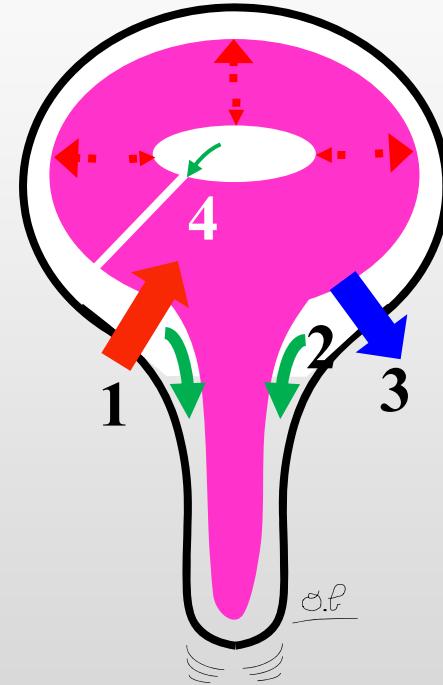


## CSF flows: From origins to alterations.



O. Balédent,

C. Gondry-Jouet, A. Fichten, S. Elsankari, R. Bouzerar  
University hospital of Picardie Jules Verne, Amiens, France.



Le système de santé français

Le CHU, une entreprise de Picardie



La Picardie

L'établissement hospitalo-universitaire de Picardie



Amiens, capitale régionale



Des projets pour moderniser

*Study supported in part by European Community  
INTERREG  
(cooperation Amiens-Cambridge) grant*

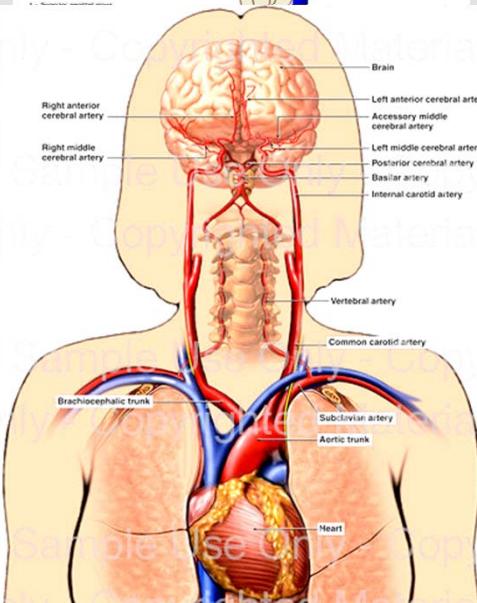
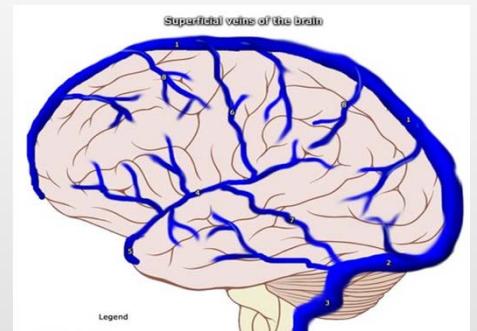
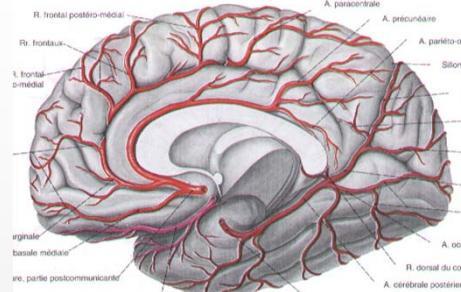
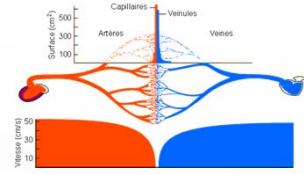
In collaboration with



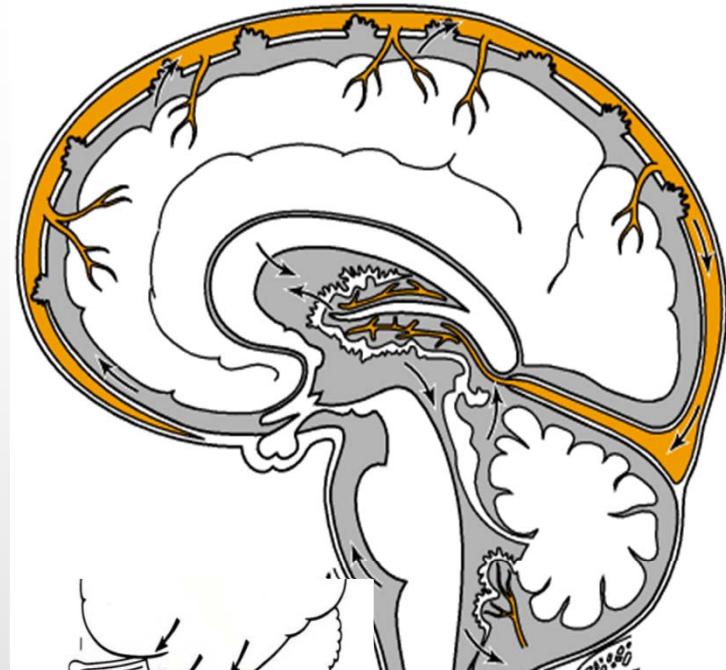
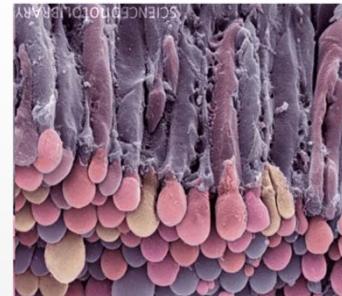
European Regional Development Fund  
The European Union, investing in your future



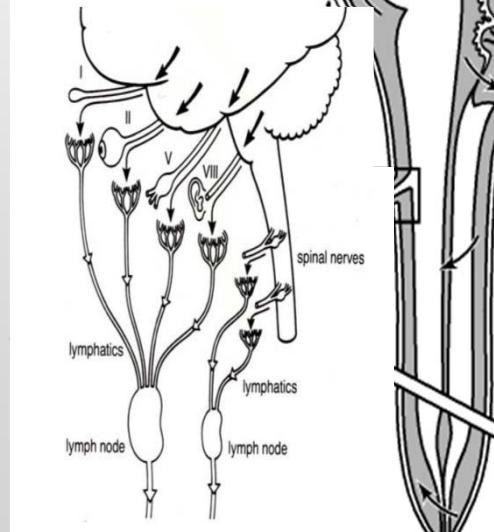
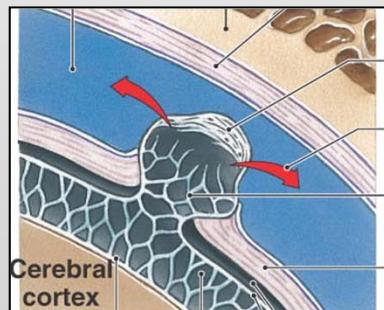
Fonds européen de développement régional  
L'Union Européenne investit dans votre avenir



## CSF Circulation and oscillations

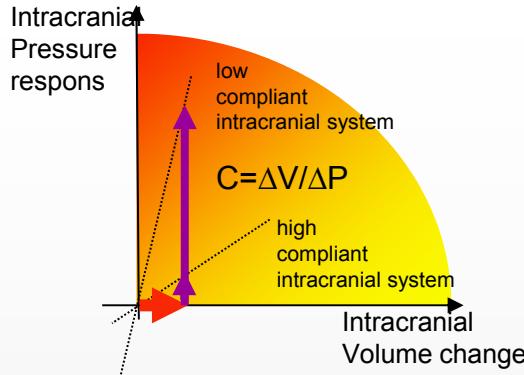


Secretion  
to  
resorption



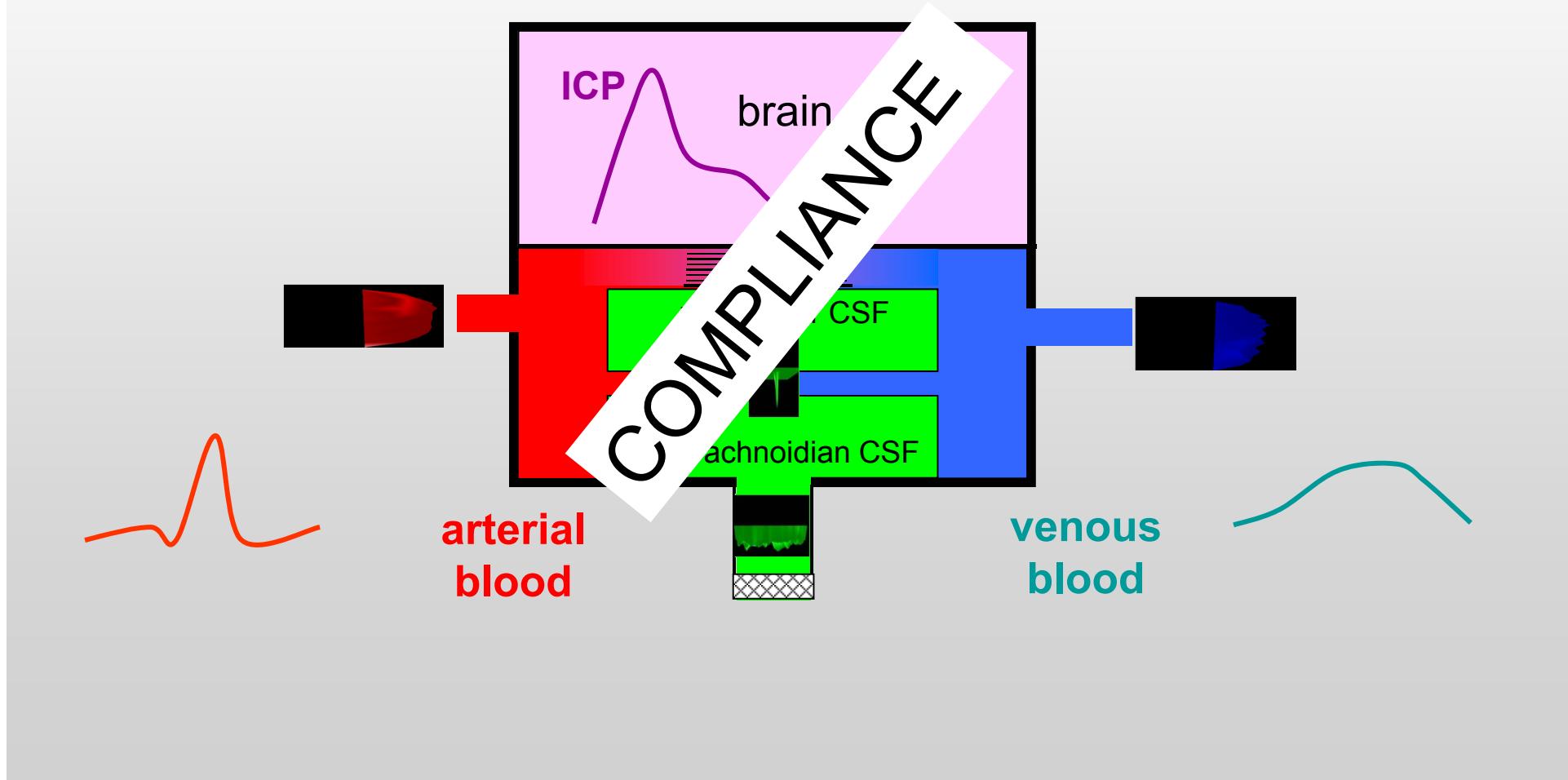
**CSF “third” Circulation**

But with important oscillations during cardiac cycle !!!

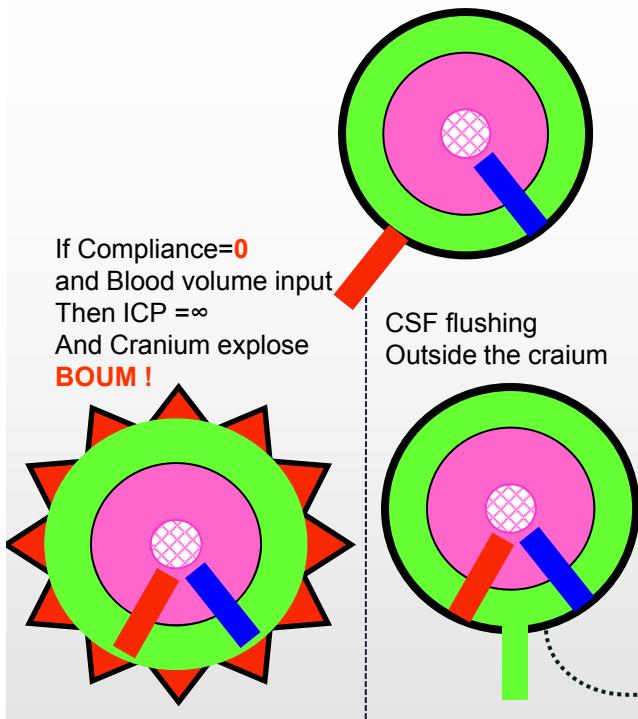


The intracranial volume is presumed to be constant (the **Monro-Kellie doctrine**)

## Intracranial compartment and dynamic relationship

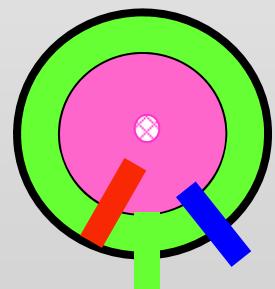
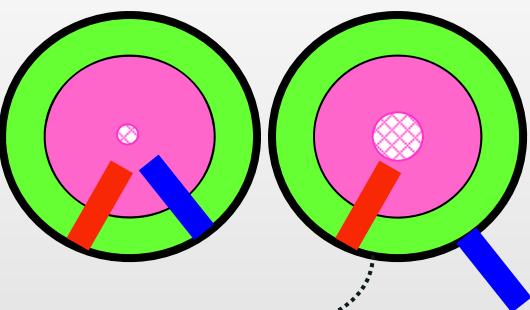


## Compliance of intracranial compartment

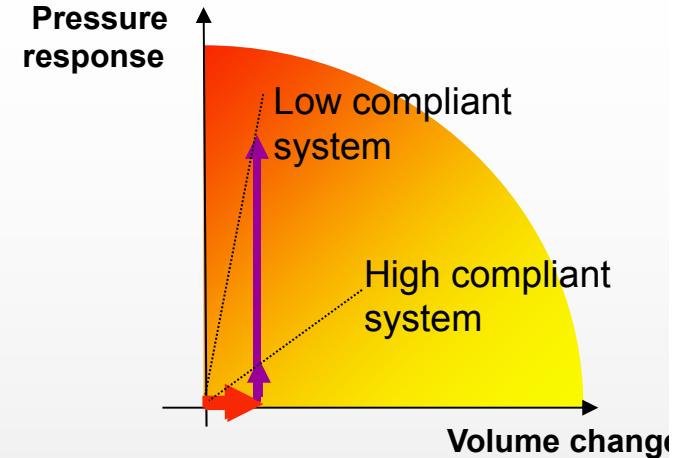


$$\text{Compliance} = \frac{\Delta V}{\Delta P}$$

Intracranial volume is ε deformable



Intracranial Compliance is Function of :  
CSF and blood viscosities,  
resistance of CSF and blood flowing,  
Thoracic pressure,  
Dural sac compliance,  
Heart venous aspiration,

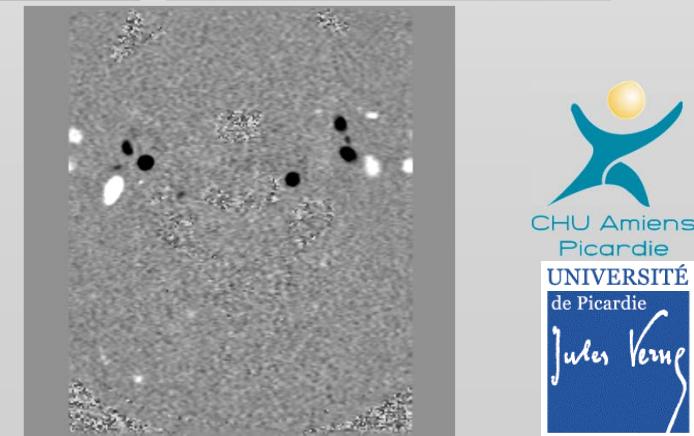
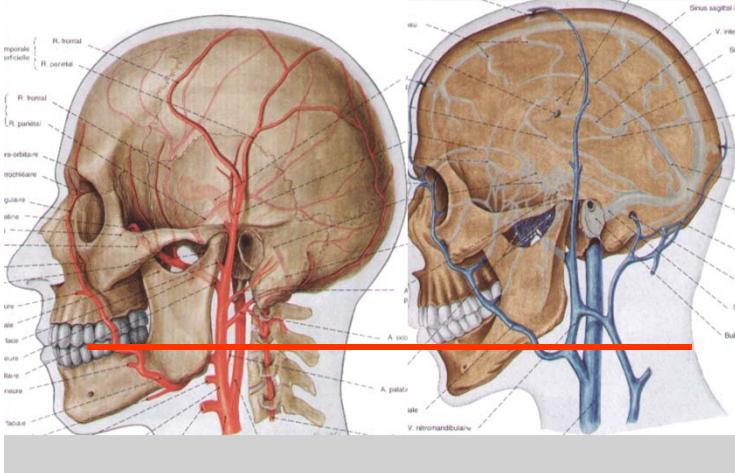
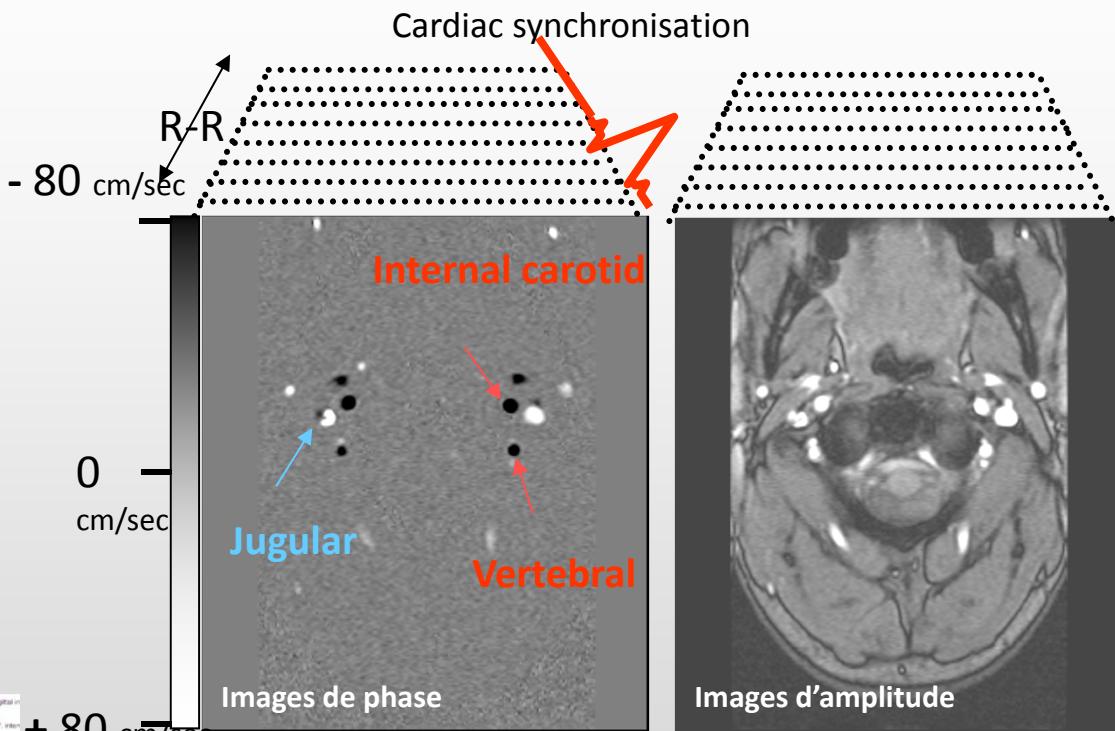
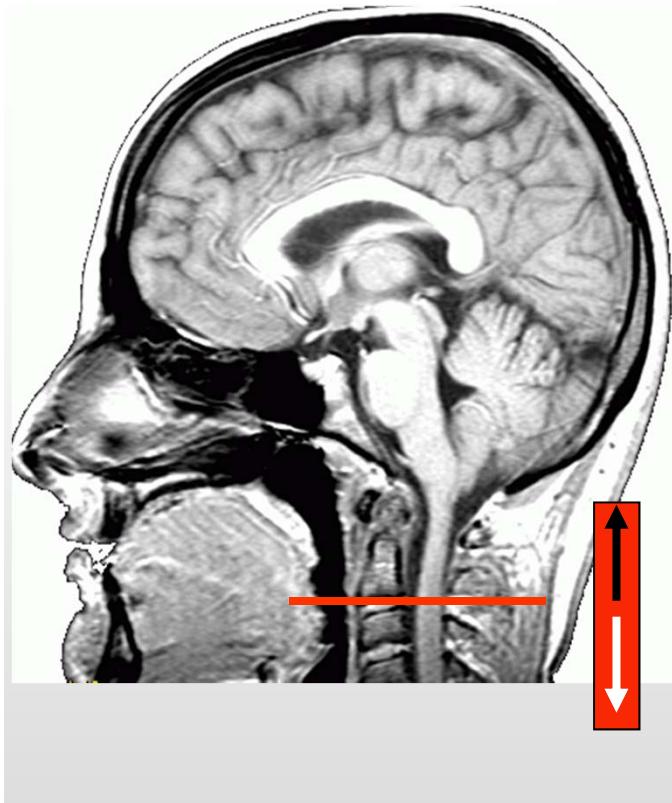


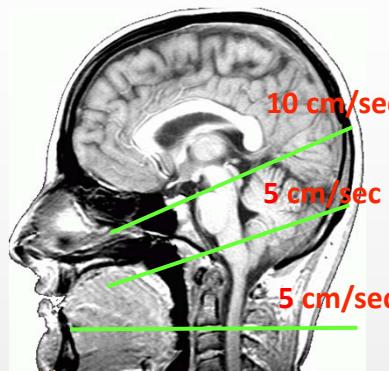
.... this compliance is complex !

