Advanced Imaging in Pediatric Hydrocephalus

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Limits of the conventional diagnostic approach

- The diagnosis of hydrocephalus in primarily morphological
  - large, bulging ventricles with effacement of pericerebral spaces
- Severity and potential for recovery are appreciated indirectly
  - clinical course: acute vs chronic
  - causal disease
  - age: parenchymal repair vs parenchymal vulnerability
- Data from neuropathology
  - vascular bed
  - axonal / neuronal injury
  - vulnerability of subventricular zone

Advanced Imaging in Hydrocephalus

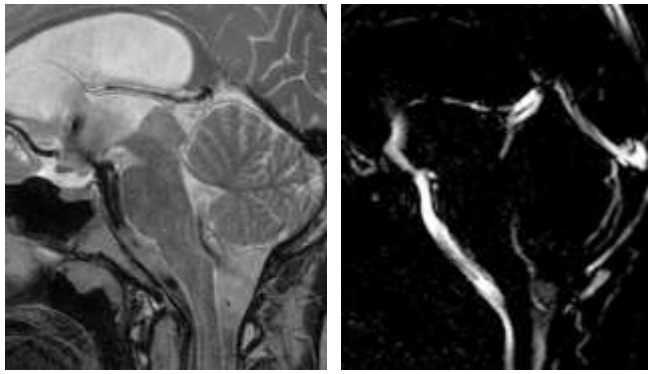
- CSF hydrodynamics quantification
- Brain elastography (compliance and brain texture)
- Brain volumetry
- Cerebral perfusion
- Cerebral metabolism (^{1}H MR spectroscopy)
- DTI – diffusivity
- DTI – connectivity

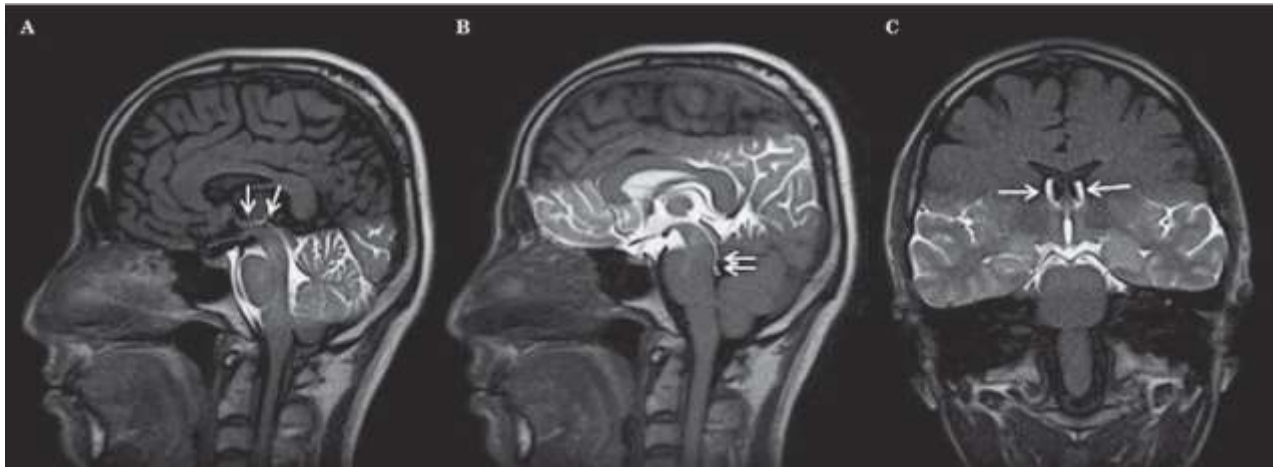
Advanced imaging: CSF flow and compliance

- CSF hydrodynamics
  - Cardiac-gated cine phase contrast flow imaging [Bradley et al 1986]
  - Spatial modulation of magnetization SPAMM [Axel and Dougherty 1989]
  - Reversed fast imaging with steady-state precession Cine-PSIF [Hoffmann at al 200]
  - Time-spatial labeling inversion pulse Time-SLIP [Yamada et al 2008]
  - Tri-dimensional sampling perfection with application optimized contrast using different flip-angle evolution 3D-SPACE [Mugler 2014]
- Compliance
  - MR elastography [Muthupillai et al 1995]

CSF flow evaluation

- Most are based on the motion-related loss of signal (protons have moved between excitation and relaxation), not better than conventional T2FSE imaging
- Quantification of flow possible with cine-phase contrast imaging; valid for groups, not for individuals
- Same applies to quantification of “flow” into shunts
- Initially supposed to be quantitative, Time-SLIP is based on spin-labeling, but diffusion more significant than flow. Vendor-specific





