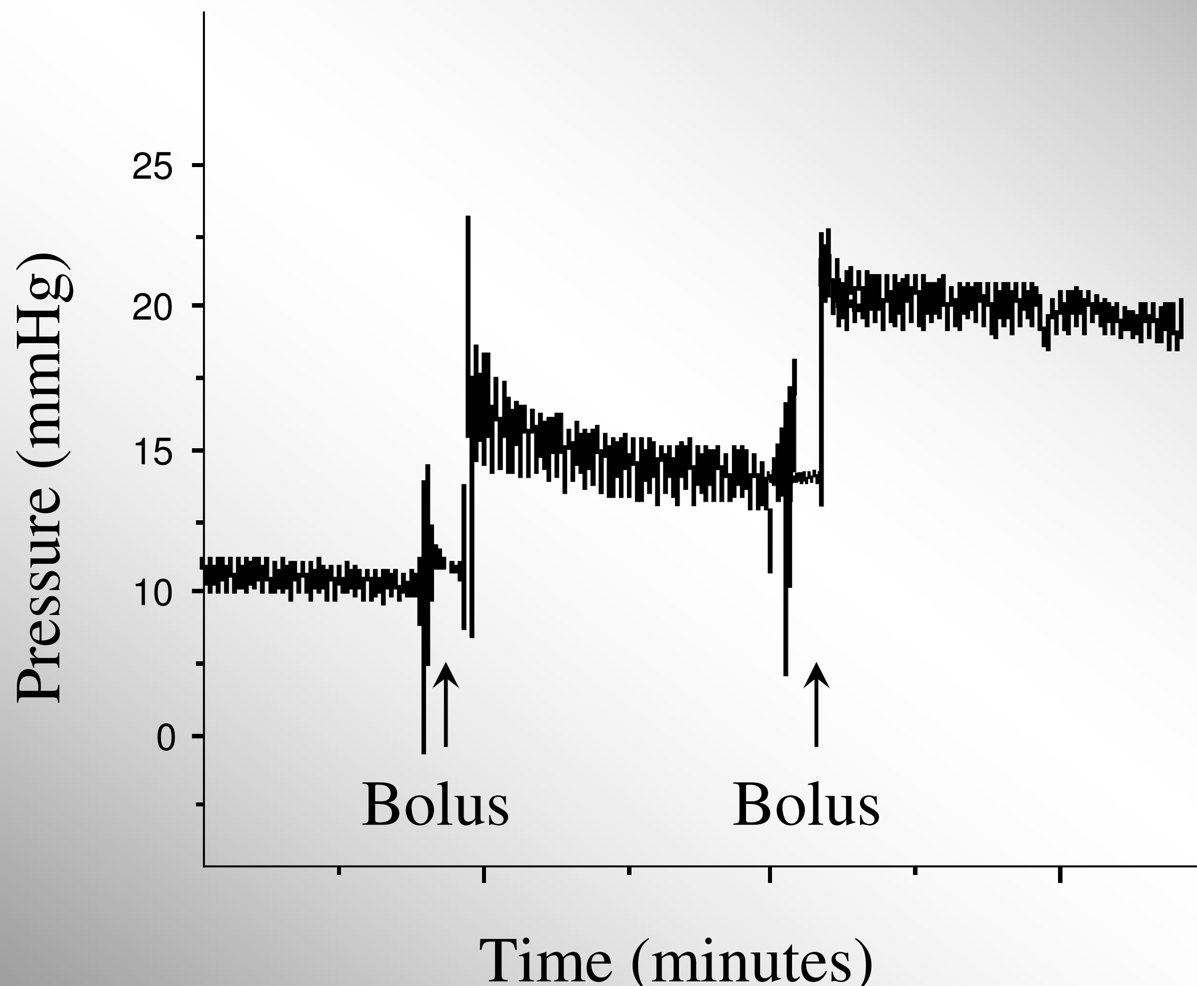
- What is the prognostic significance of elevated resistance to CSF outflow ?