And determine ICPPower

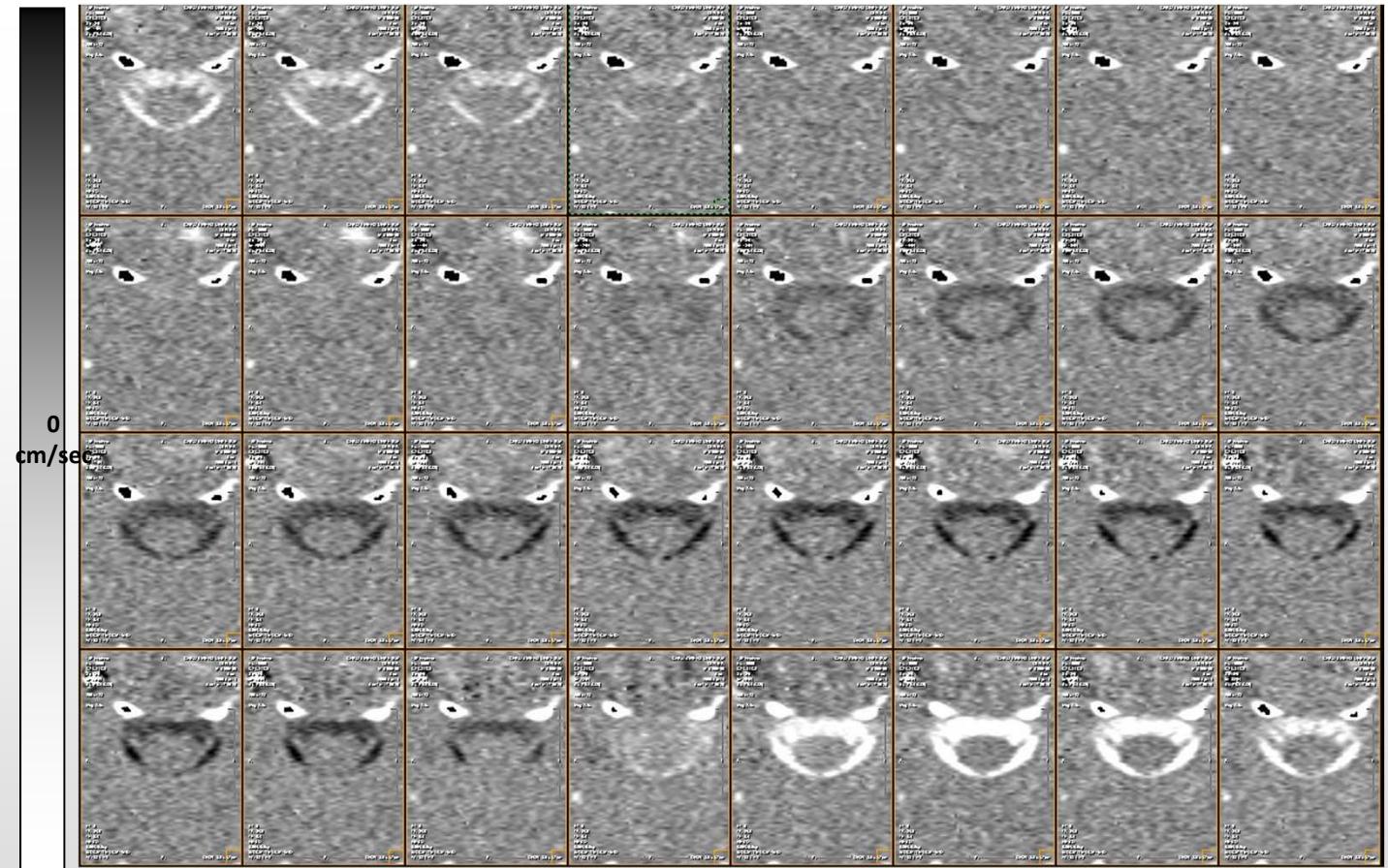
# PCMRI

Vascular acquisition ( $V_{enc} = 80 \text{ cm/sec}$ ).  
 32 images of phase and 32 images of amplitude,  
 Covering a cardiac cycle.

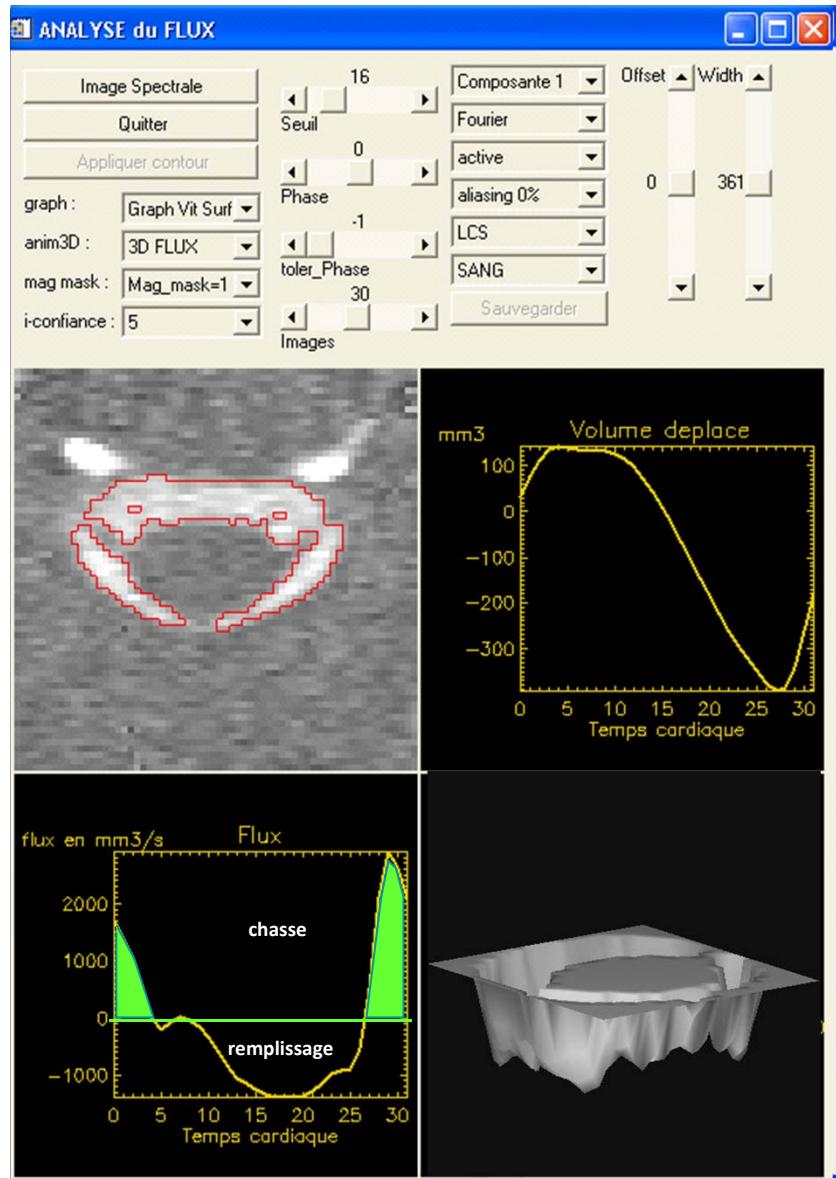




-5 cm/sec

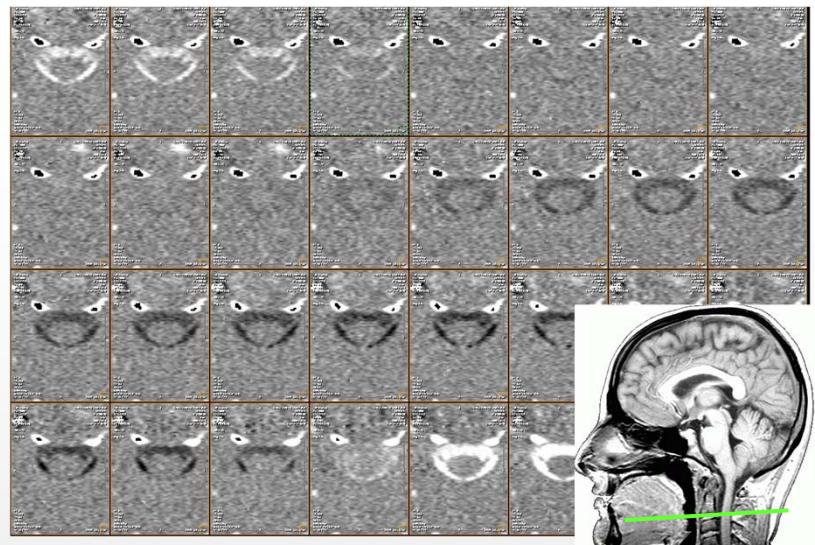


+5 cm/sec

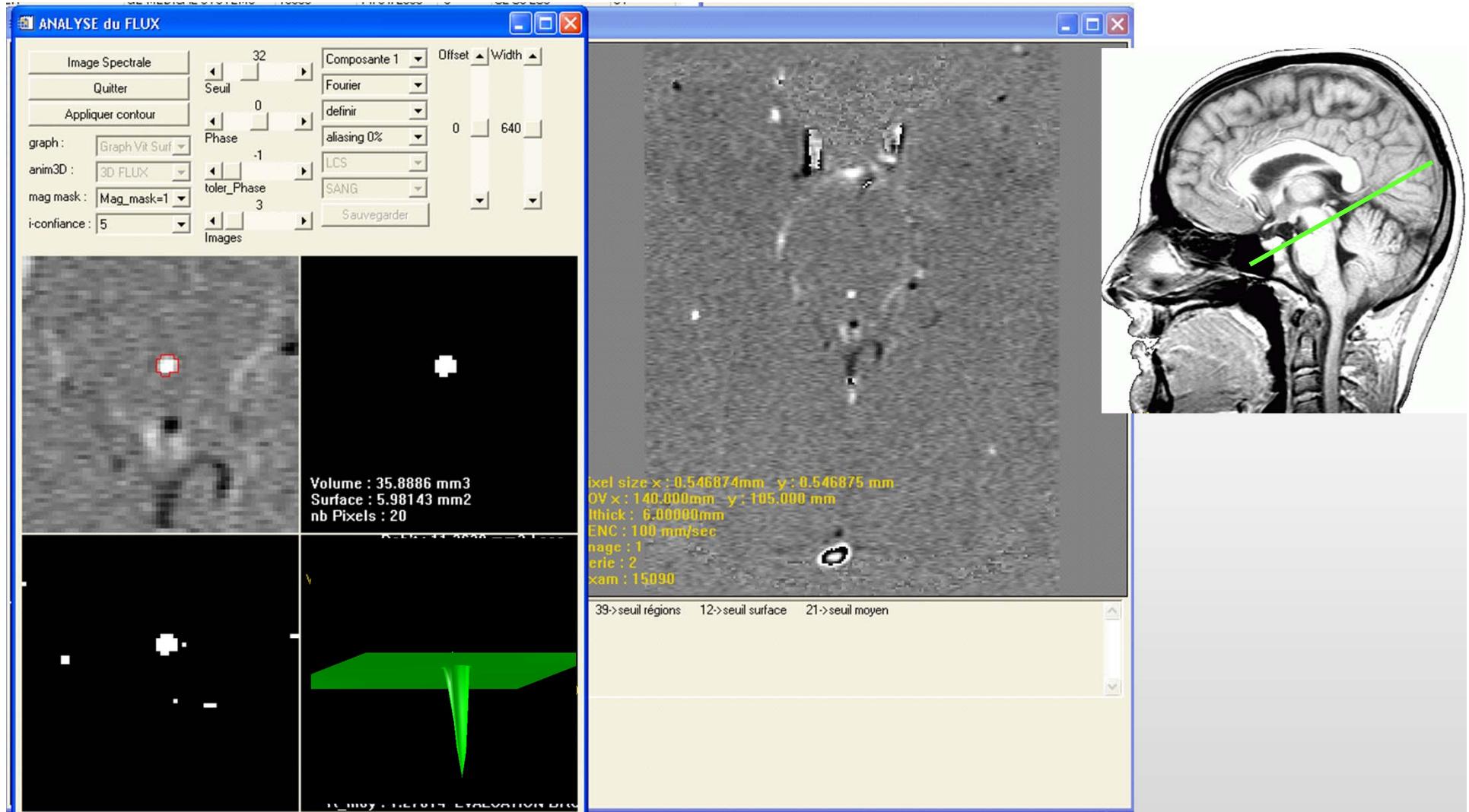


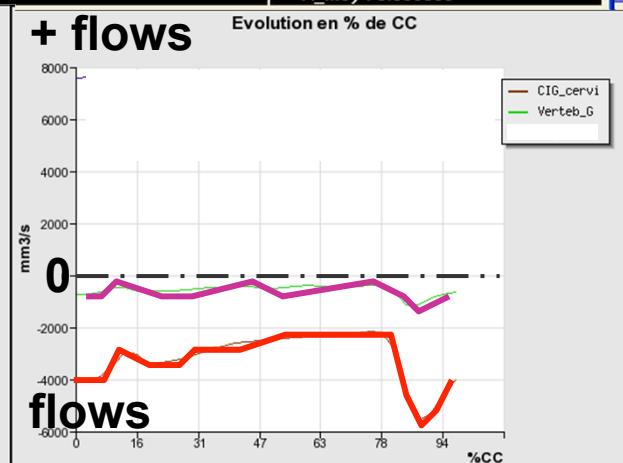
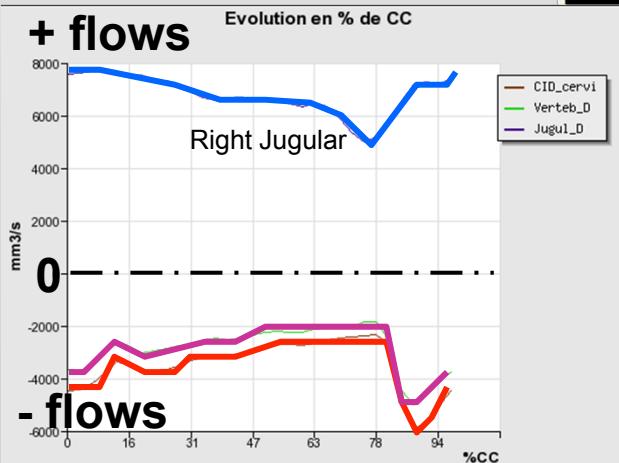
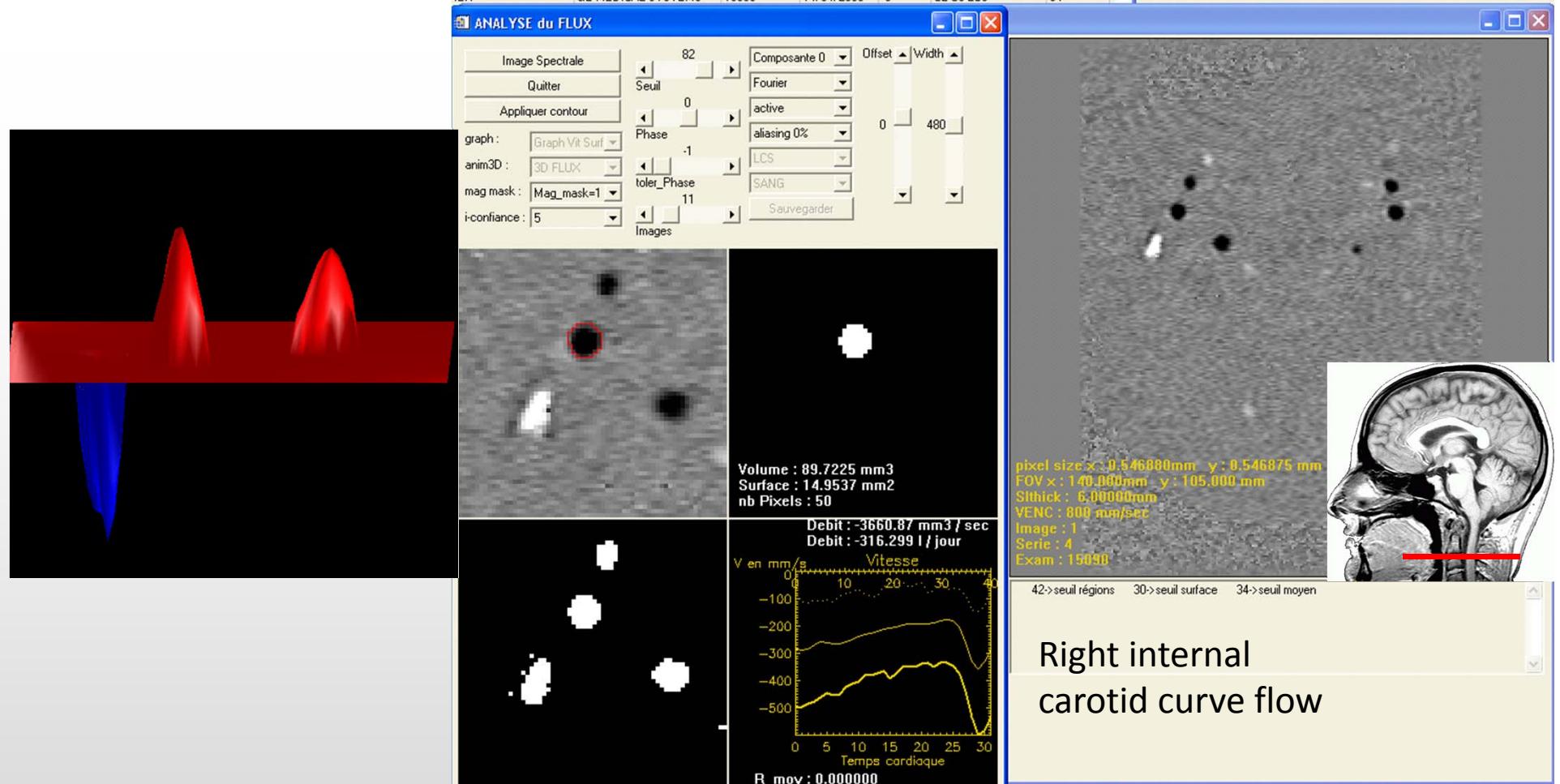
Balédent et al. Investigative radiology 2001

Free access of our flow software  
<http://www.tidam.fr>

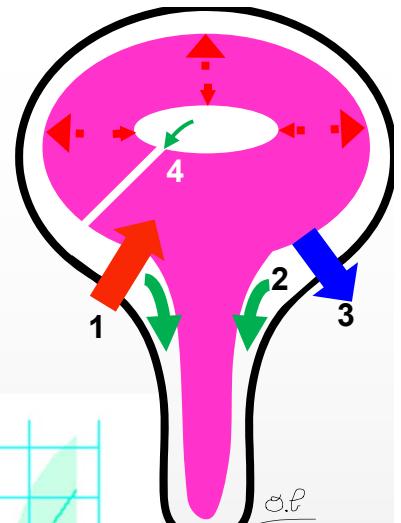
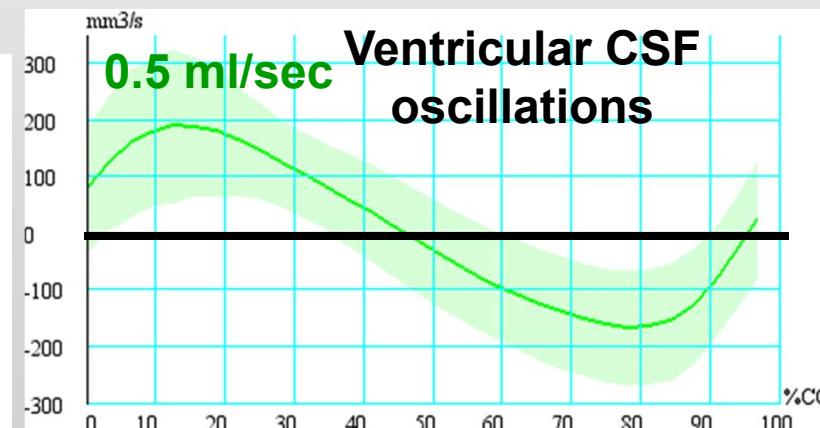
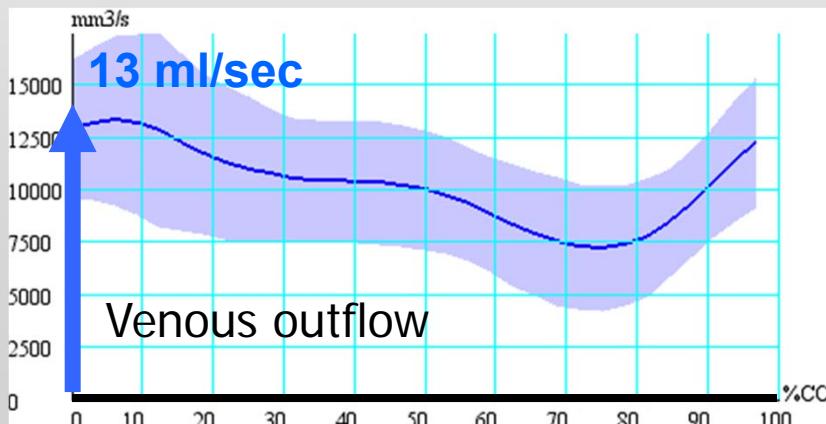
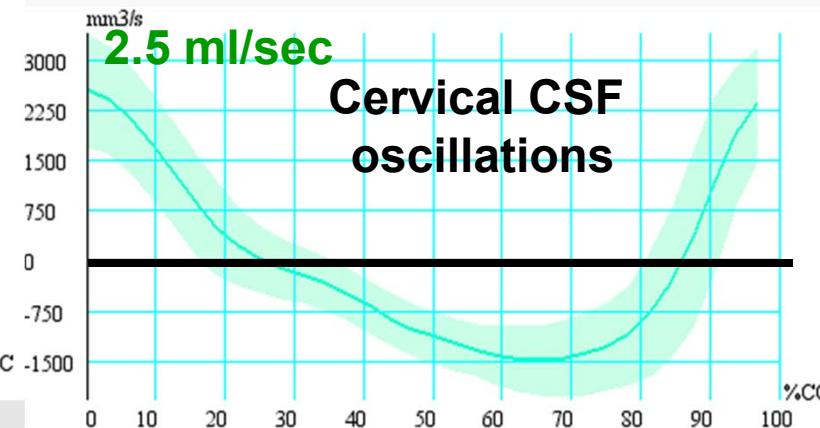
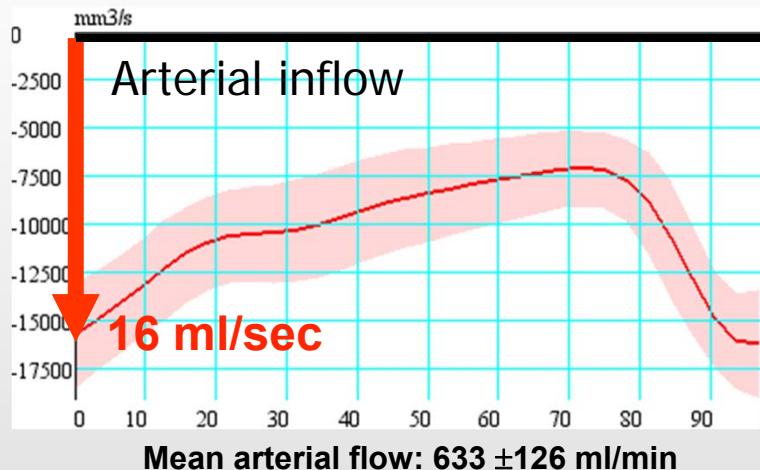