Abe et al 2014

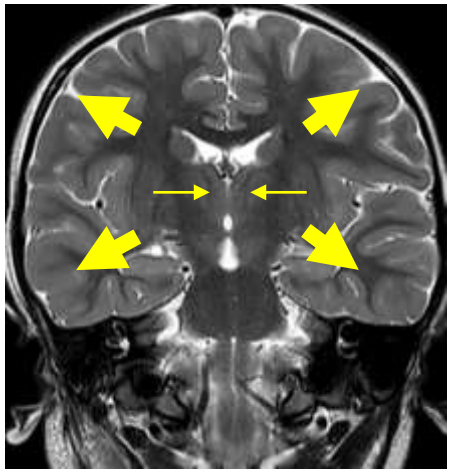
CSF flow evaluation

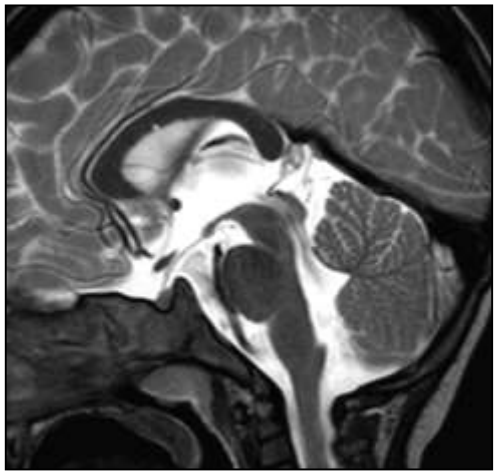
- Ventricular CSF flow measured at aqueduct (velocity)
  - CSF production variable: rest vs arousal, vasomotor factors, ICP
  - based on wrong paradigm (single bulk flow of Dandy and Blackfan)
  - depends on degree of supra-tentorial ventricular absorption
  - studied in adult NPH mostly (flow reversal suspected)
- CSF flow in shunt
  - even if present, very low velocity in shunted patients
  - depends on same factors as aqueductal flow
  - low vs high ICP headaches?

Meaning of CSF aqueductal hyper-pulsatility

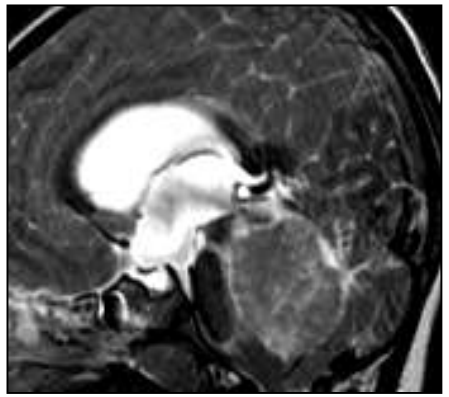
- The extracerebral, intracranial CSF space is huge, maybe 10 times the ventricular space; much of it is in the posterior fossa, but the supratentorial part of it is significant
- In normal subjects, inward pulsation volume is1.7 ml/min; outward, 14.3 ml [Enzmann and Pelc 1996]
- By effacing the pericerebral spaces, hydrocephalus transfers CSF from the periphery to the ventricles; this corresponds to re-orienting the force that displaces a volume of 16 ml supratentorial CSF
- This volume of CSF pulsates against the brain (if ventricles obstructed) or against the theca and brain (if no, or extraventricular, obstruction)