Opening ICP Distribution in NPH Patients



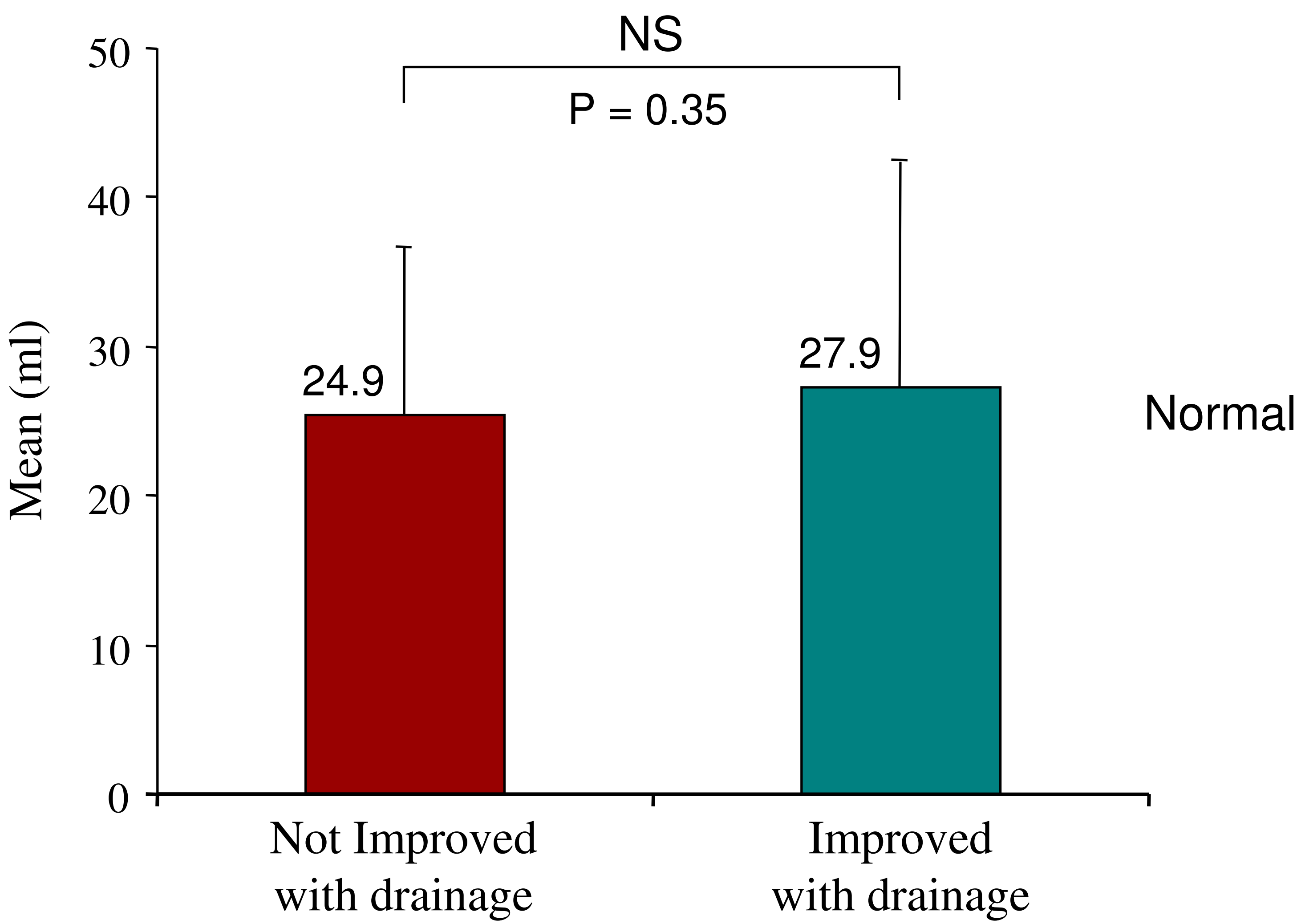
Oct 02

Ro > 4



Infusion Study: PVI

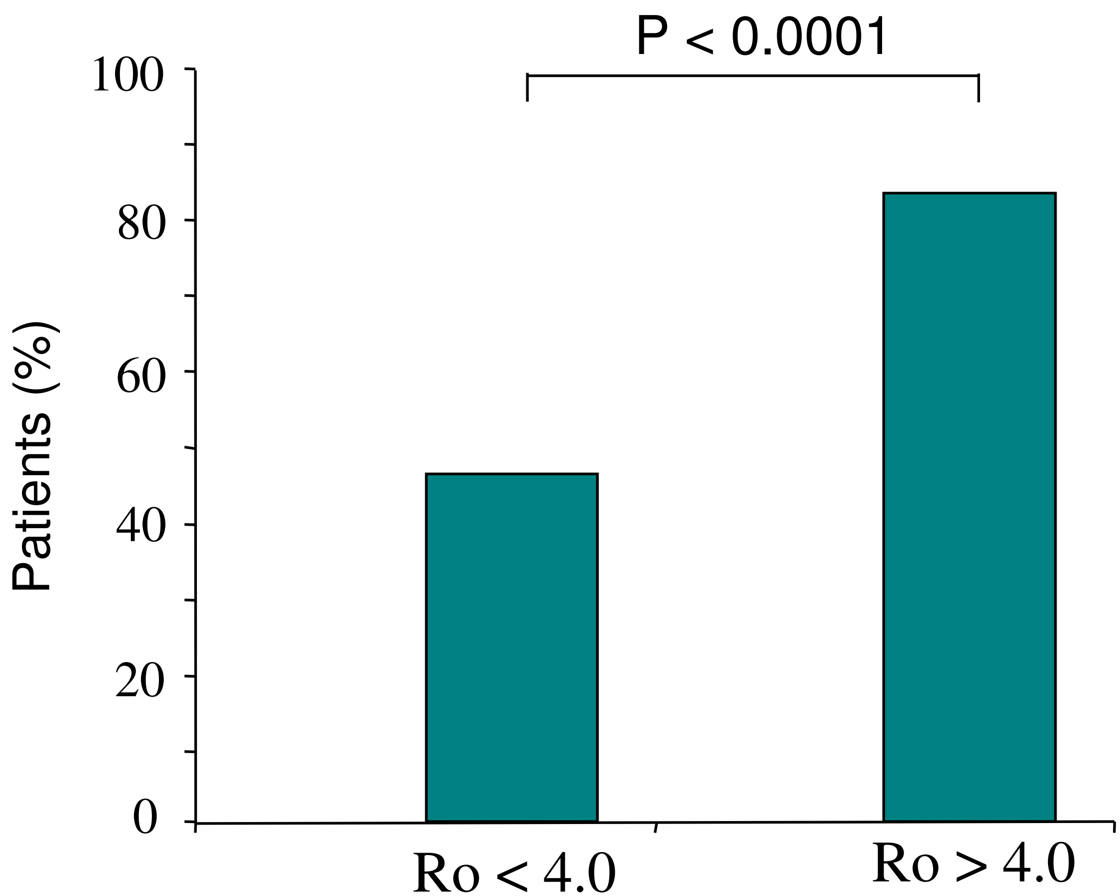
N = 135



VCU Neurosurgery