**STROKE VOLUME**



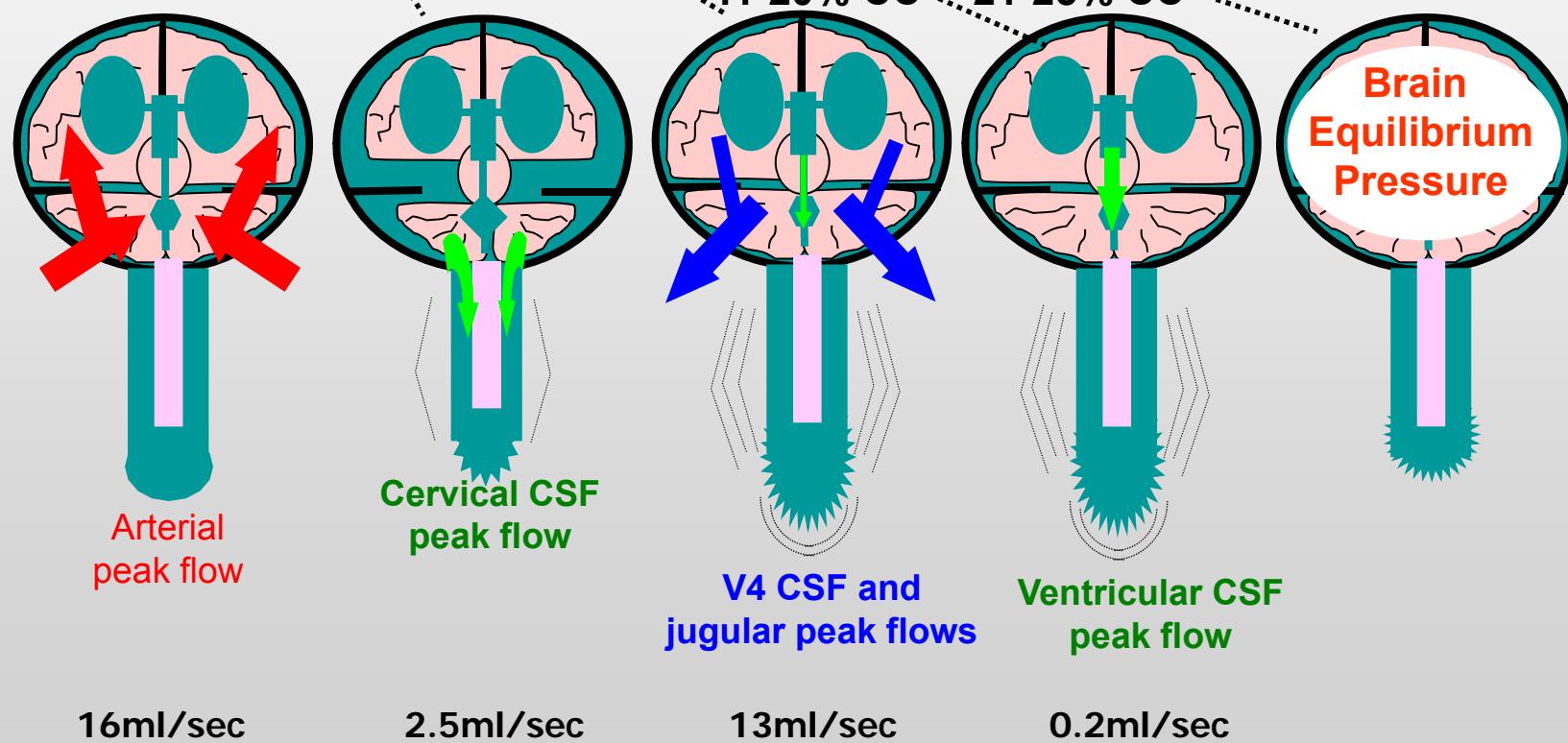
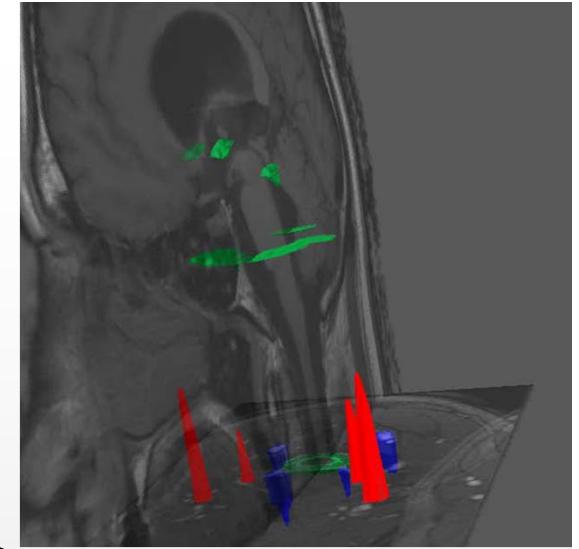
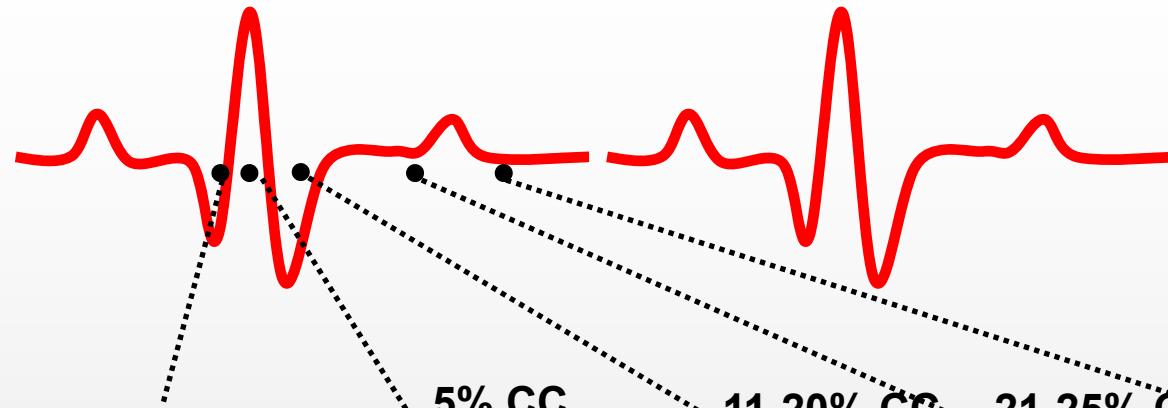


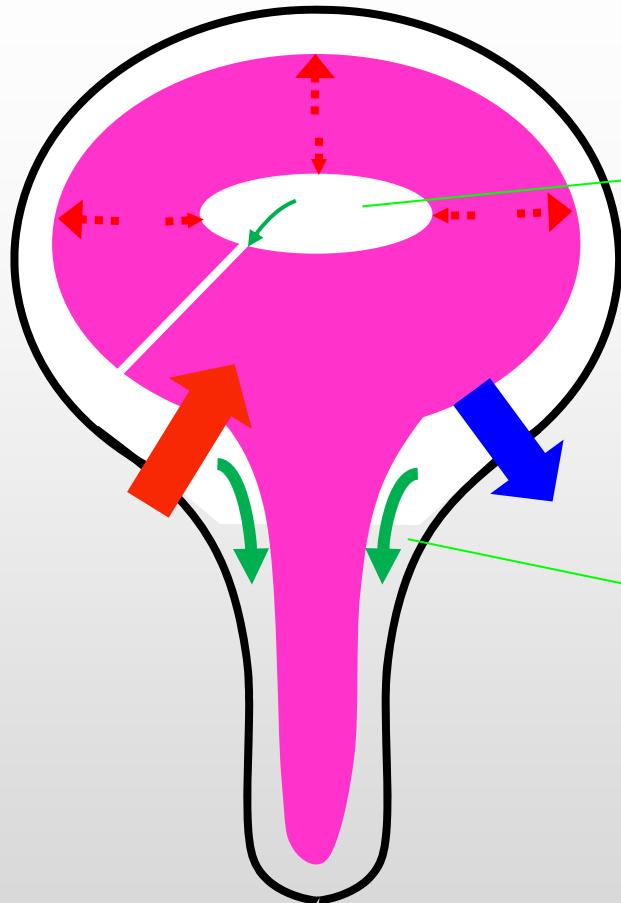
## Cerebral blood and CSF flow curves across the CC



40 YOUNG ADULTS (18 – 40 years old)

## Chronological succession of cerebral blood and CSF flow peaks across the CC



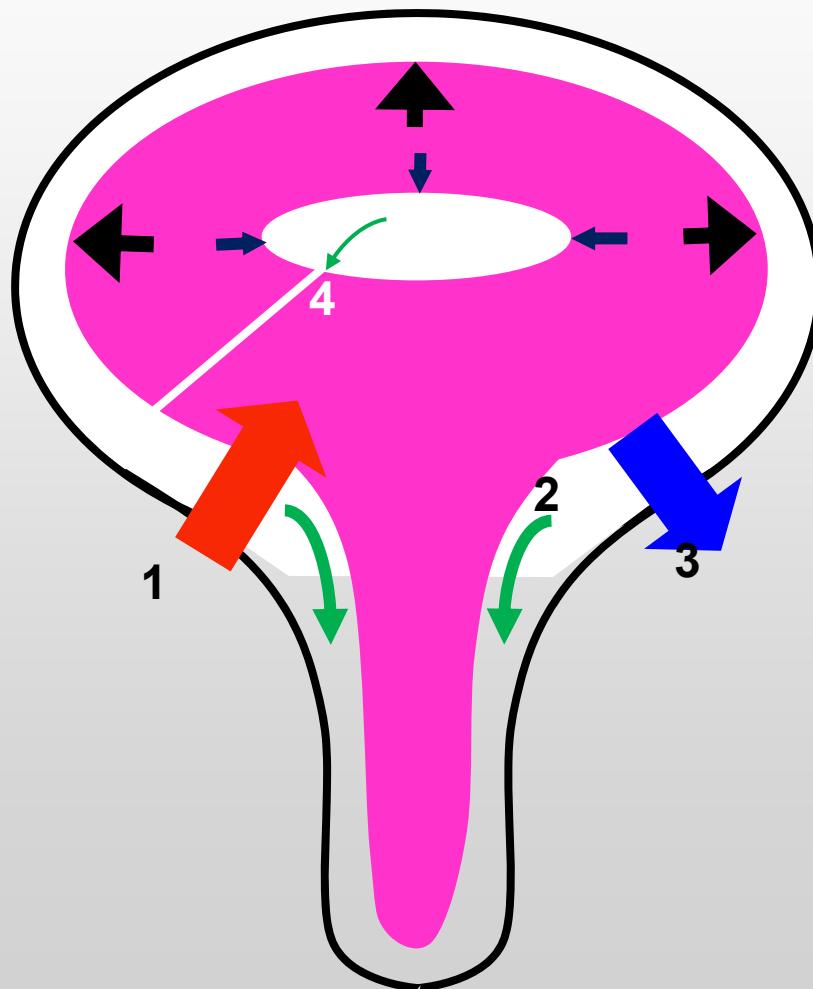


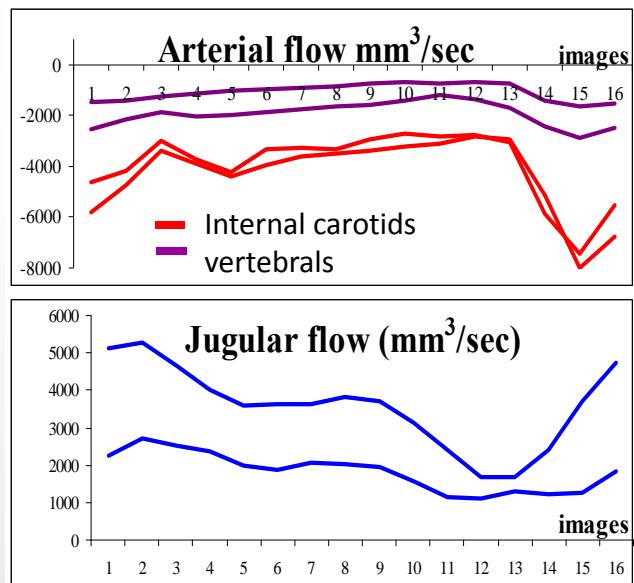
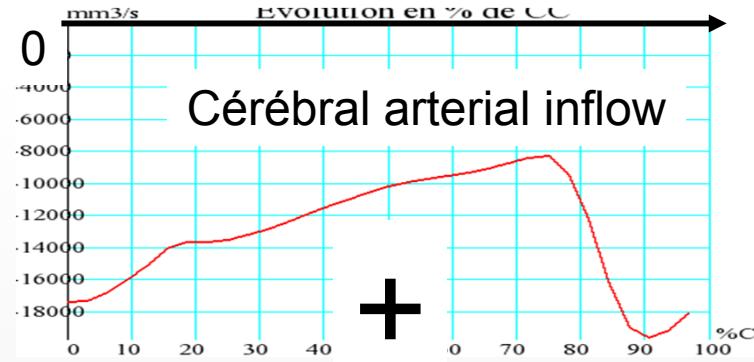
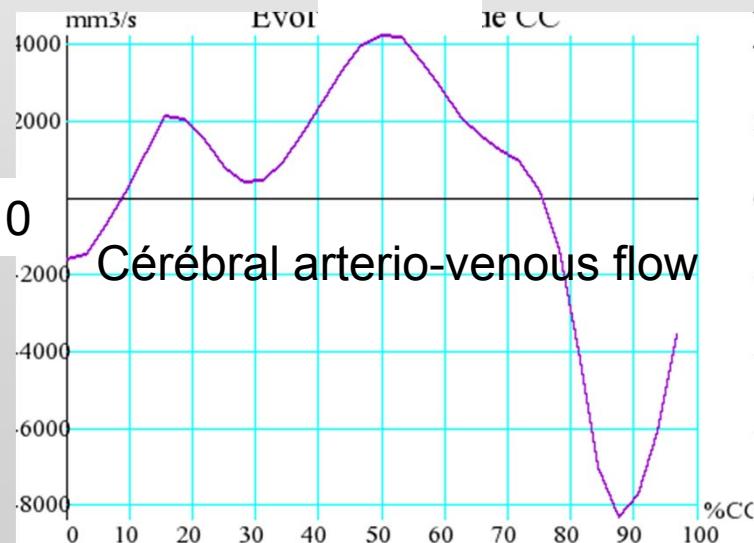
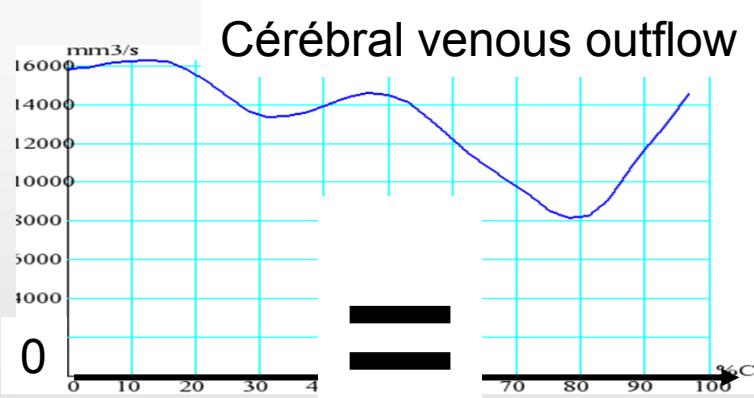
Ventricular  
CSF  
Peak flush  
**0.2 ml/sec**

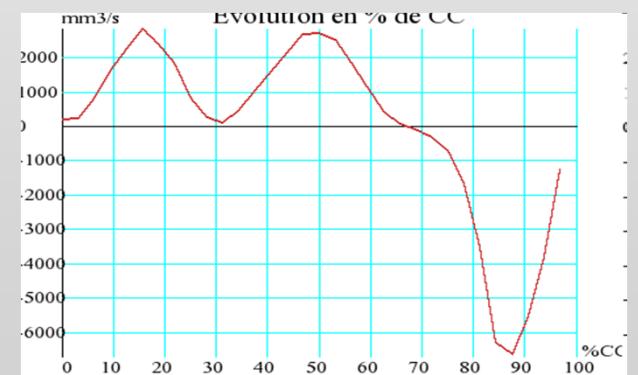
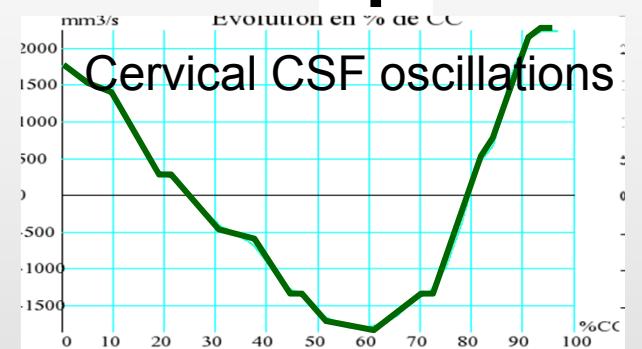
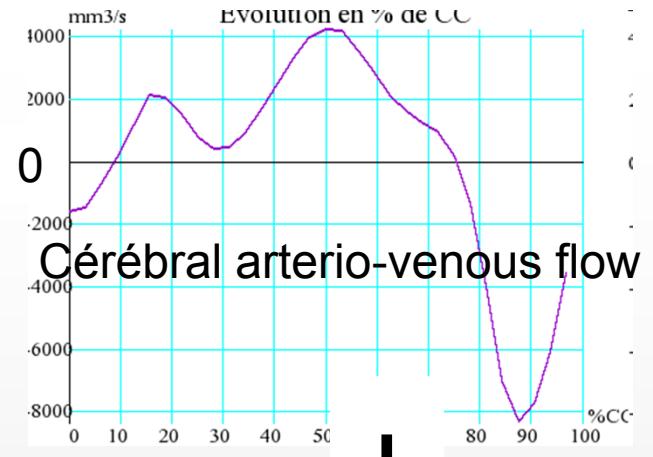
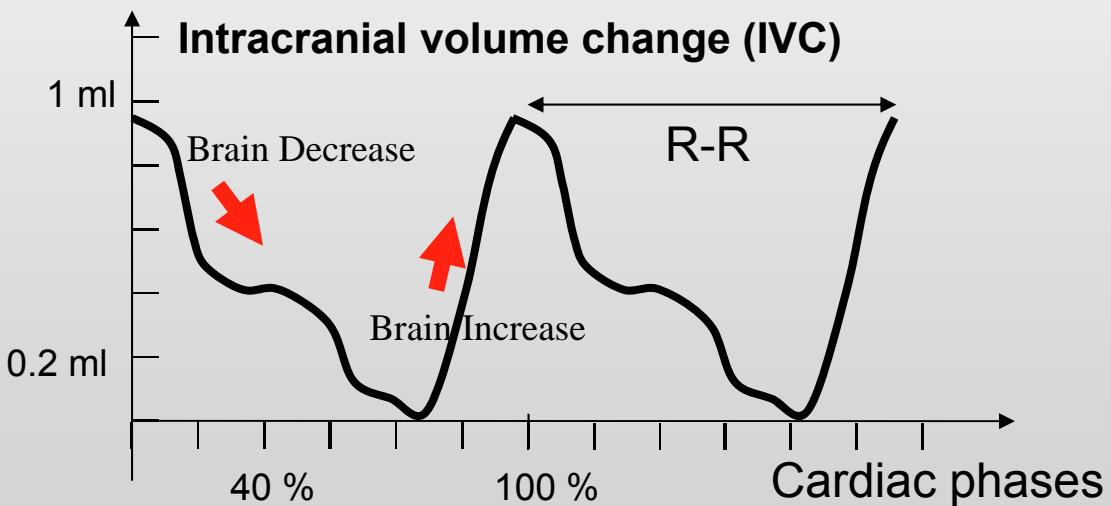
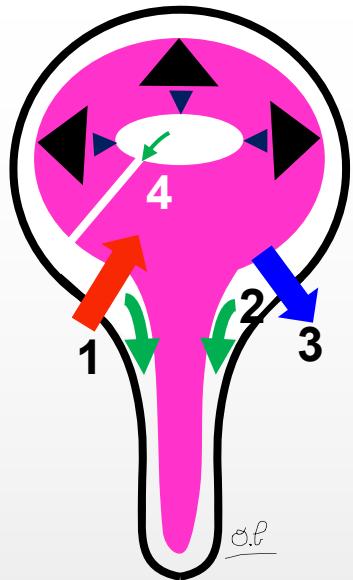
Cervical  
CSF peak  
flush  
**2.5 ml/sec**