Pericerebral space effacement redirects CSF flow medially

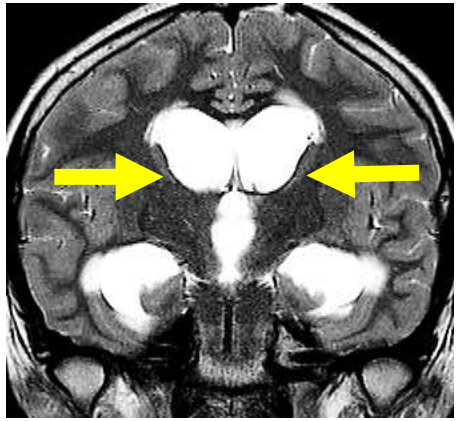




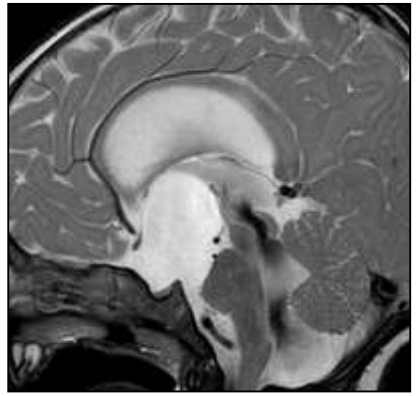
normal



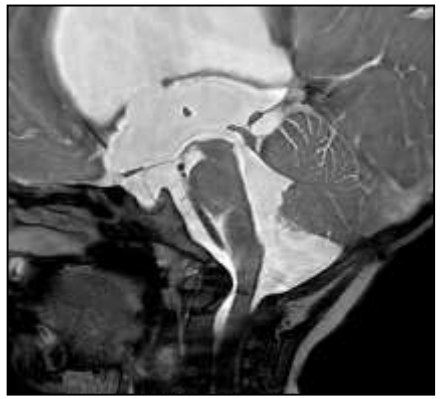
ventricular obstructive

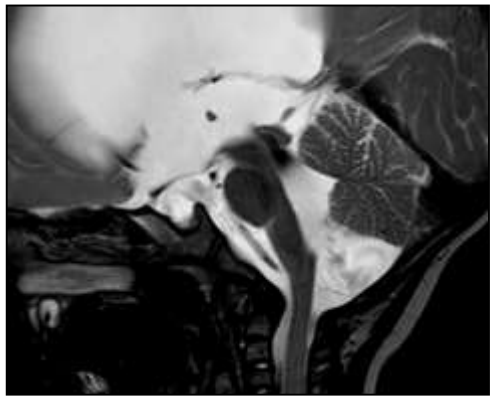


effaced pericerebral spaces



cisternal obstructive

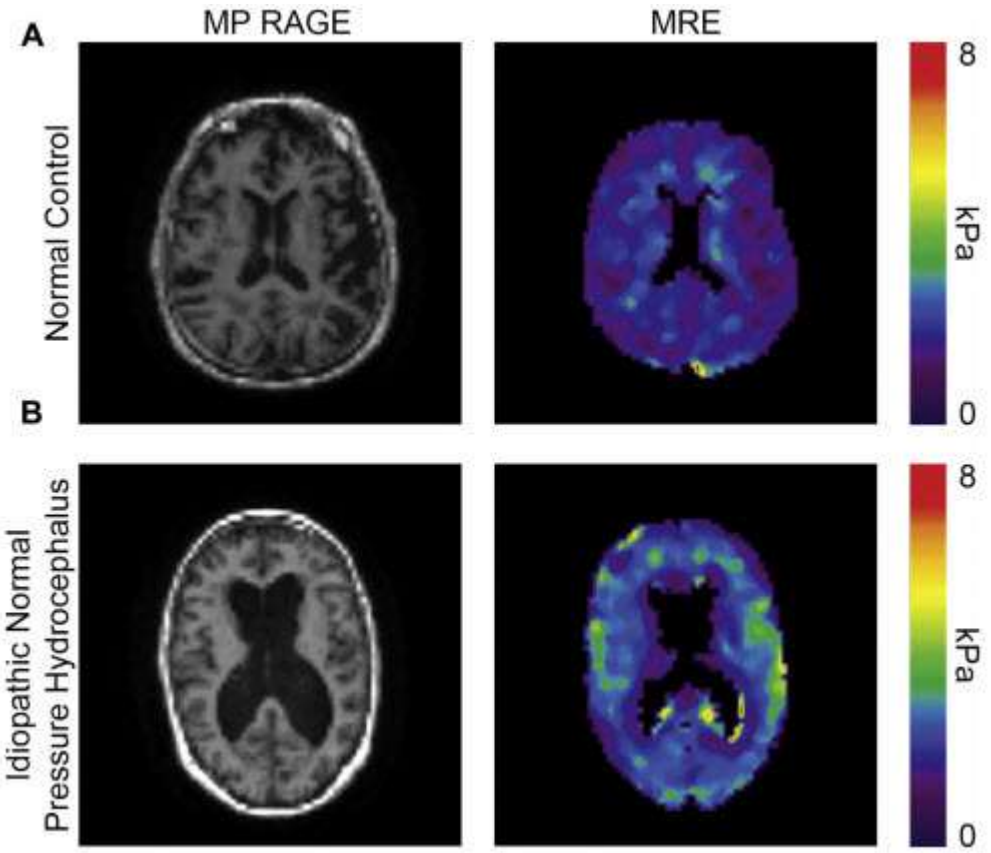




communicating

Elastography

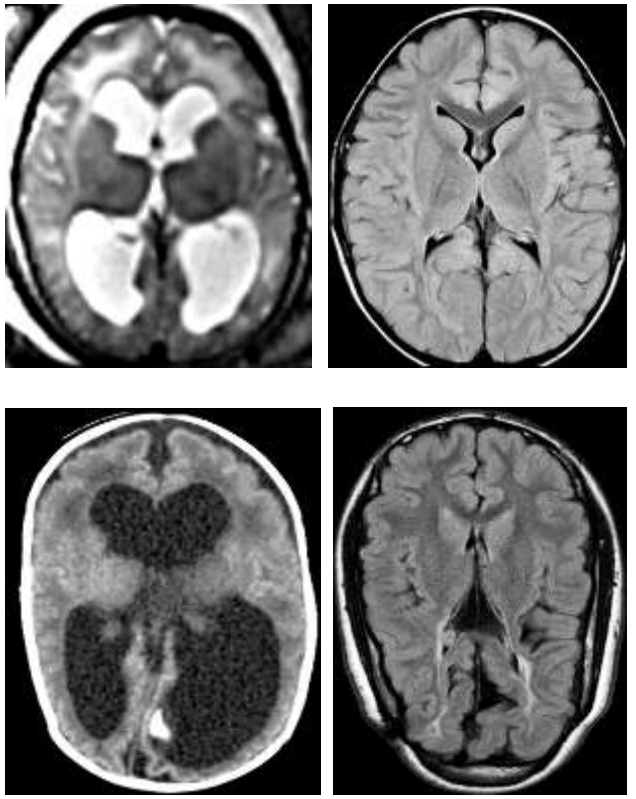
- MR elastography (MRE): measures tissue stiffness by imaging the propagation of mechanical vibrations with motion-sensitive MR gradients
- May demonstrate decreased brain visco-elasticity
  - turgor, gliosis, fibrosis
- Therefore correlates to compliance



Perry et al 2017

Brain volumetry

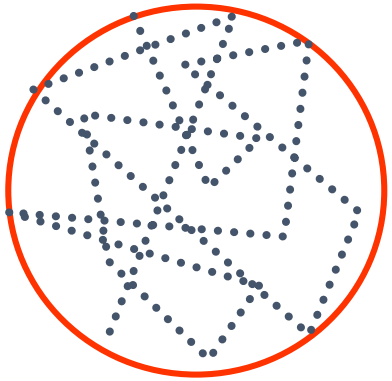
- Hydrocephalus = increased CSF and (with time) decreased brain volumes
- Making ventricular volume normal does not necessarily make cerebral volume normal