Oct 02

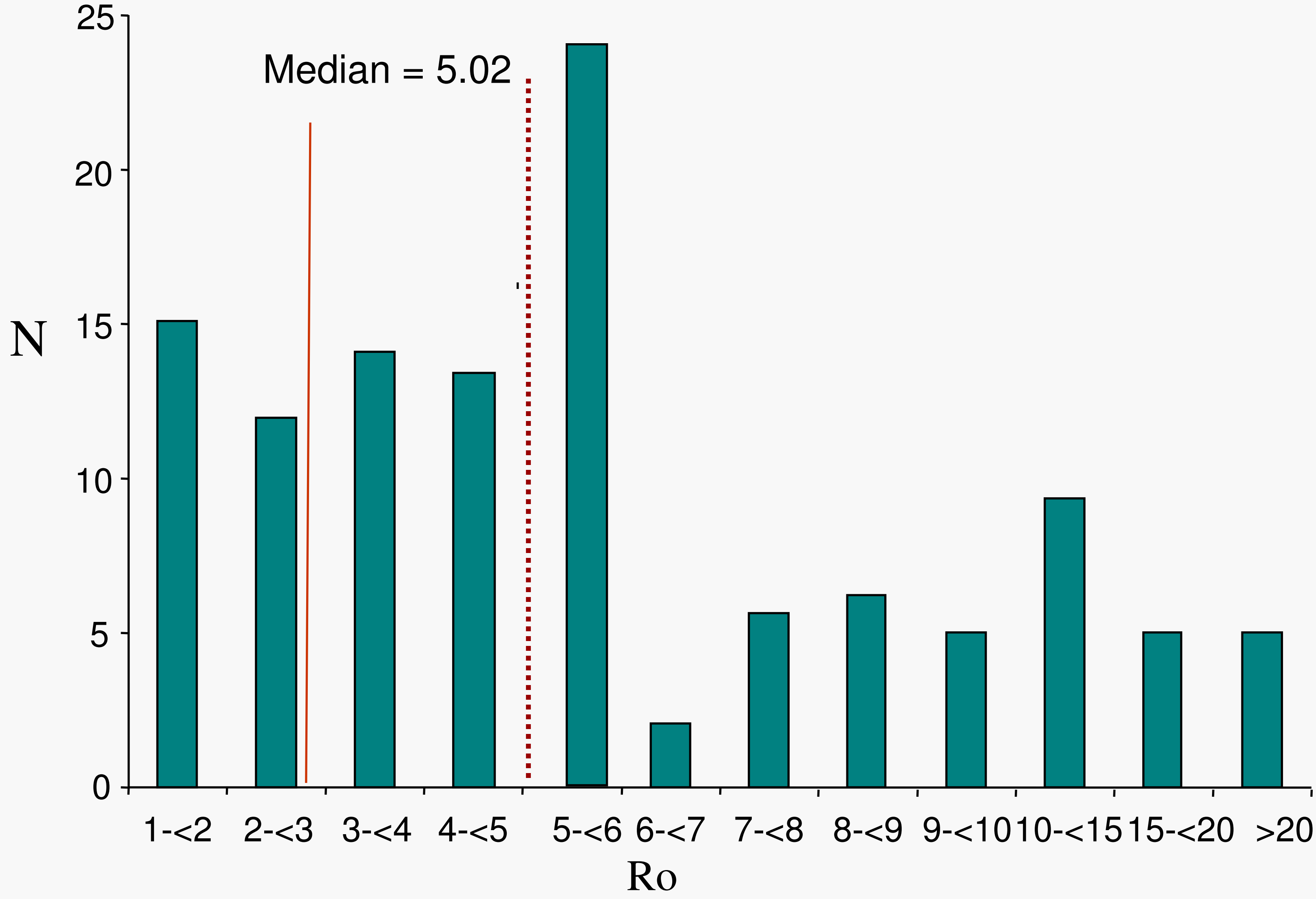
Infusion Study: Ro Improved with Drainage



→ Patients who show Ro > 4.0 significantly improved with drainage compared to Ro < 4.0.