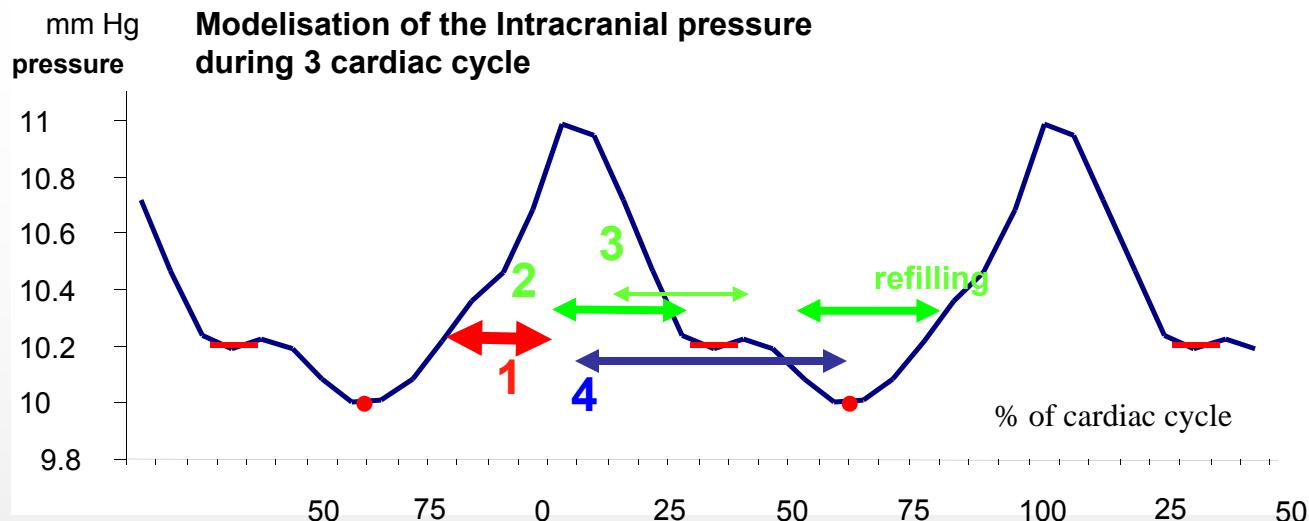
Ventricular CSF flow represents **only 10%** of cervical CSF flow

If Ventricular CSF flow represents **Only** 10% of cervical CSF flow that means that the brain expansion is mainly directed **outward**




 $\Sigma =$ 

 $\Sigma =$ 






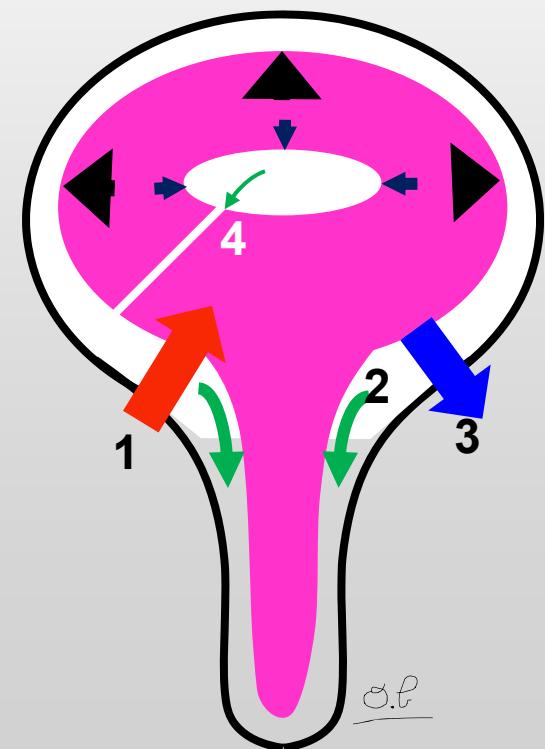
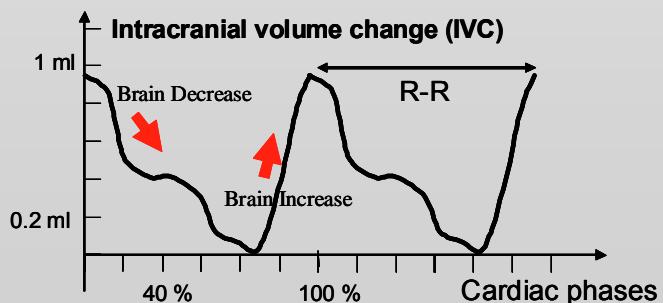
Marmarou's equation:

$$\text{ICP}(t) = P_0 \cdot e^{(k \cdot \text{IVC}(t))}$$

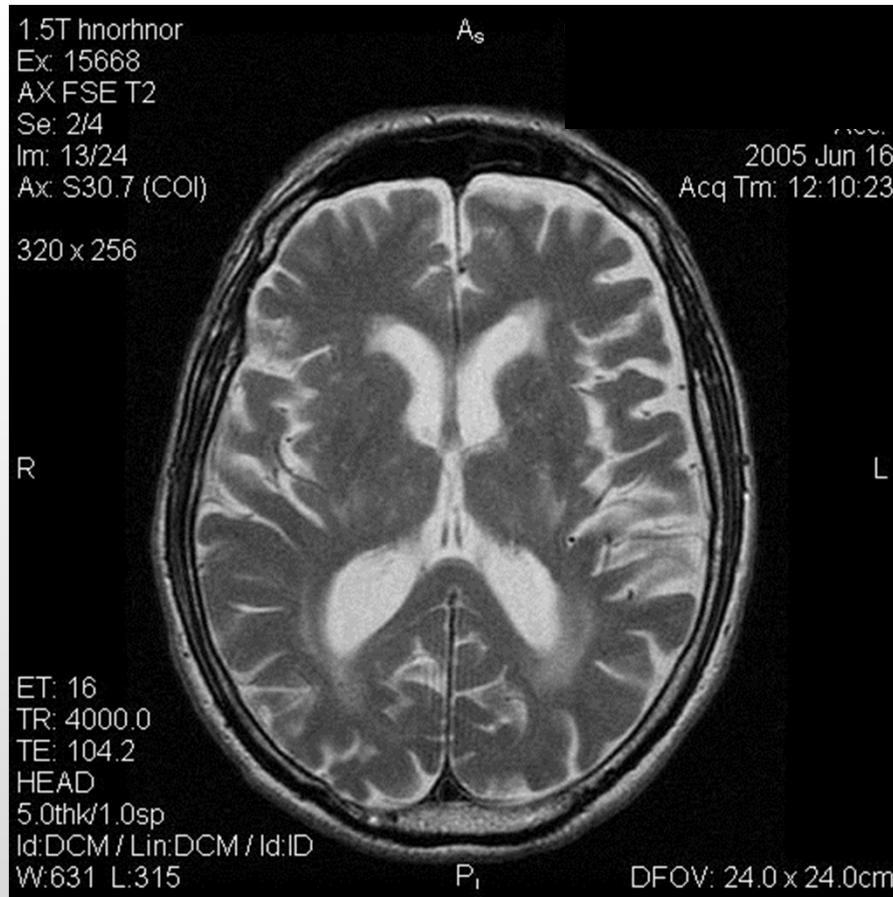
Resting  
pressure

Brain  
elastance

Intracranial  
volume  
change



# Aging



## Brain

Cerebral atrophy >>>

Ventricle dilatation

« Brain distension » (Greitz, 1969)

## Vessels

Structural changes

(Kalaria, 1996)

↓ CBF (Kashimada,1994/Buijs,1998)

## CSF

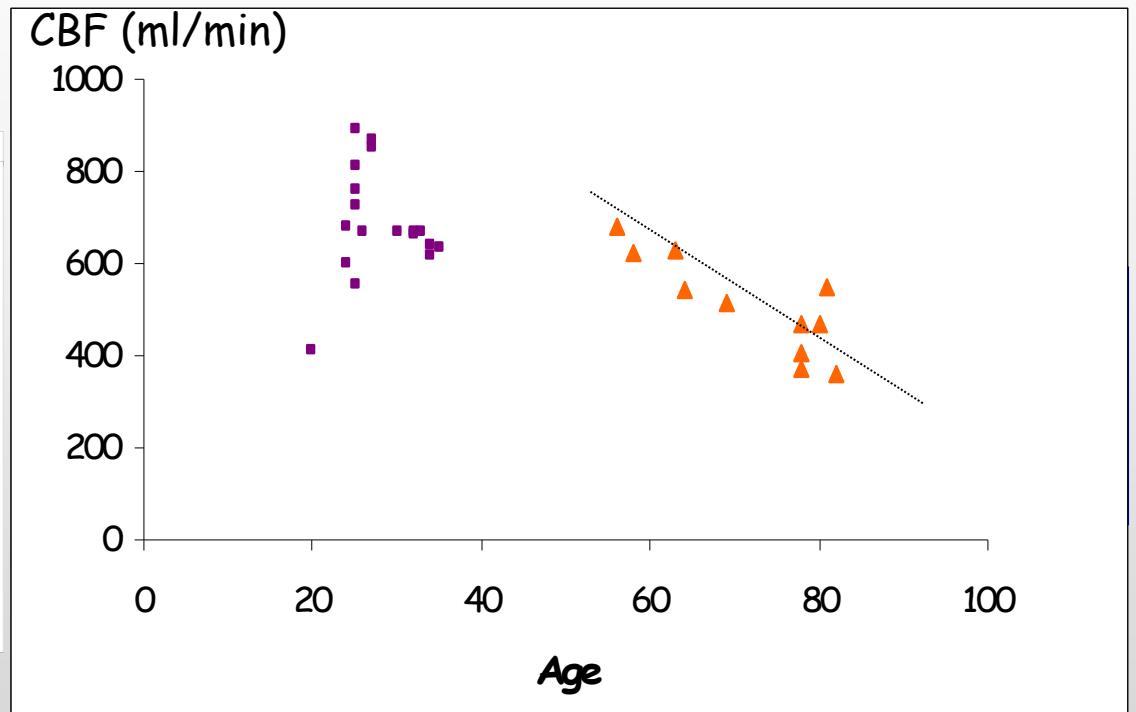
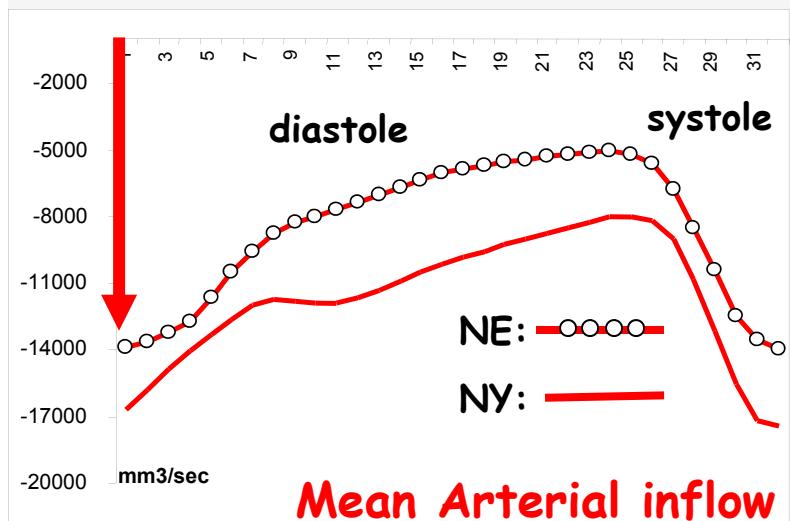
↓ Secretion/ turnover  
(May, 1990 / Silverberg, 2003)

?Dynamics (Barkhof,1994/  
Uftring, 2000/Luetmer, 2002)

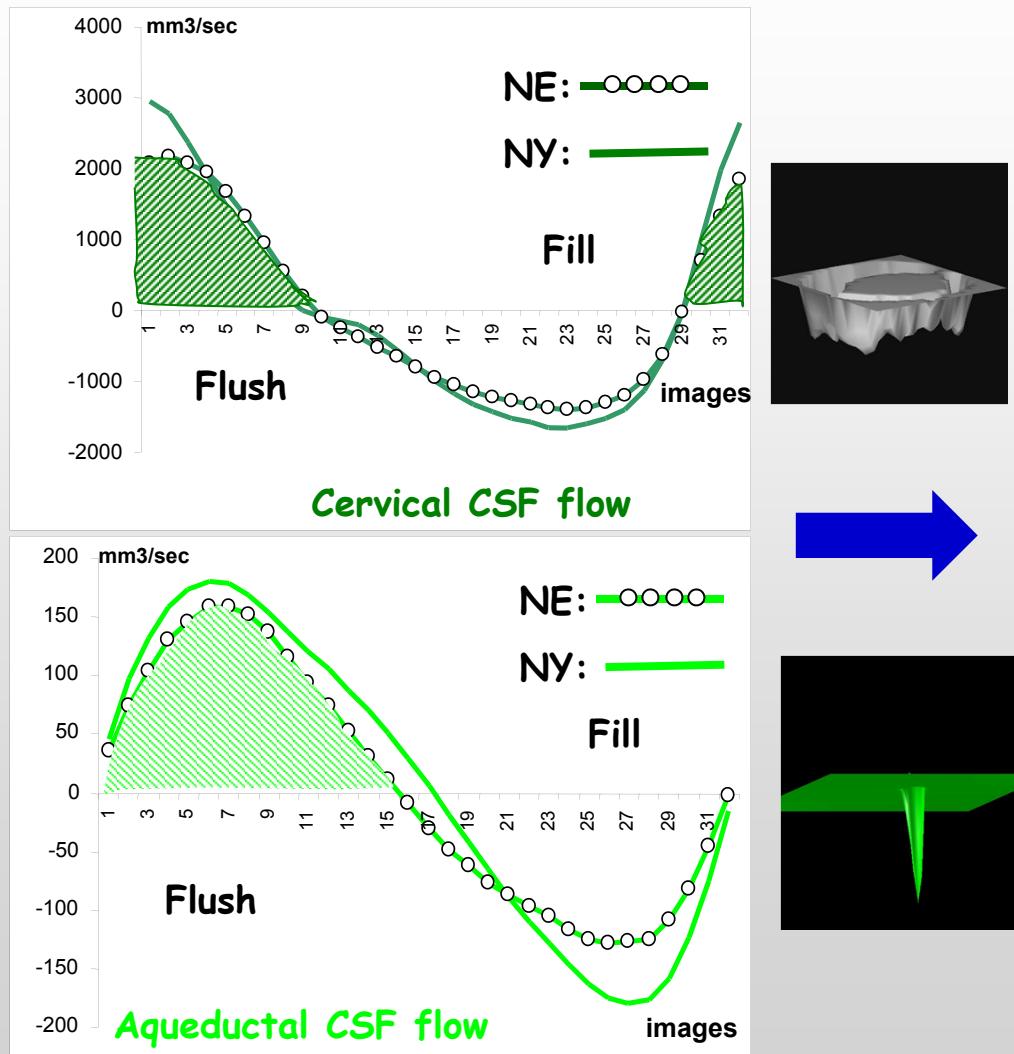
# Vascular flow curves comparison between

Normal Young  $27 \pm 4$  years

and Elderly subjects  $71 \pm 9$  years



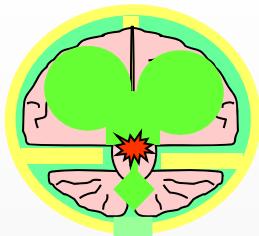
# CSF flow curves comparison in Normal Young $27 \pm 4$ years and Elderly subjects $71 \pm 9$ years



- Loss of pulsatility in CSF curves
- Reduction in CSF stroke volumes :

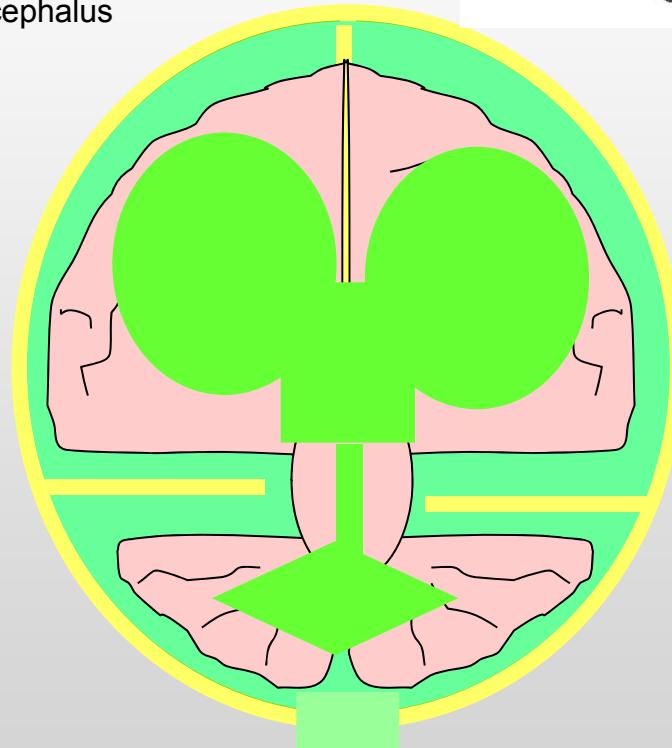
But preservation of  
Aqueductal to Cervical CSF  
stroke volumes

# Hydrocephalus

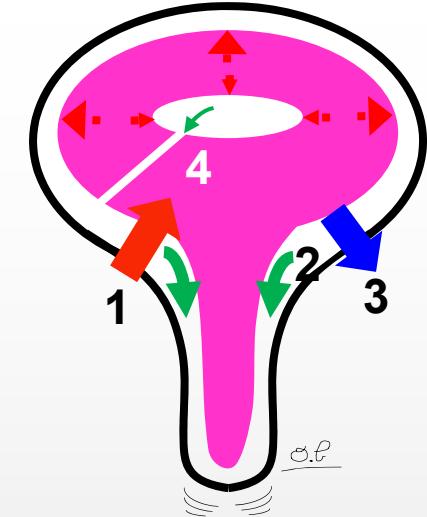


Obstructive  
hydrocephalus

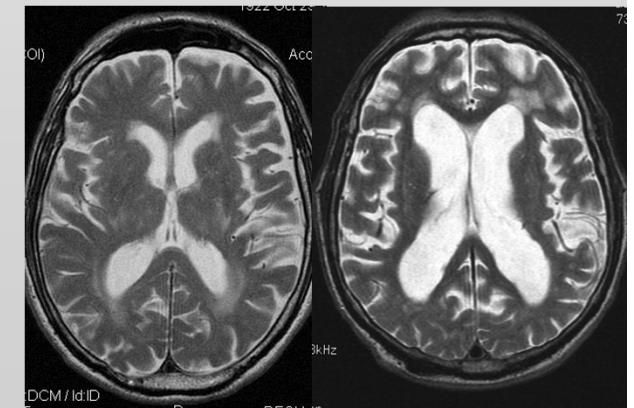
Aqueduct  
stenosis

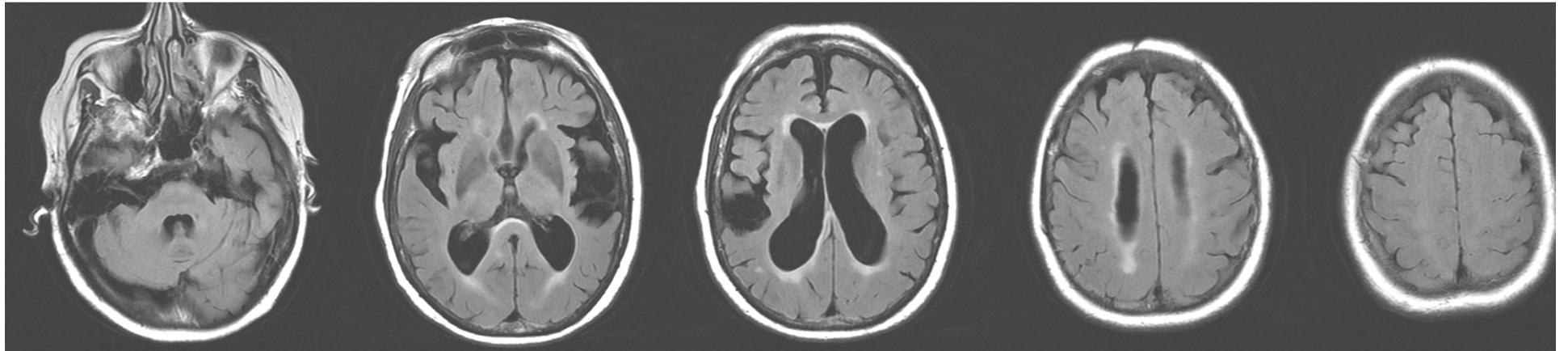


Communicant hydrocephalus



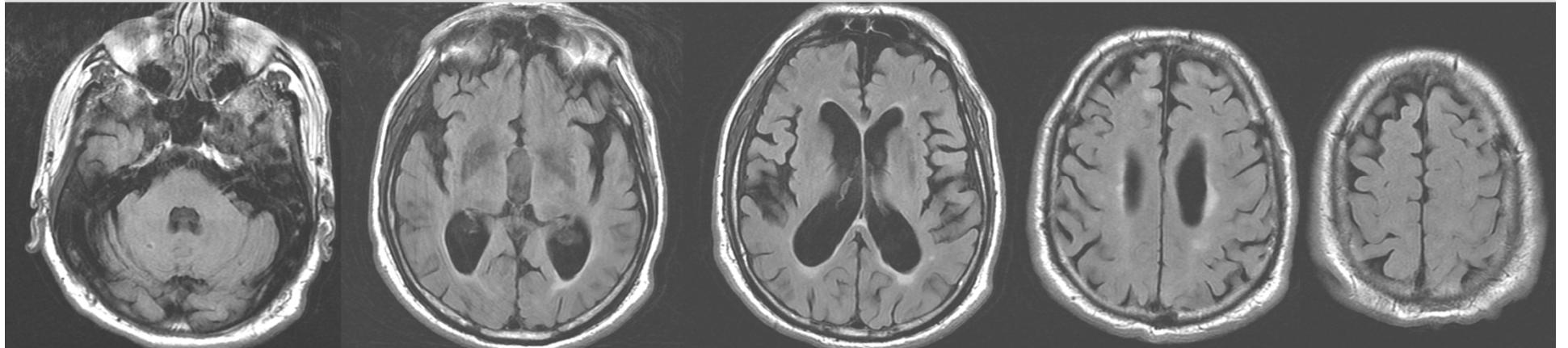
**Normal Pressure  
Hydrocephalus !!!**





# Who is who ?

Active hydrocephalus or atrophy



# 12 Patients with Communicating Hydrocephalus

And Hakim triade



## Aqueductal csf

VOLUNTEERS HYDROCEPHALUS

Flush duration (% of CC)       $53 \pm 2$     p<0.001     $48 \pm 6$

Area (mm<sup>2</sup>)       $8 \pm 2$     p<0.001     $17 \pm 11$

stroke volume \* (μl per cycle)     $51 \pm 25$     p< $6 \cdot 10^{-5}$      $196 \pm 100$

## Cervical csf

VOLUNTEERS HYDROCEPHALUS

$40 \pm 10$     NS     $40 \pm 4$

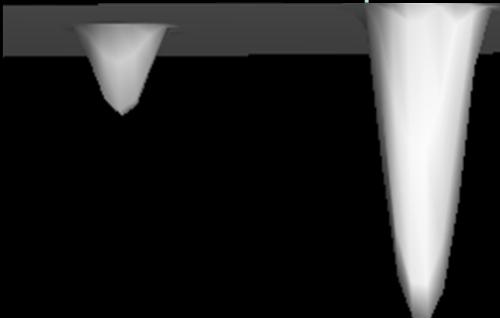
$102 \pm 32$     NS     $87 \pm 37$

$467 \pm 147$     NS     $467 \pm 260$

## Aqueductal flush

Healthy  
volunteer

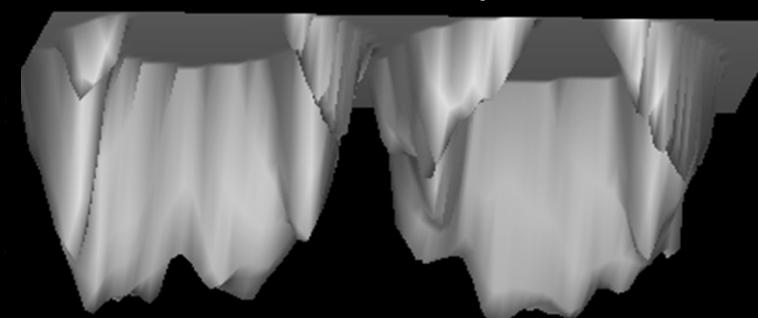
Hydrocephalus  
patient

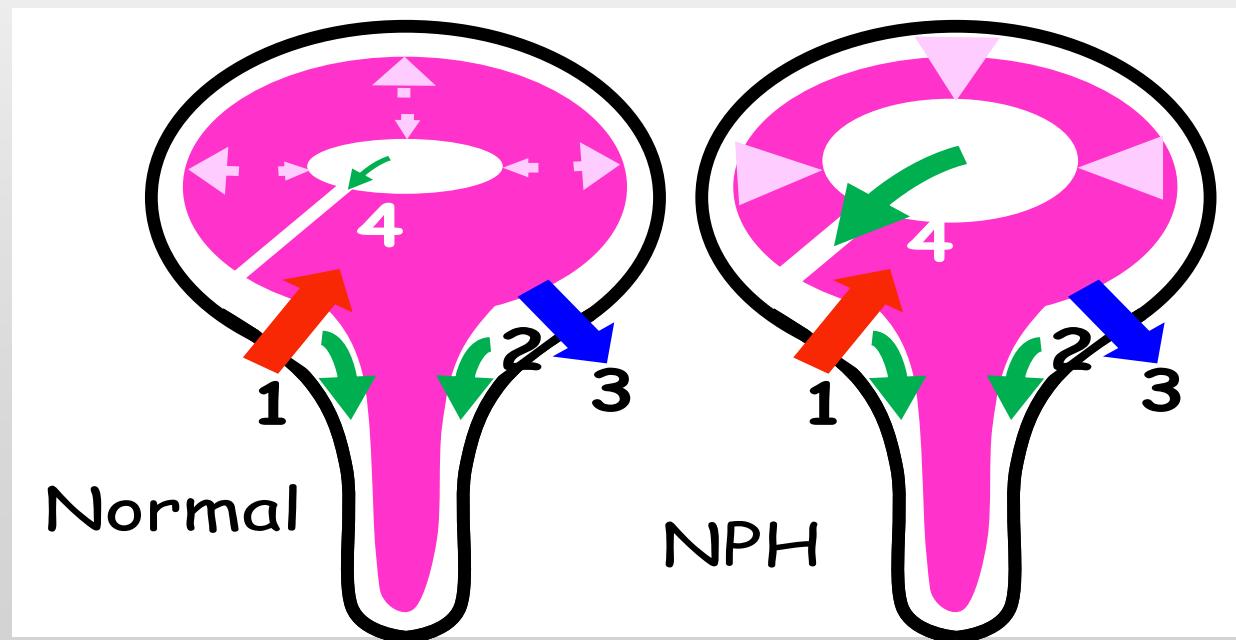
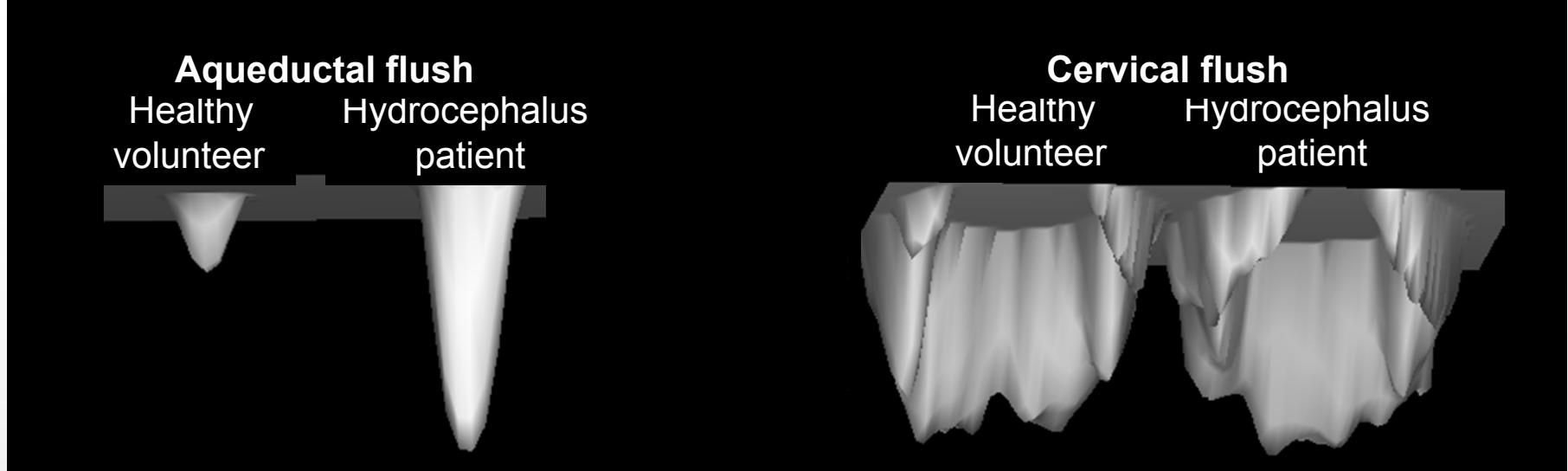


## Cervical flush

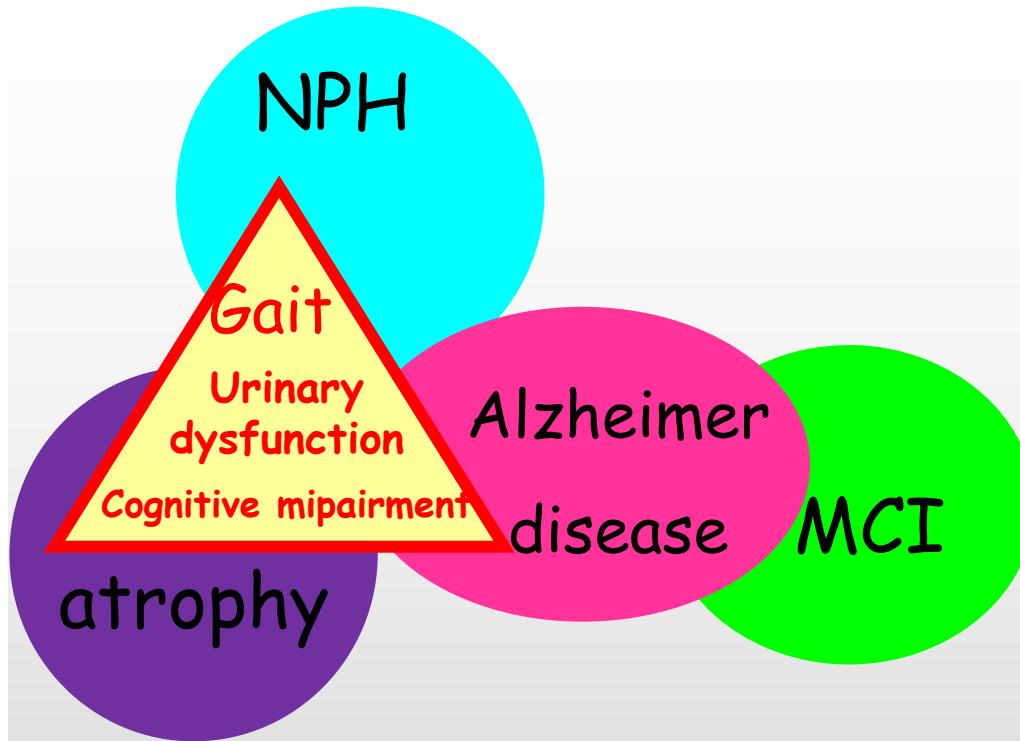
Healthy  
volunteer

Hydrocephalus  
patient

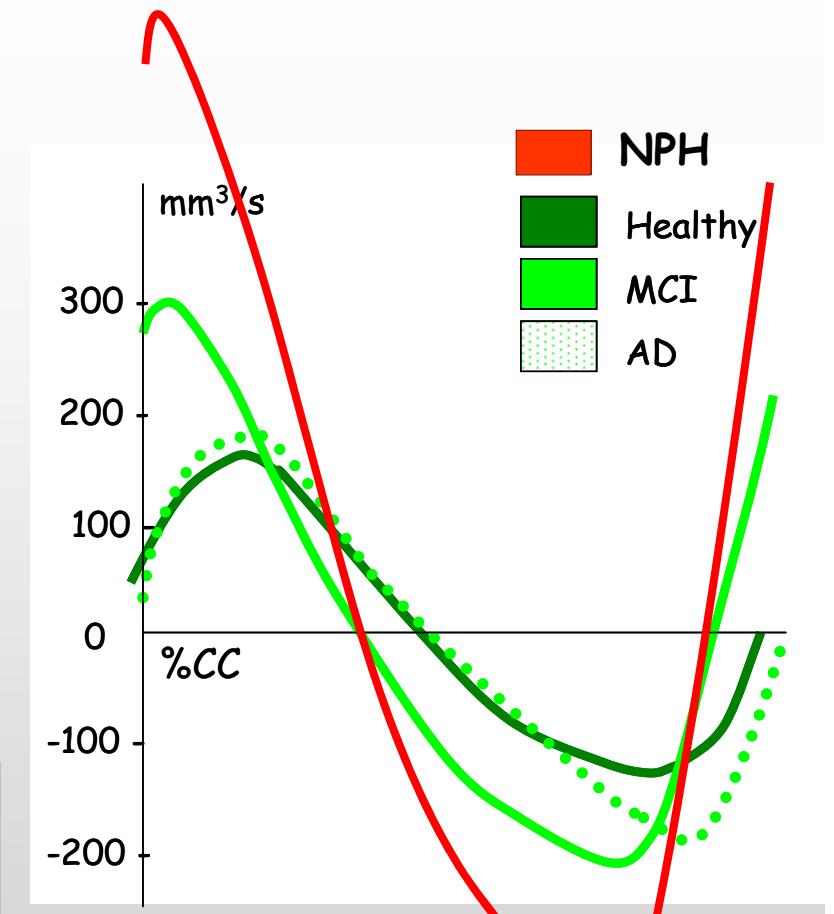




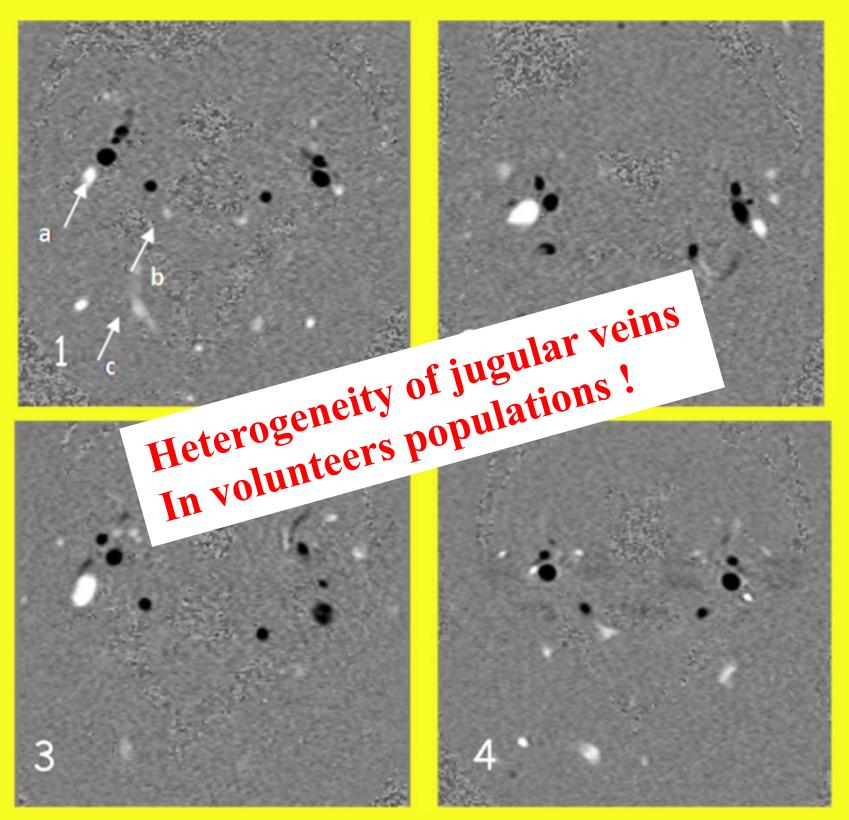
## CSF flows in Neurodegenerative pathologies



Aqueductal CSF oscillations:  
help to differentiate Alzheimer  
and NPH



- MCI and NPH : Hyperdynamic aqueductal CSF flows
- MCI Less than in NPH
- ??? Alteration of ventricular compliance



- Heterogeneity of cerebral venous flows  $\neq$  Arterials
- Right dominance

**Role of accessory cervical drainage pathways, not only postural**

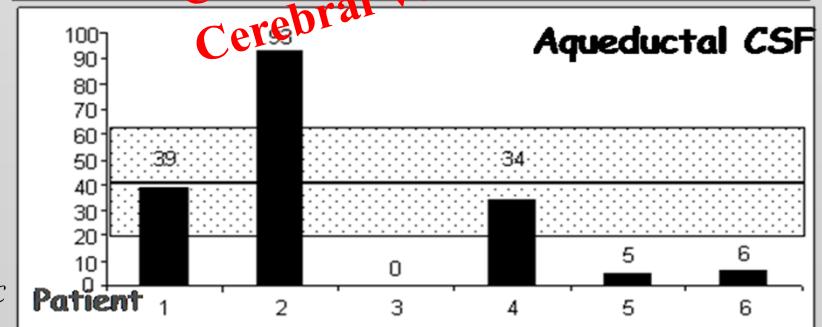
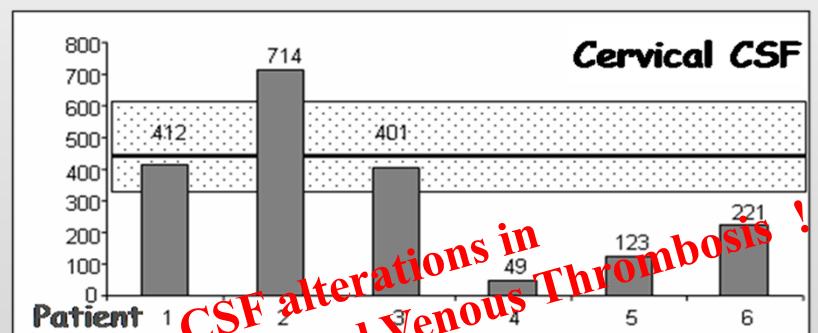
*Stoquart-ElSankari S, et all. A phase contrast MRI study of physiologic cerebral venous flow. J Cereb Blood Flow Metab. 2009*

### In Cerebral Venous Thrombosis:

- individual CSF flow modifications
- Variability
- Complementary to Conventional MR protocols

**Only one** CSF stroke volumes in 6 patients with cerebral venous Thrombosis is **normal**.

The dashed rectangle corresponds to volunteers



## Conclusion

ICP must be preserved in medicine but arterial input is vital !

In healthy subject, vascular brain expansion is quickly compensated by CSF flush, whereas ventricular CSF only brings a small contribution.

Because blood and CSF are not compressible and the cranium considered as a rigid box, arterial input volume have to be balanced by flushing of CSF and blood out of the cranium.

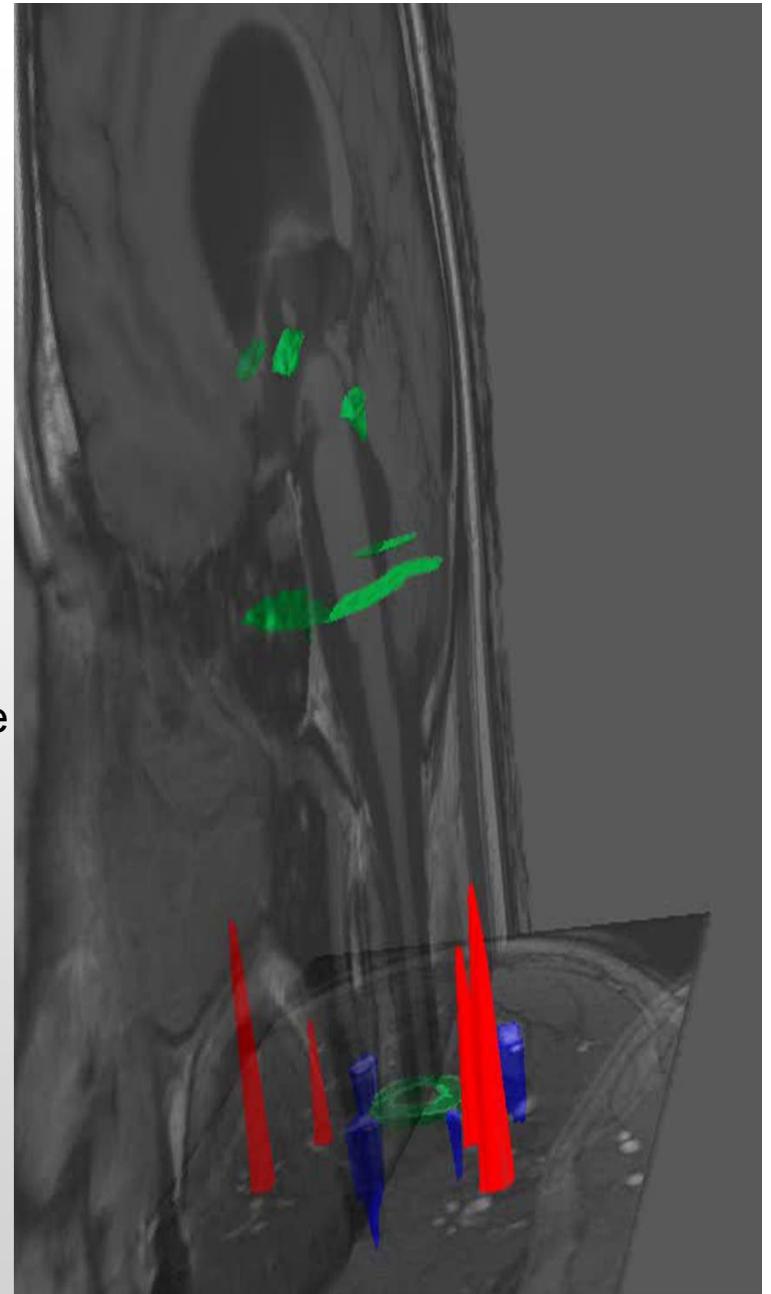
Compensation is not instantaneous and intracranial pressure variation during the cardiac cycle is still observed.

Modifications of CSF flows could lead to ventricular dilation or ventricular dilation lead to increase CSF pulsation ?

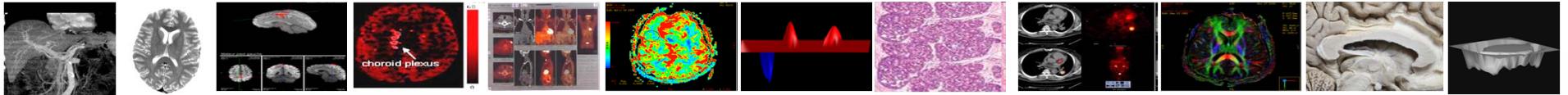
What about cardiac aspiration during diastole ?