Ro Distribution

N=123



Effect of Increased Ro on ICP

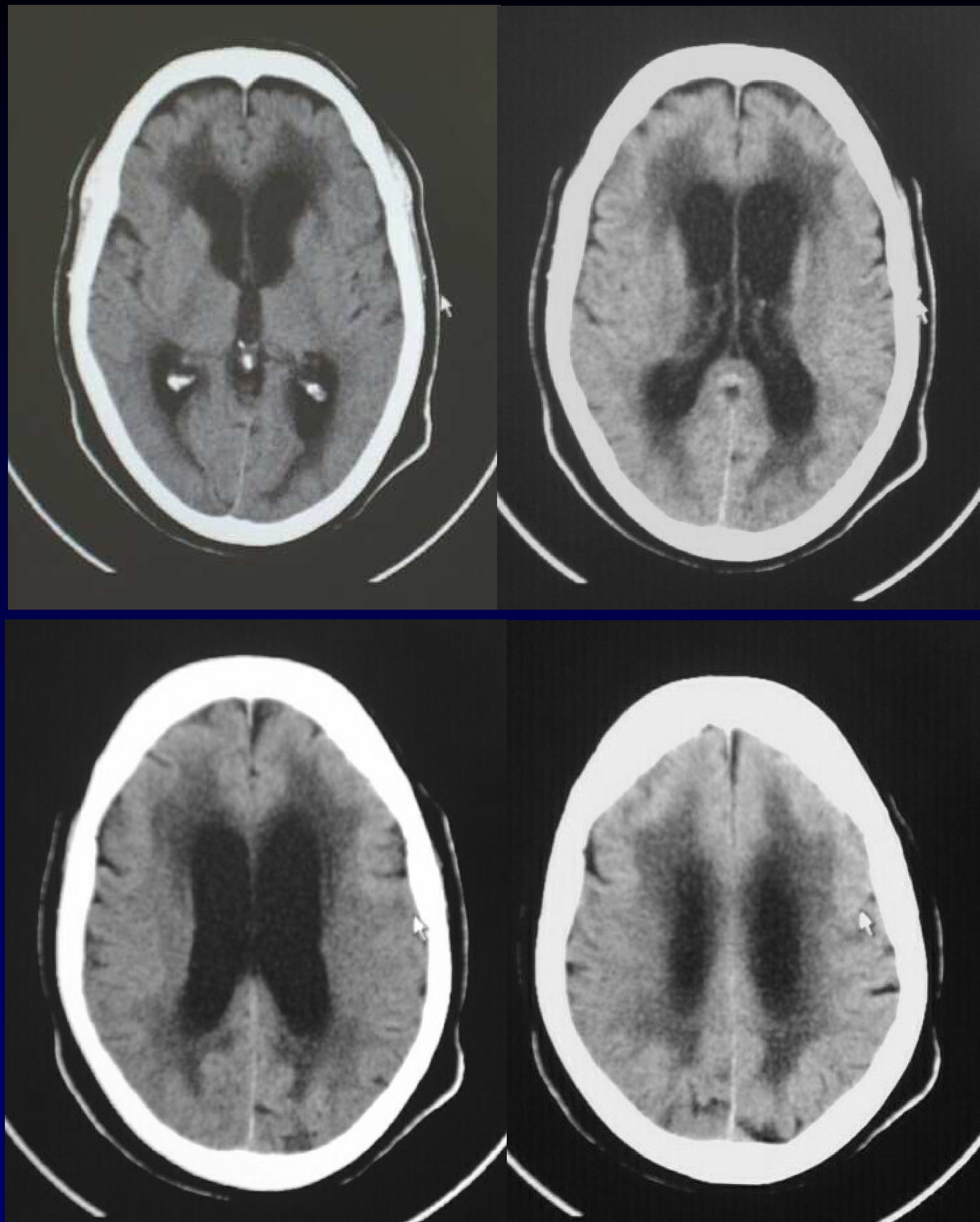
$$ICP = I_f R_o + P_v$$

$$10.00 = .35\ [4] + P_D$$