What about thoracic and abdominal pressure

Lot of brain pathologies not still understood could be explained by better knowledge of the cranio-spinal CSF biomechanics



*Free access of our flow software  
<http://www.tidam.fr>*

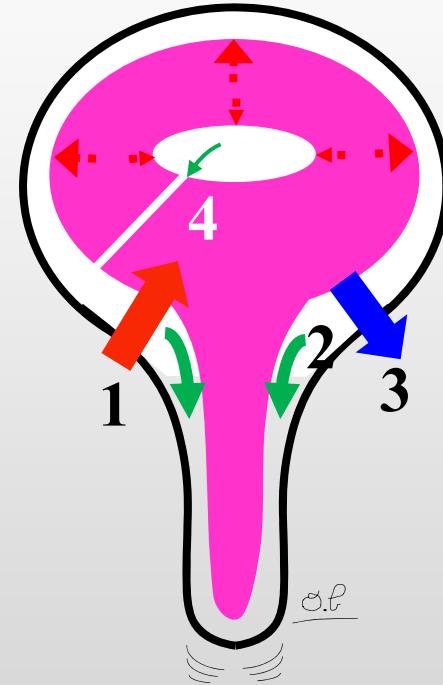
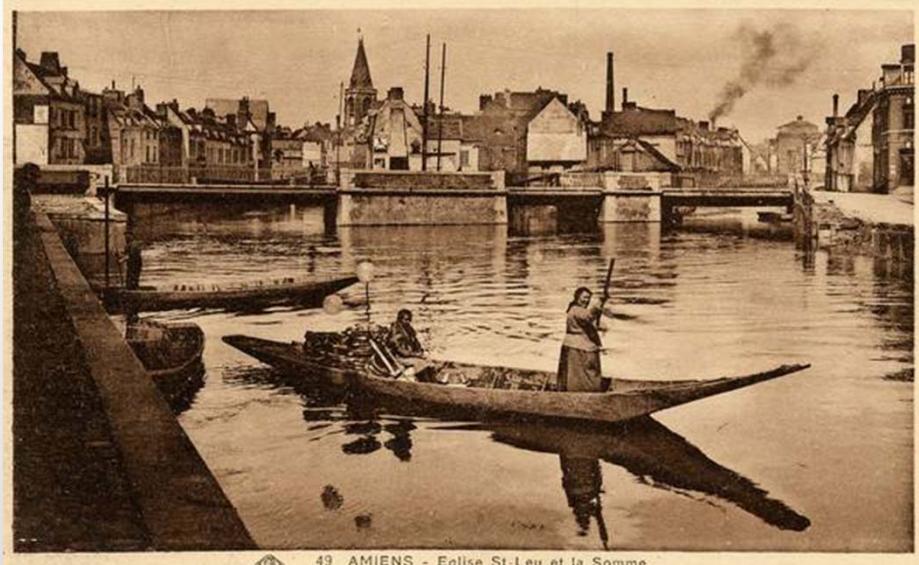


## CSF flows: From origins to alterations.



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C. Gondry-Jouet, A. Fichten, S. Elsankari, R. Bouzerar  
University hospital of Picardie Jules Verne, Amiens, France.



**Le système de santé français**

Le CHU, une entreprise de Picardie

**La Picardie**

L'établissement hospitalo-universitaire de Picardie

**Amiens, capitale régionale**

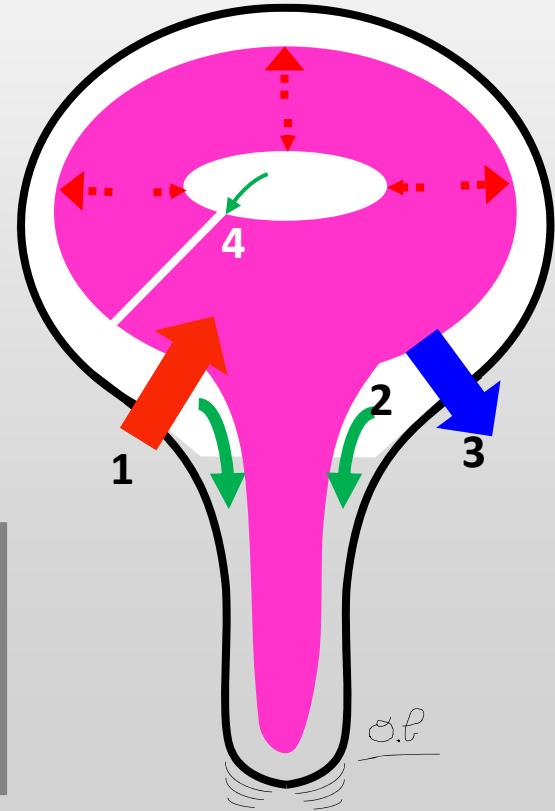
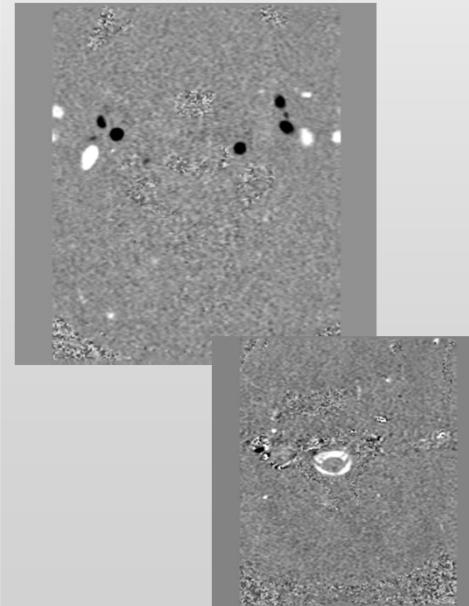
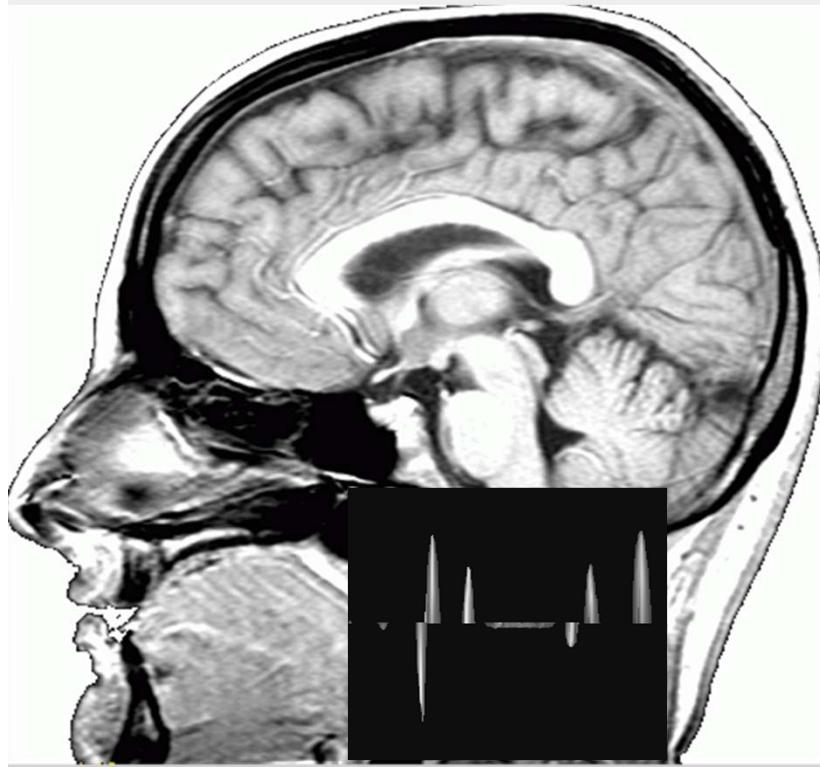
Des projets pour moderniser

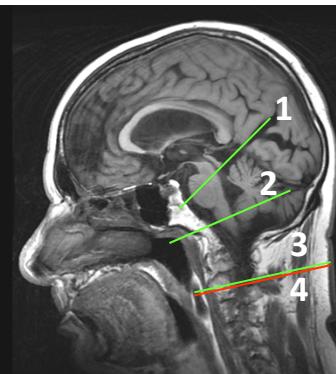
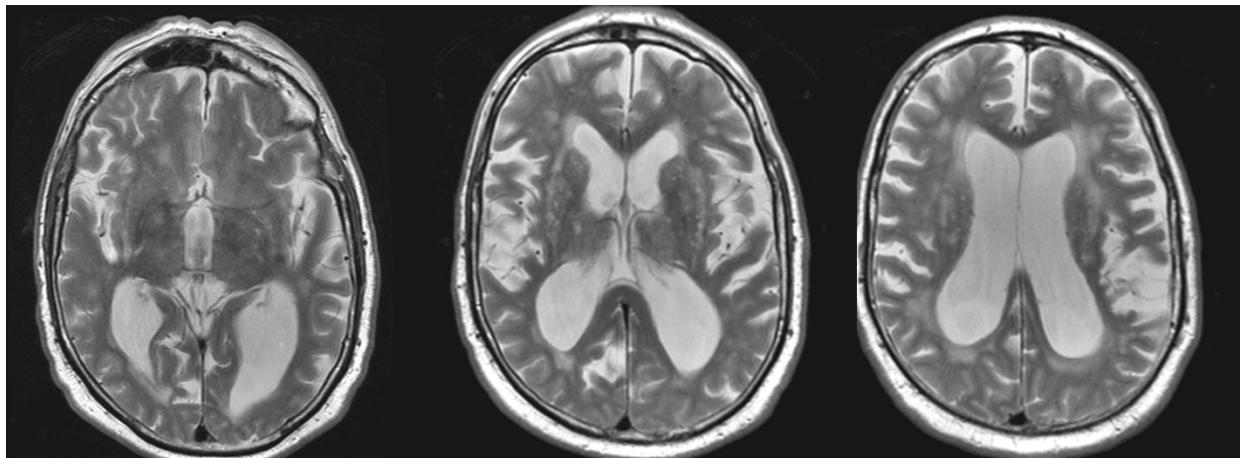
*Study supported in part by European Community  
INTERREG  
(cooperation Amiens-Cambridge) grant*

In collaboration with



# In clinical practice





man 72 years old  
symptoms for 2 years,  
Wheel chair,  
incontinent,  
Cognitive impairment,  
pseudo-Parkinson

Volume Oscillatoire du LCS	PATIENT	TEMOINS	
	Mesuré (µl/R-R)	Moyenne (µl/R-R)	Ecart-type (µl/R-R)
Aqueduc	<b>150</b>	34	16
V4	<b>68</b>	28	18
C2-C3	<b>420</b>	457	147
Citer prep	<b>357</b>	239	187

Débit Sang	Mesuré (ml/min)	Moyenne	Ecart-type
cérébral	<b>531</b>	498	57

CSF flows :

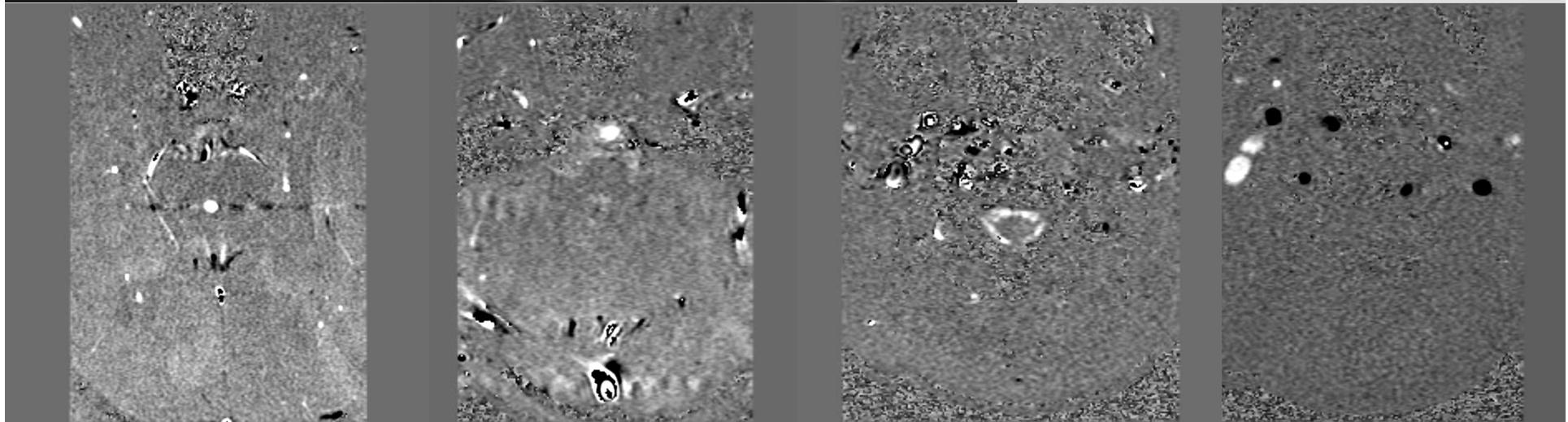
Hyper dynamic in aqueduc

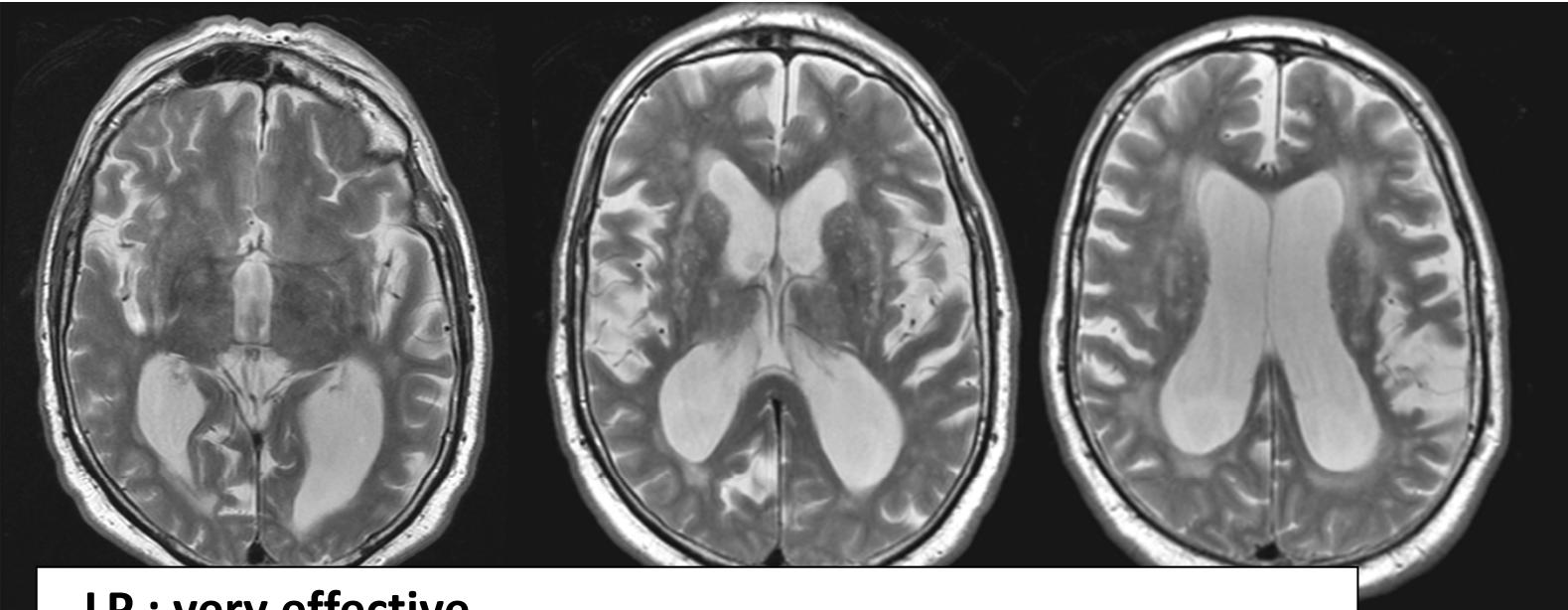
1

2

3

4



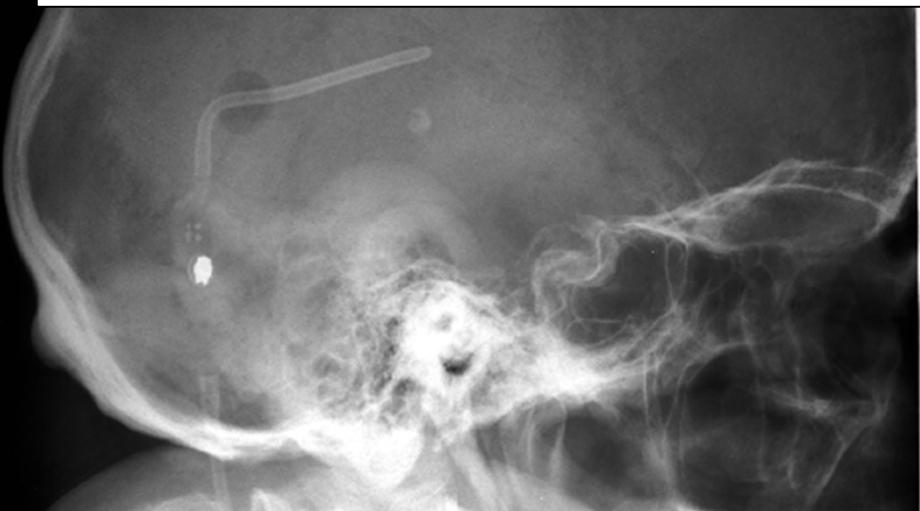


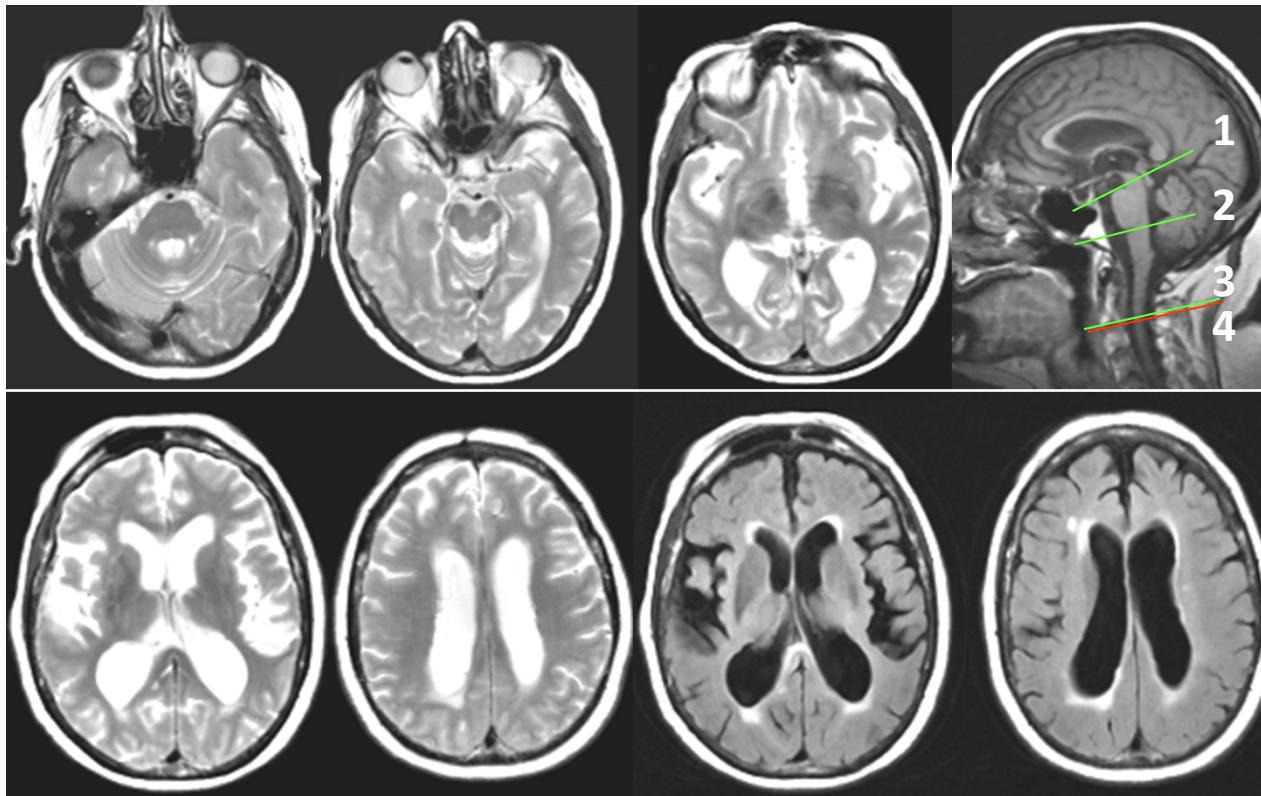
man 72 years old  
symptoms for 2 years,  
Wheel chair,  
incontinent,  
Cognitive impairment,  
pseudo-Parkinson

- LP : very effective

- Treatment : shunt

- Result : walk at D1 after surgery, continent at D15,  
normalization of cognitive function after 1 month





women 72 years old  
Slowly progressive  
dementia  
parkinson yndrome  
+ gait disturbances

	STROKE VOLUME		
	Patient	Population témoin	
LCS	Mesurée ( $\mu$ l/min)	Moyenne	Ecart-type
Aqueduc	<b>43</b>	34	16
V4	<b>10</b>	28	18
C2-C3	<b>431</b>	457	147
Citer prep	<b>158</b>	239	187

Débit Sang	Mesurée (ml/min)		
		Moyenne	Ecart-type
cérébral	492	498	57

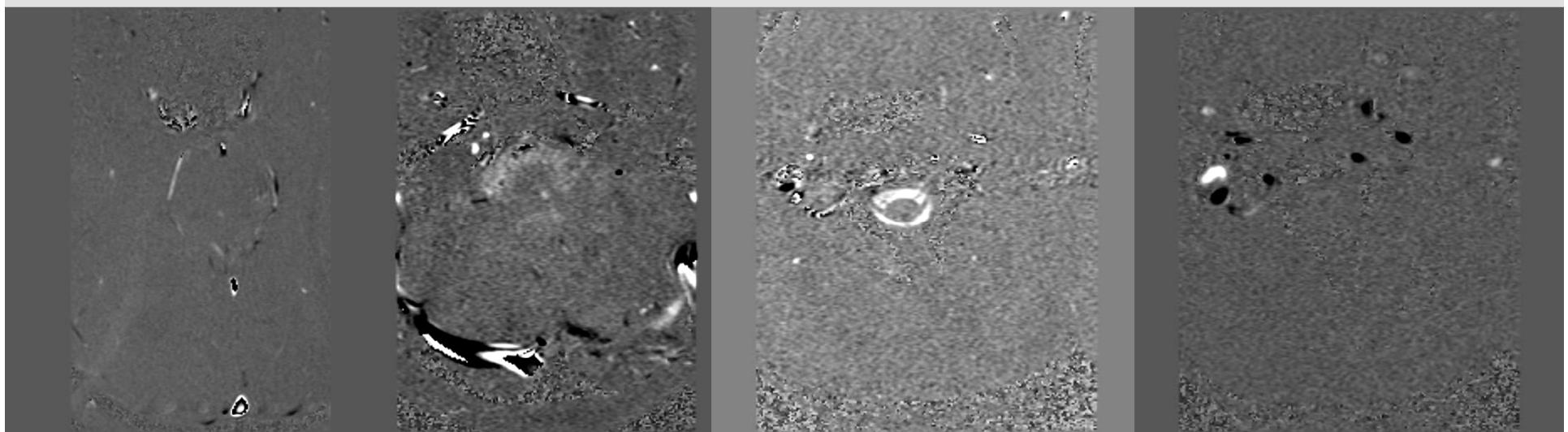
CSF flows : Normal

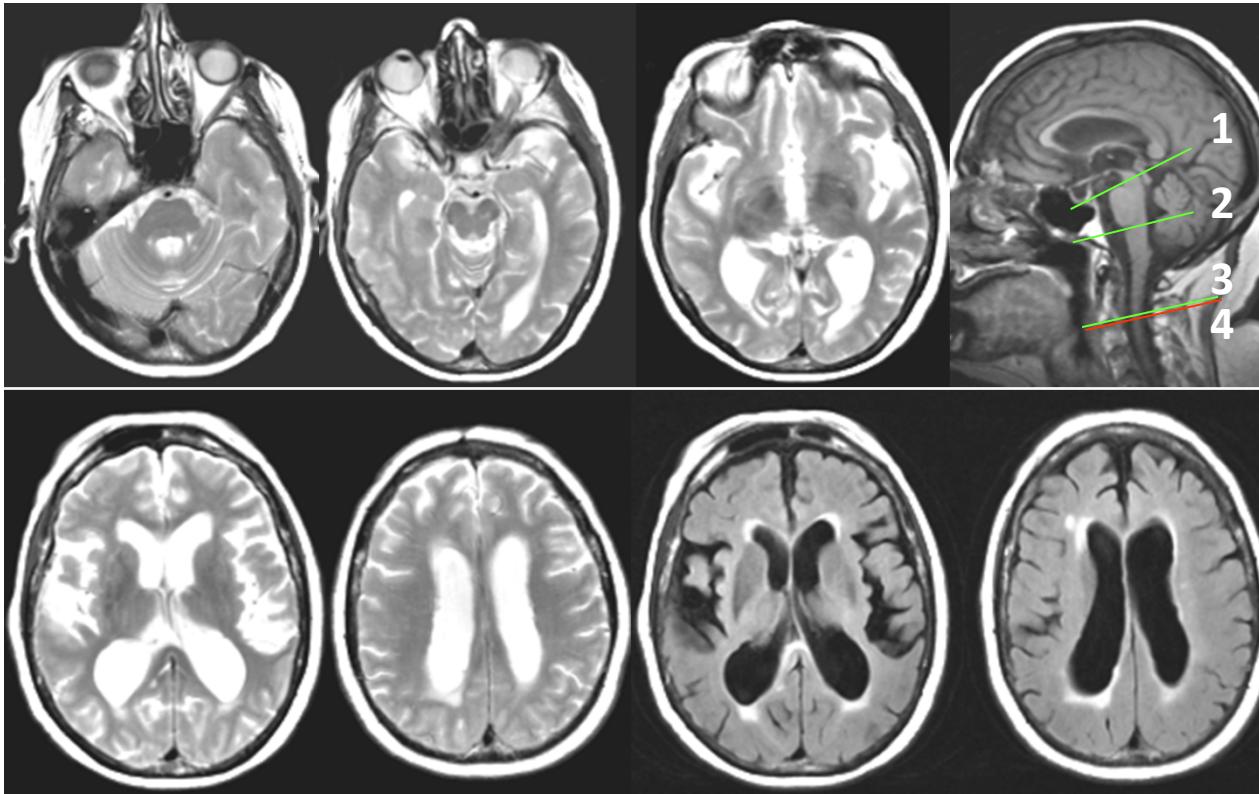
1

2

3

4

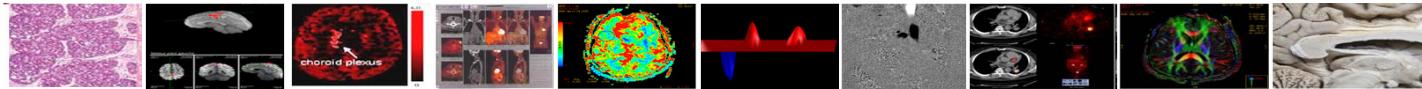




women 72 years old  
Slowly progressive  
dementia  
parkinson yndrome  
+ gait disturbances

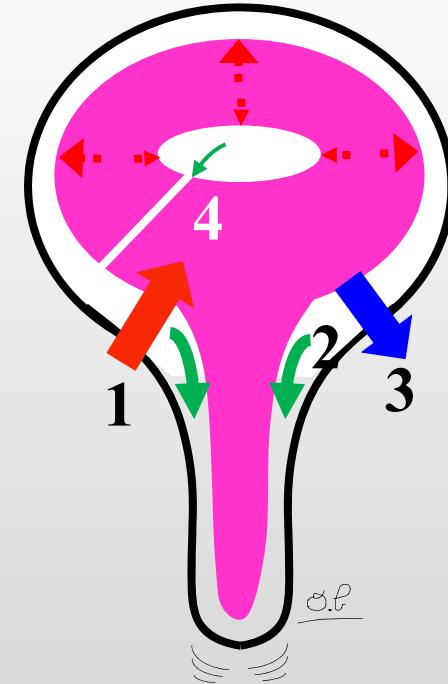
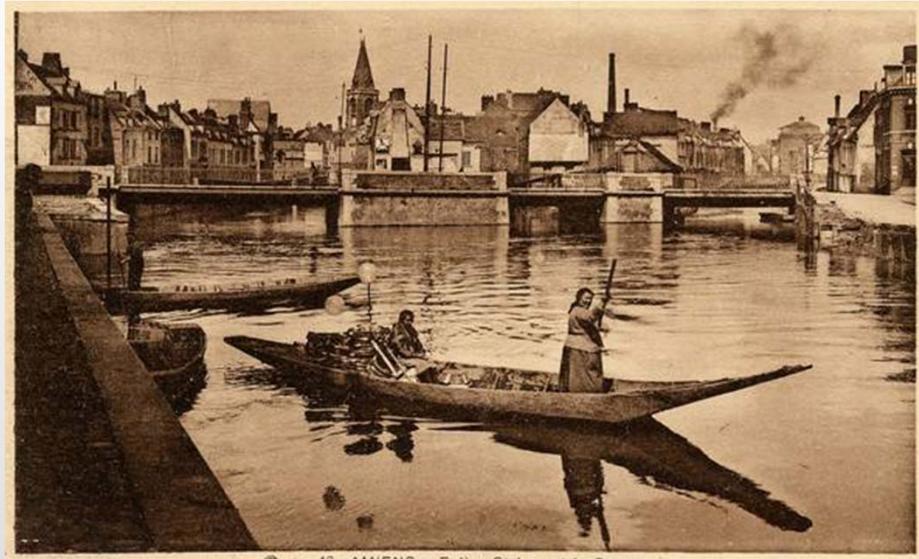
- LP : Not efficient, post-lumbar puncture headaches

- Treatment : not retained indication



## CSF flows: From origins to alterations.

O. Balédent,  
C. Gondry-Jouet, A. Fichten, S. Elsankari, R. Bouzerar  
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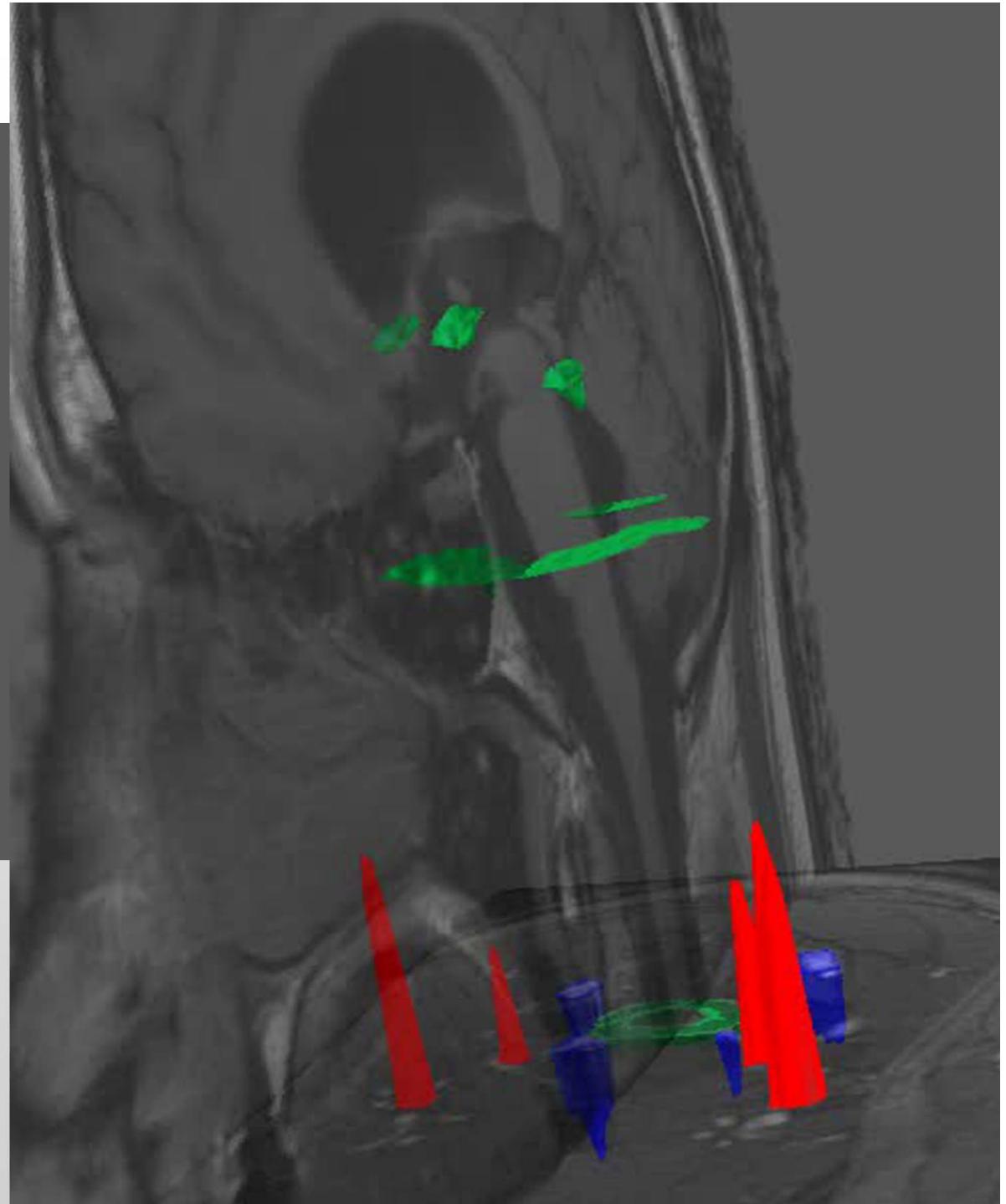
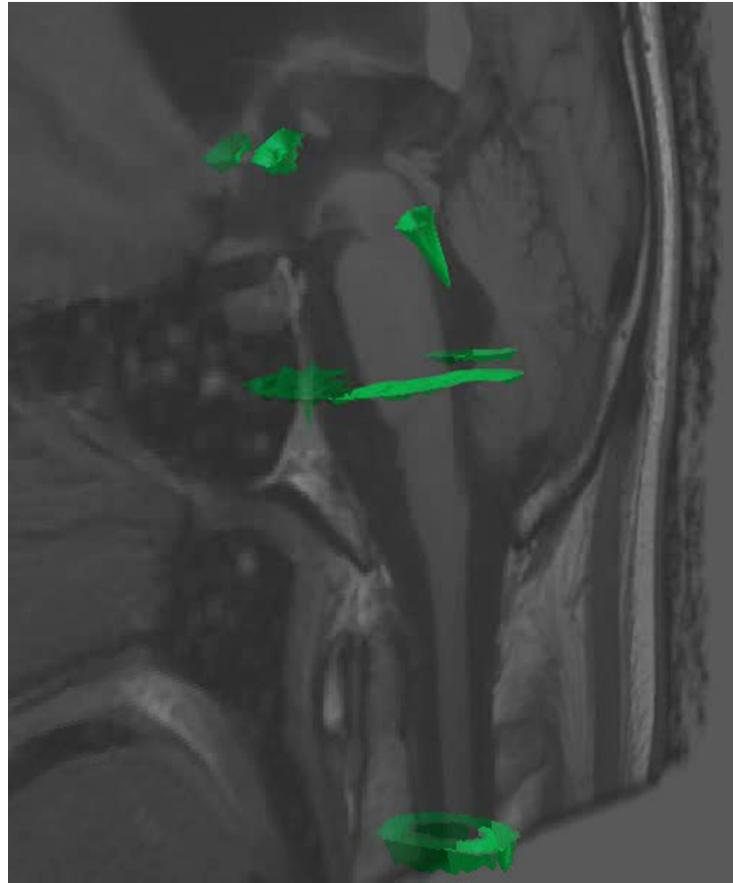


Des projets pour moderniser

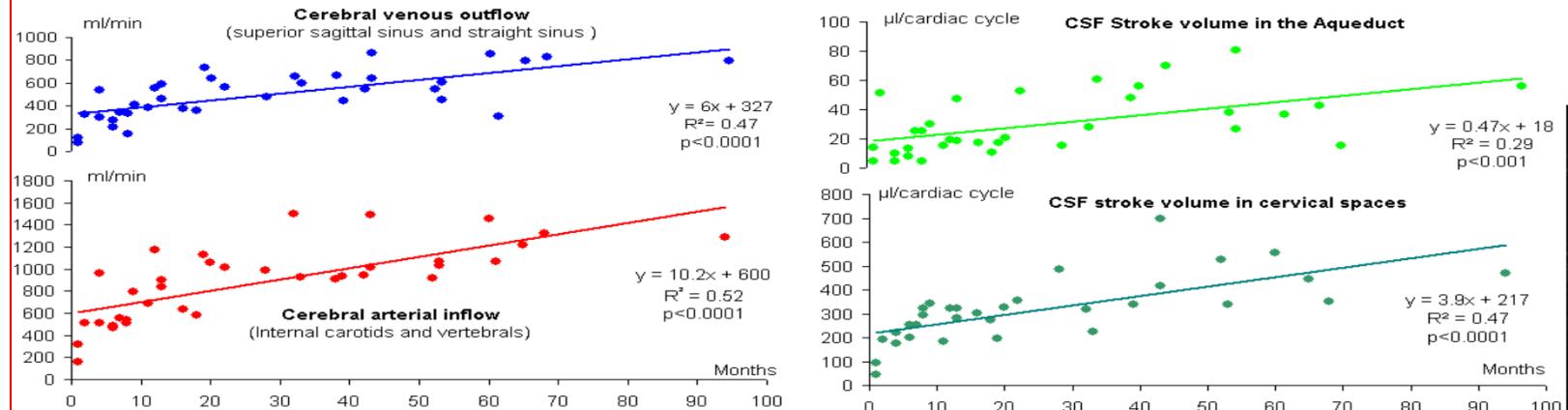
Study supported in part by European Community  
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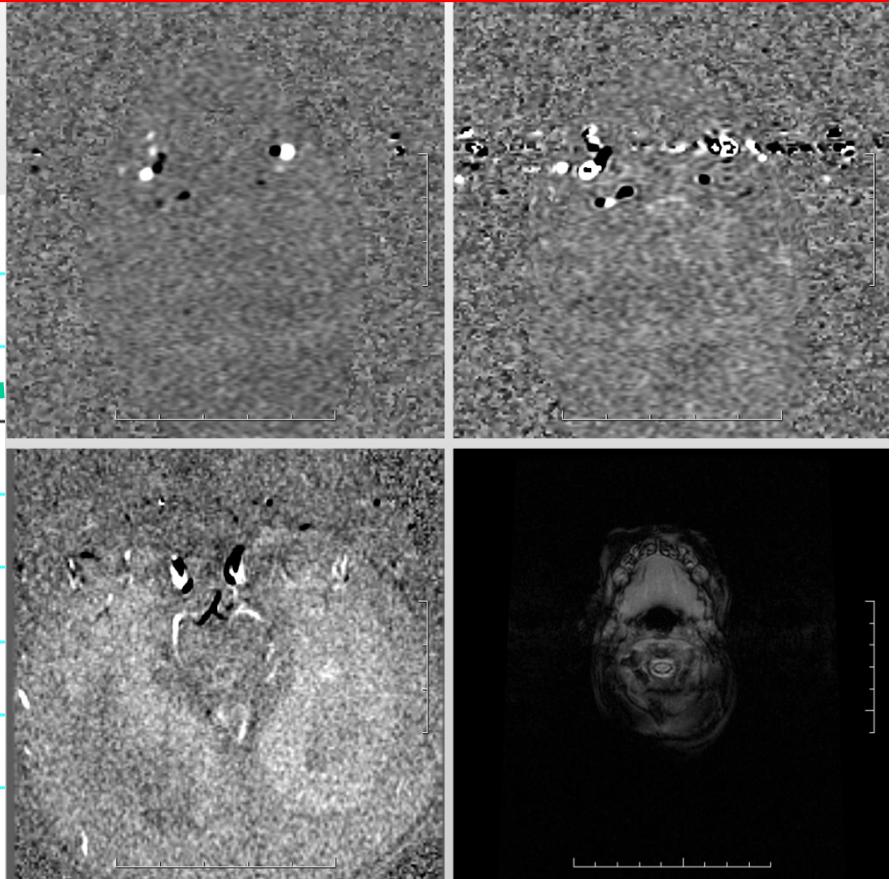
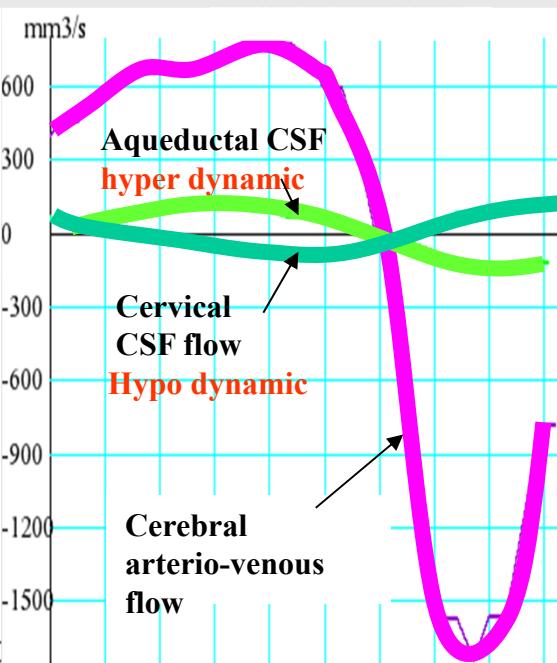
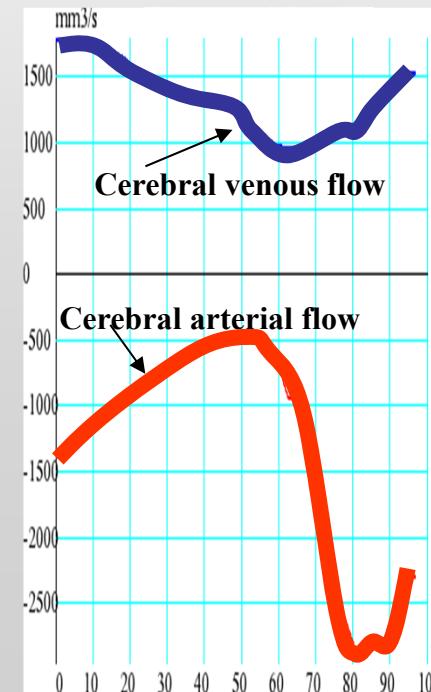


## CSF and cerebral blood flows in paediatric: Evaluation with Phase contrast MRI



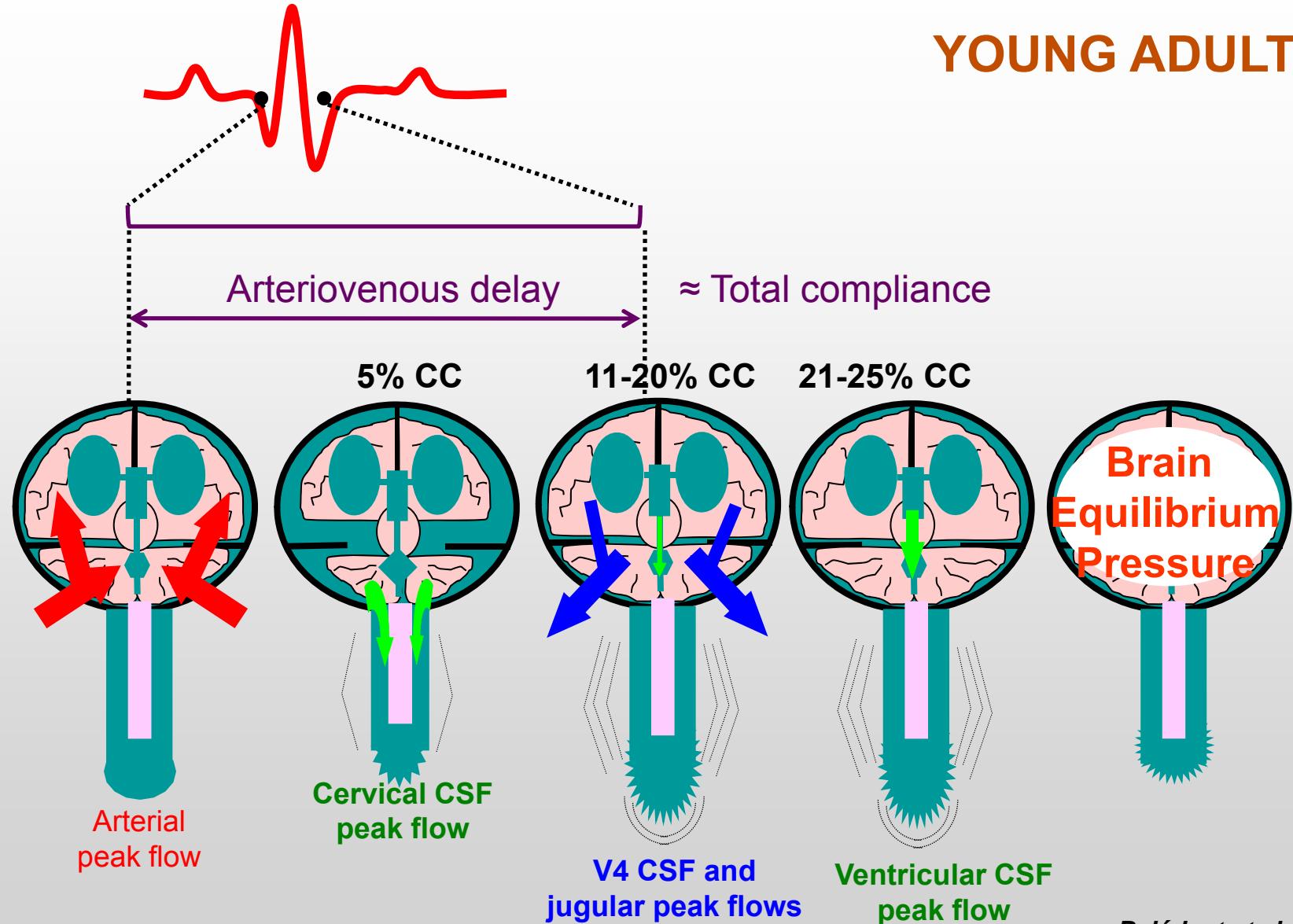
Intracranial hydrodynamics' evolution in a paediatric control population, represented as a function of age.

one week newborn,  
With ventricular hemorrhage and altered CSF oscillations !!!