$$11.38 = .35\ [8] + P_D$$

$$12.70 = .35\ [12] + P_D$$

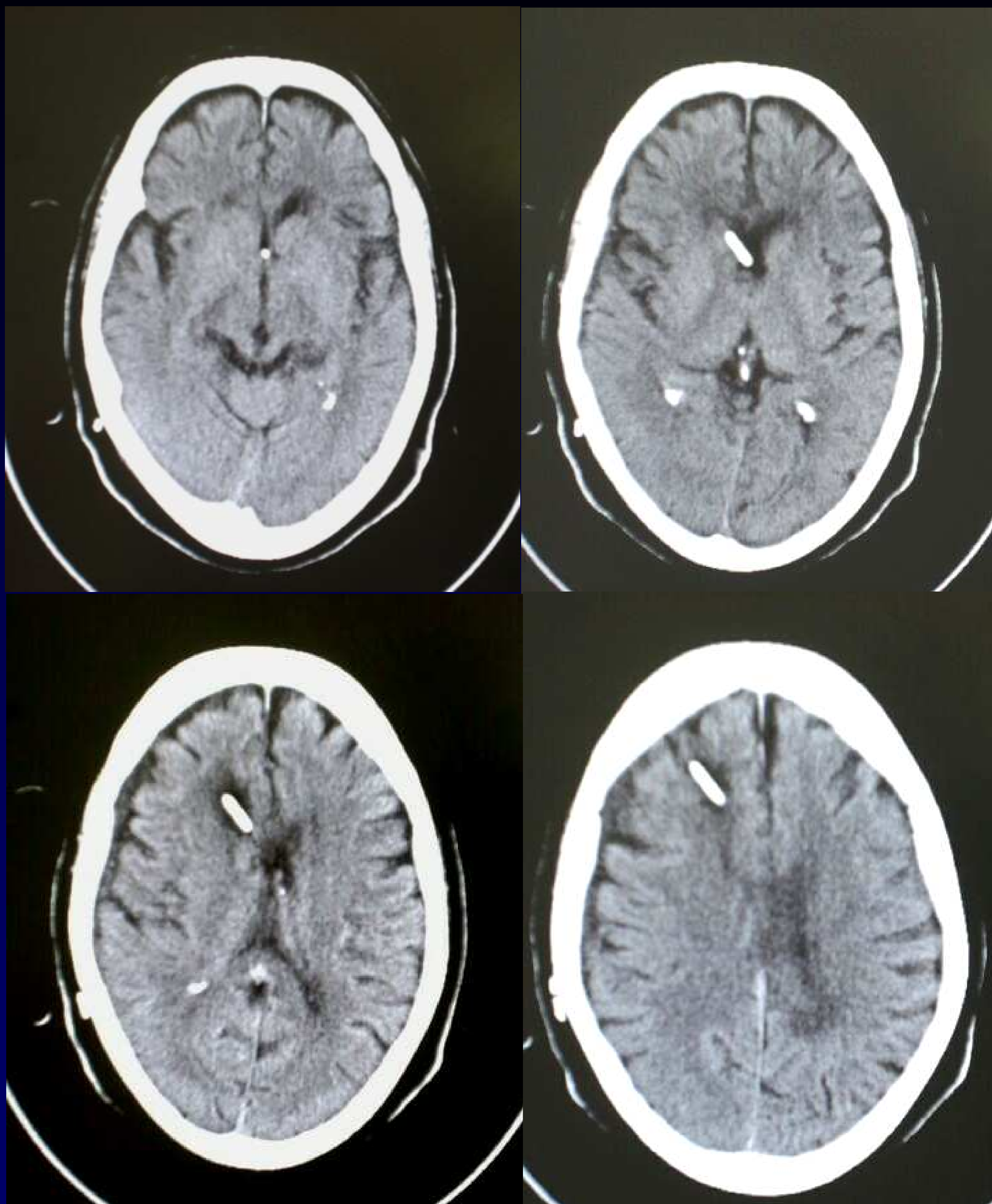
$$14.18 = .35\ [16] + P_D$$



Patient MP:

Female/79yrs

Before Shunt

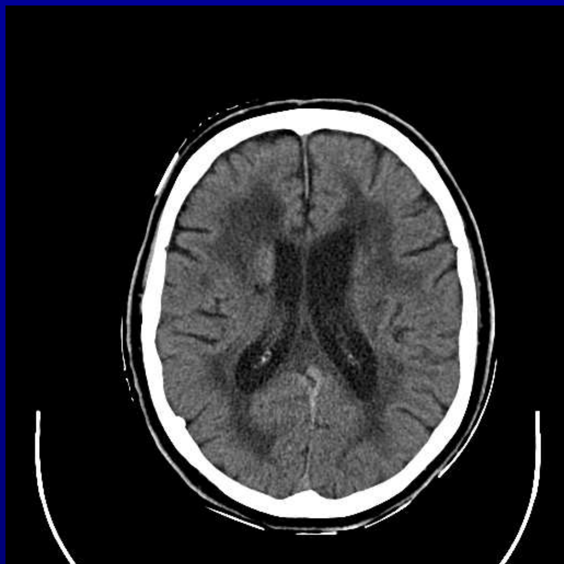


Patient MP

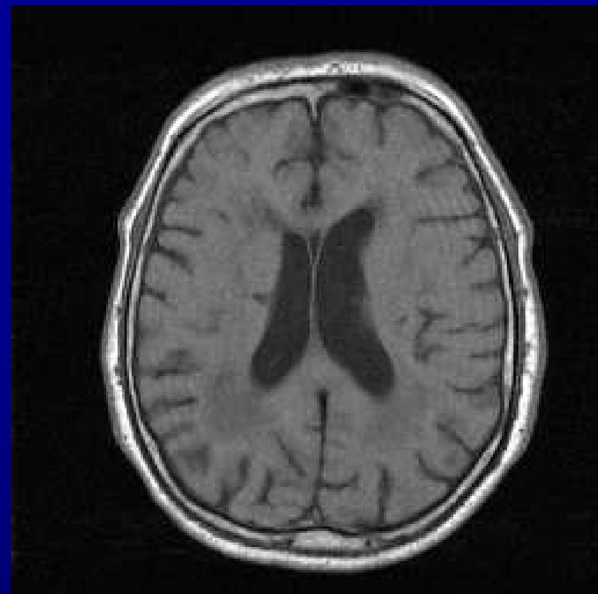
Female 79yrs

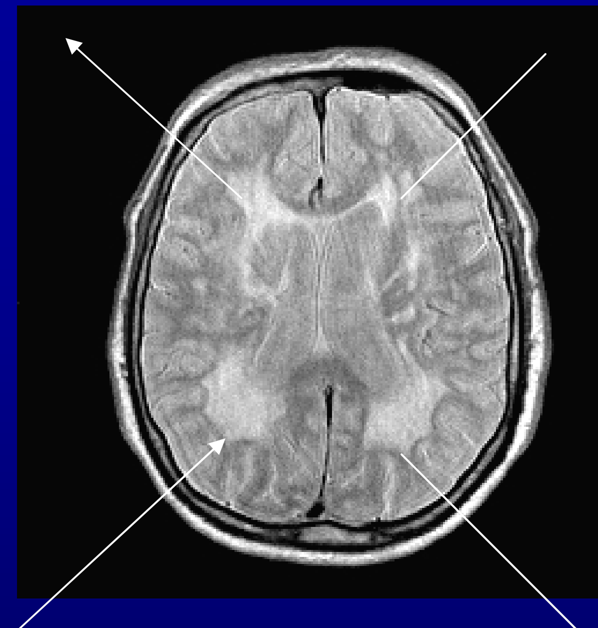
1 year post shunt

CT

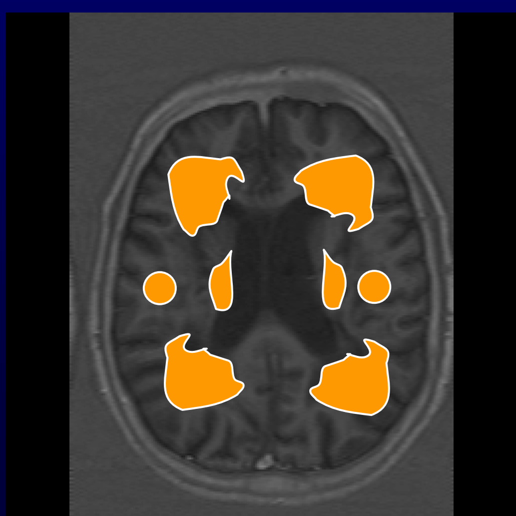


T1 and T2 MRI



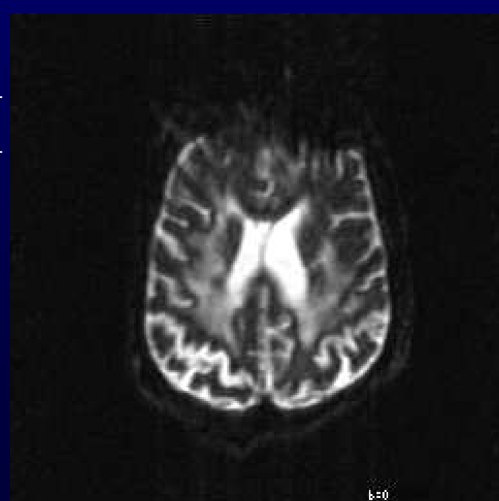


MRI Water

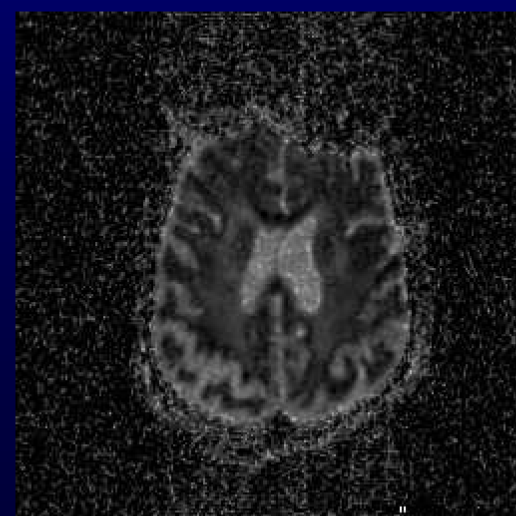


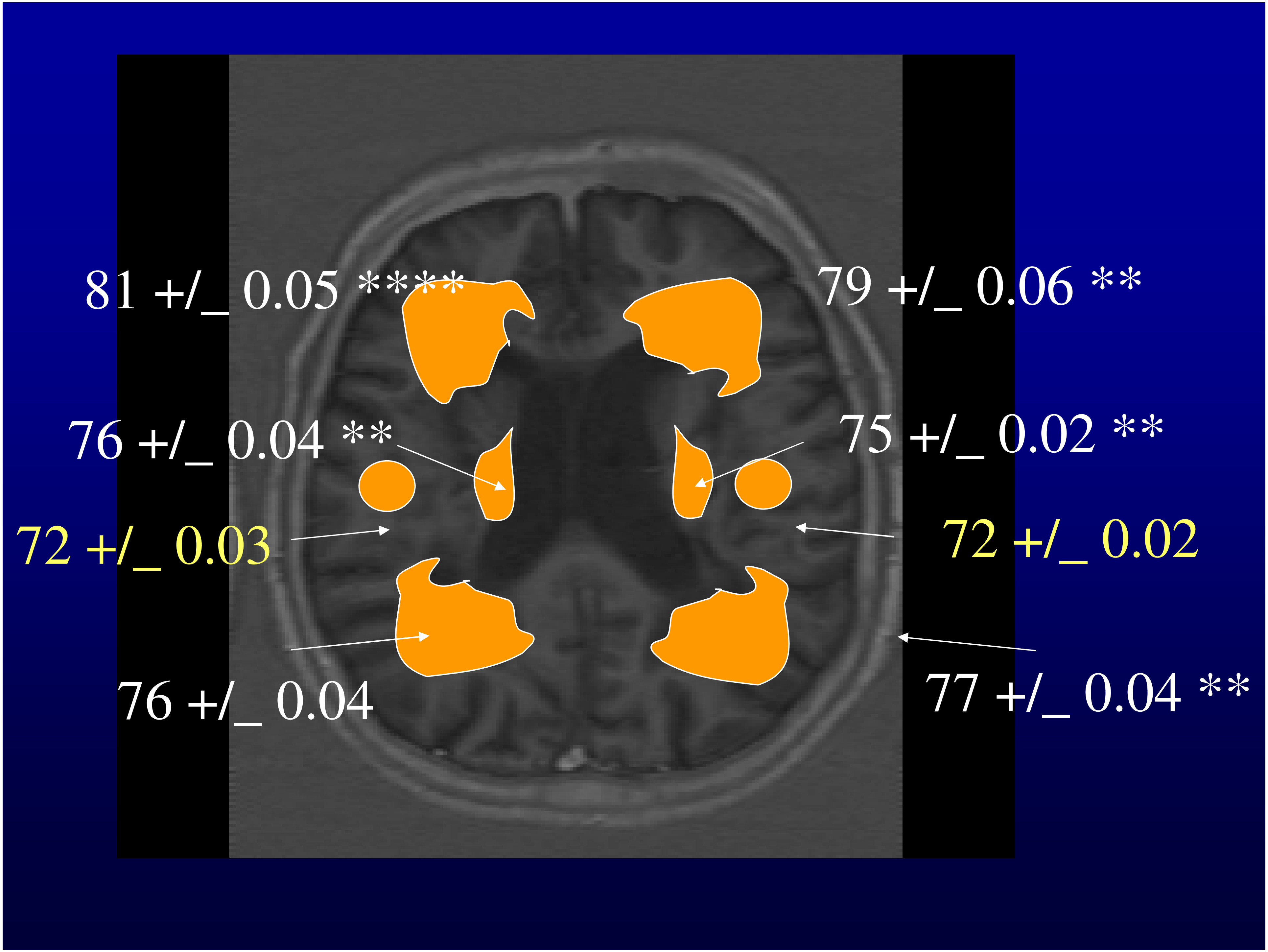
ROI

DWI-MRI



ADC-MAP





81 +/_ 0.05 ****
79 +/_ 0.06 **
76 +/_ 0.04 **
75 +/_ 0.02 **
72 +/_ 0.03
72 +/_ 0.02
76 +/_ 0.04
77 +/_ 0.04 **

Using CSF Resistance to Predict Drainage Outcome

Sensitivity: The percentage of patients with Ro> 4 among patients whose outcome improved after drainage

Sensitivity: 0.75

(95 % Confidence Interval) 0.67 to 0.84

Specificity: The percentage of patients with Ro < 4 among patients who are not improved

Specificity: 0.63

(95 % Confidence Interval) 0.48-0.78

Accuracy: % of Total Correct Predictions = 71.5 %

Conclusion

- A simplified model of the cerebrospinal fluid system has provided valuable information to assist in clinical management of head injury and normal pressure hydrocephalus

Conclusion

- Further effort should focus on the influence of the vascular component of ICP, specifically the gradient along the bridging veins