## Chronological succession of cerebral blood and CSF flow peaks across the CC

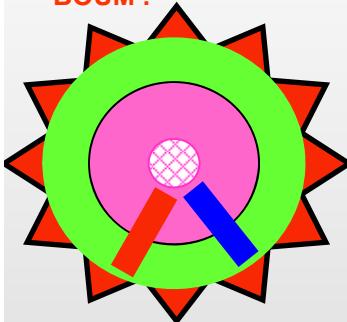
**YOUNG ADULTS**



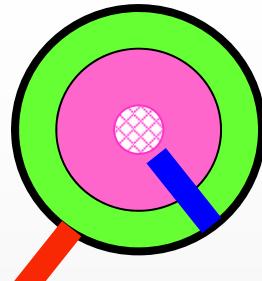
Balédent et al. 2001

## Compliance of intracranial compartment

If Compliance=0  
and Blood volume input  
Then ICP = $\infty$   
And Cranium explode  
**BOUM !**

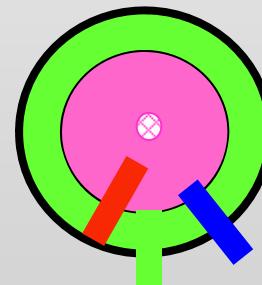
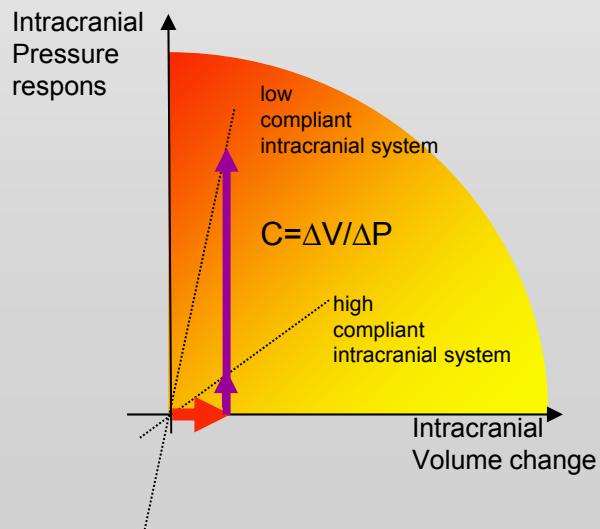
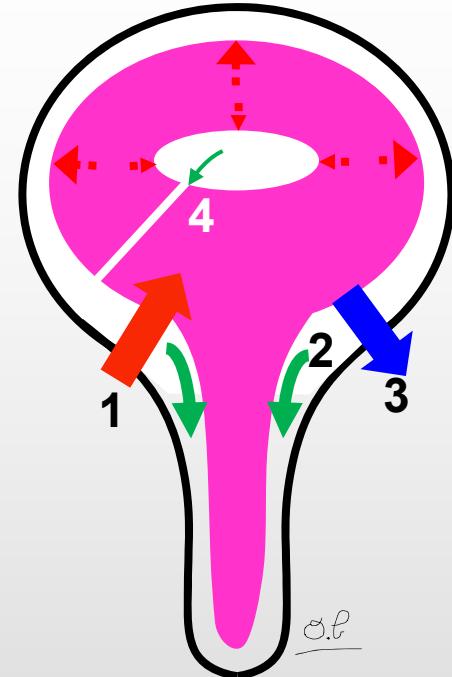
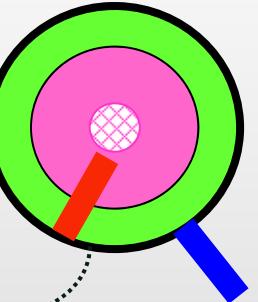
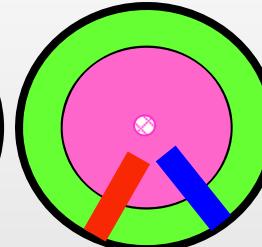


CSF flushing  
Outside the cranium



Intracranial volume  
is ε deformable

Blood flushing  
Outside the cranium



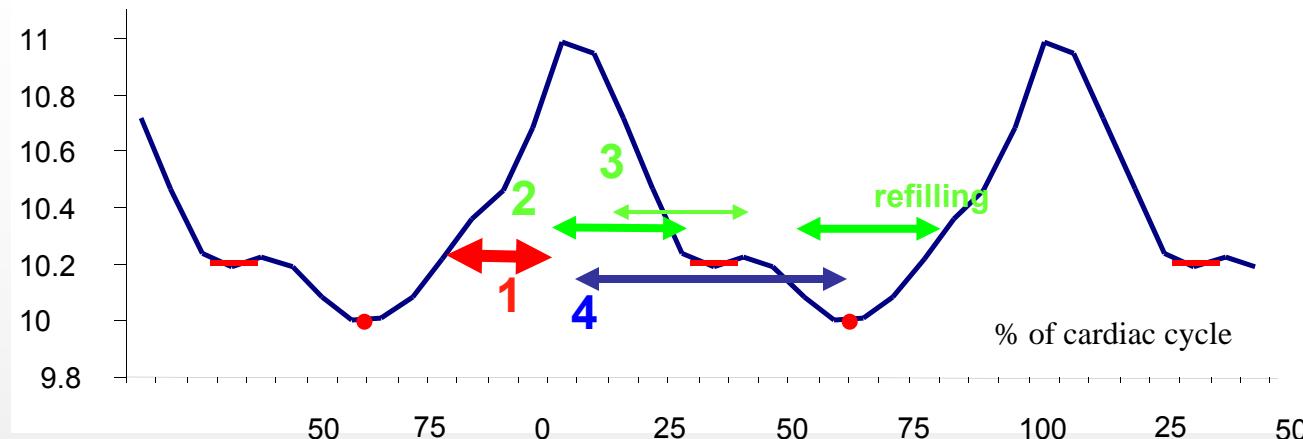
Intracranial Compliance is Function of :  
CSF and blood viscosities,  
resistance of CSF and blood flowing,  
Thoracique pressure,  
Dural sac compliance,  
Heart venous aspiration,

.... this compliance is complex !

And determine ICPPower !!

mm Hg  
pressure

### Modelisation of the Intracranial pressure during 3 cardiac cycle



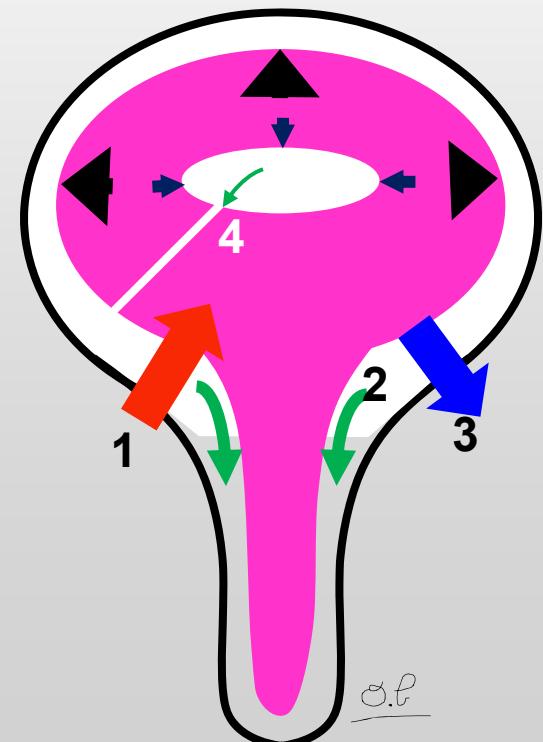
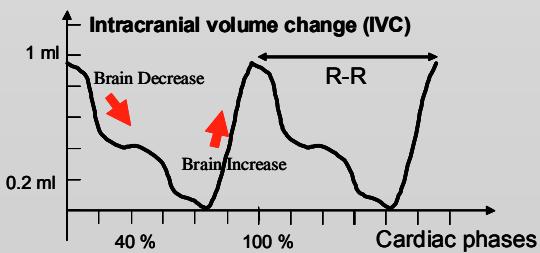
Marmarou's equation:

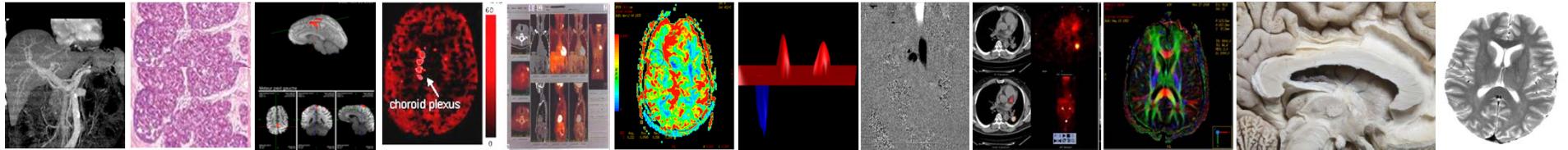
$$ICP(t) = P_0 \cdot e^{(k \cdot IVC(t))}$$

Brain  
elastance

Resting  
pressure

Intracranial  
volume  
change





Olivier.baledent@chu-amiens.fr

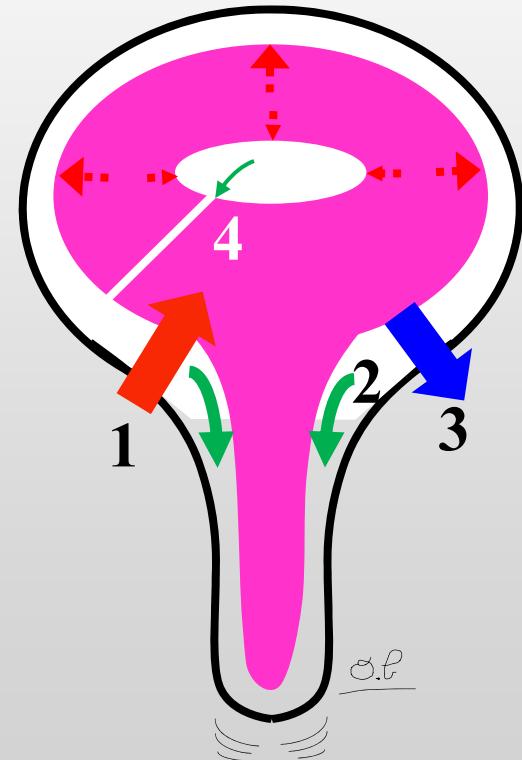
## Phase Contrast Magnetic Resonance Imaging (PCMRI)

to study CSF and blood flow interactions in the brains

### Research Population studies

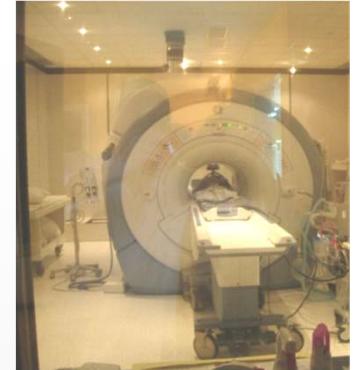
- Healthy volunteers (newborn, children, adult)
- Aging impact
- **Hydrocephalus patients**
- Cerebral venous thrombosis
- Subarachnoid hemorrhage patients

Brain  
hydrodynamics  
view



## Data Acquisition by PC-MRI

3 Tesla *General Electric Healthcare*  
(also *siemens, philips, toshiba,..*)



An example !

Retrospectively-gated Cine phase-contrast  
Cardiac synchronization with peripheral gating

FOV : 160x120 mm

Matrix : 256x128

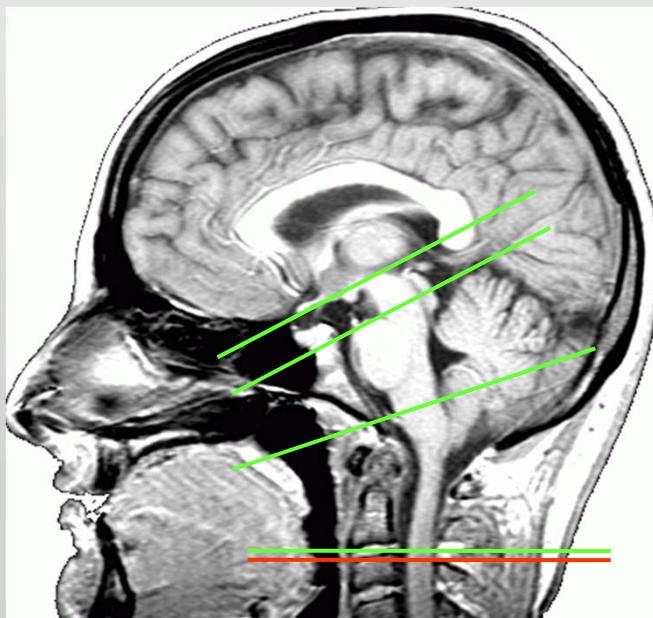
Section thickness : 5mm

*Human brain motion and cerebrospinal fluid circulation demonstrated with MR velocity imaging (old one but good one)*

*Feinberg DA, Mark AS.*

*Radiology 1987*

Acquisition of 32 cardiac phases



V3 aperture : **5 à 10 cm/sec**

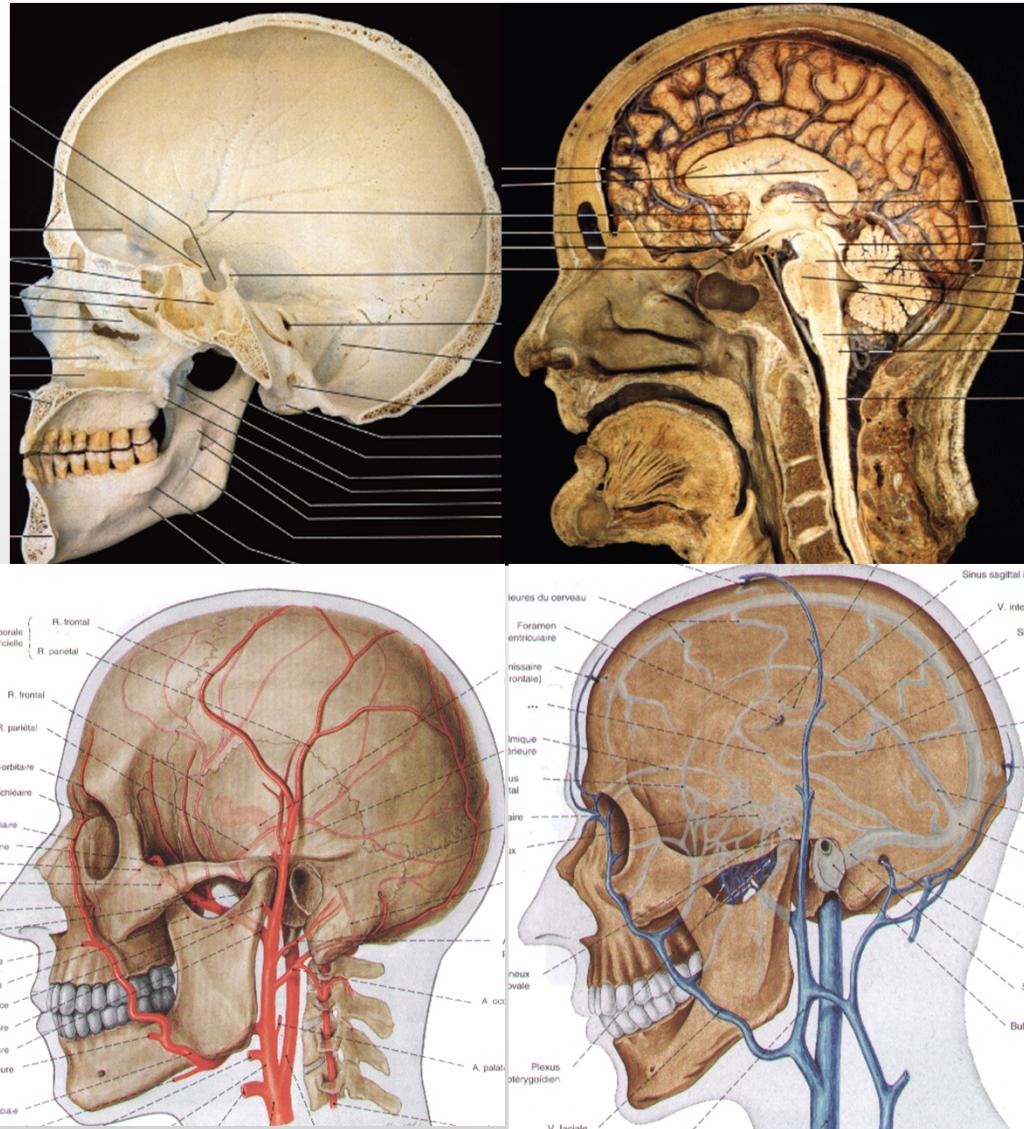
Aqueduc : **5 à 20 cm/sec**

Pontine cistern et Magendie : **5 cm/sec**

CSF C2C3 : **5 à 10 cm/sec**

Blood C2C3 : **80 cm/sec**

# Descriptive anatomy Conventional imaging



# In Non communicating Hydrocephalus patients

Can detect the absence of CSF flow in the aqueduct

Can detect and quantify CSF flow in the V3 aperture

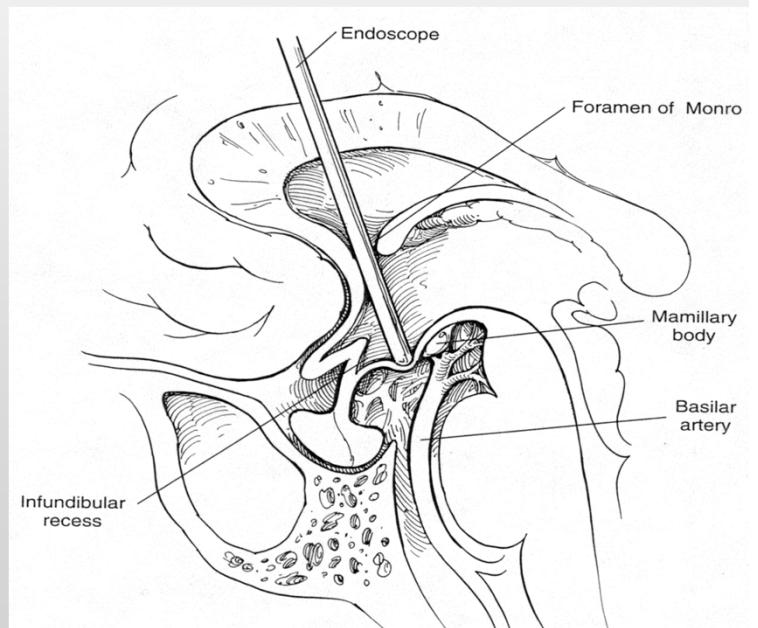
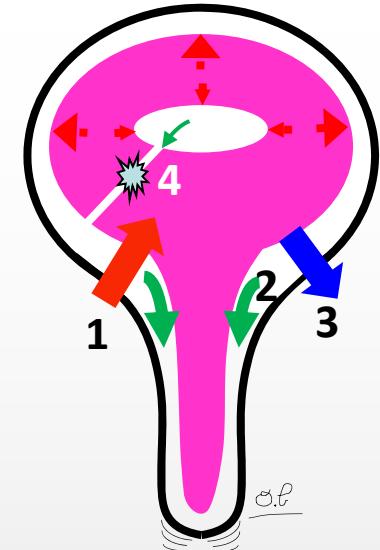
Can quantify cerebral vascular flows

impact of Cervical CSF flow ?

impact of cerebral vascular flow ?

**11 patients (aged  $63 \pm 10$ ) presenting non  
communicating Hydrocephalus  
who improved after ETV**

PC-MRI were performed **before and after** surgery,  
in order to evaluate the evolution of CSF and blood flows



# Hydrodynamic Results

- Before ETV : absence of CSF flow in the Sylvius' aqueduct was **confirmed**
- In one patient a **normal CSF flow** in the **aqueduct** was found after ETV !!!
- Functioning of the third ventricle aperture has been quantified with a stroke volume **>>> SV** aqueduct
- **Decrease** of cervical CSF oscillations was noticed. (*ICP decrease ?*)
- **Increase** (15% ; p<0,05) in mean cerebral blood flow was measured concomitantly to blood flow curves' shape modifications

Population	CBF (ml/min)	Cervical CSF (µl/CC)	ventricular CSF (µl/CC)
Healthy (n=12)	700 ±135	430 ±190	40 ±20
Pre ETV (n=11)	555 ±123	594 ±250	0
Post ETV (n=11)	670 ±105	496 ±147	210 ±100

# PCMRI in hydrocephalus ?

Normal-pressure hydrocephalus: evaluation with cerebrospinal fluid flow measurements at MR imaging, Bradley WG, Radiology 1996

Measurement of cerebrospinal fluid flow at the cerebral aqueduct by use of phase-contrast magnetic resonance imaging: technique validation and utility in diagnosing idiopathic normal pressure hydrocephalus , Luetmer PH, Neurosurgery 2002

Relationship between cerebrospinal fluid and blood dynamics in healthy volunteers and patients with communicating hydrocephalus , Balédent O, Invest Radiol. 2004

Phase-Contrast MR Imaging Support for the Diagnosis of Aqueductal Stenosis.

Stoquart-El Sankari S, Am J Neuroradiol 2009