- Neurocognitive outcome correlates the restoration of brain volume [Mandell 2015b]
- Particle filter segmentation of brain/CSF seems to be a clinically practical volumetric tool for the follow-up of hydrocephalic children [Mandell 2015a]



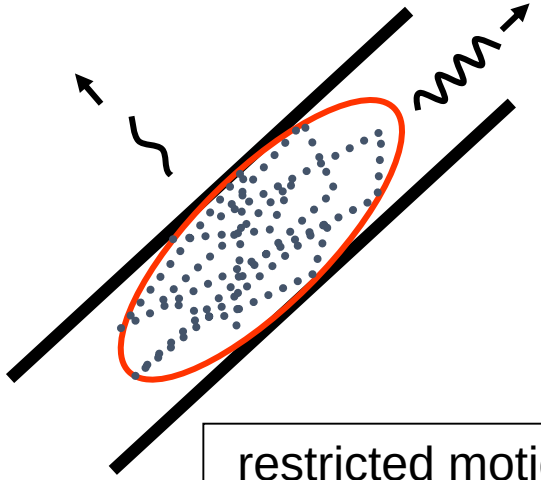
Cerebral blood flow and metabolism in hydrocephalus

- ASL (arterial spin-labeling) perfusion imaging: protons are excited in the proximal artery segments, resonant signal registered and quantified in the parenchyma (intrinsic contrast medium) [Yeom et al 2014]
  - in tumoral hydrocephalus, CBF decreased by nearly 50% as compared to normal subjects
  - follow-up 1d-to-7m after surgery (average 27d): significant restoration after shunting
- MR spectroscopy: scarce and uncertain results
  - Lactate, glutamine and alanine increased in hydrocephalic infants [McNatt et al 2007]
  - Inositol decreased in hydrocephalic fetus [Kok et al 2003]

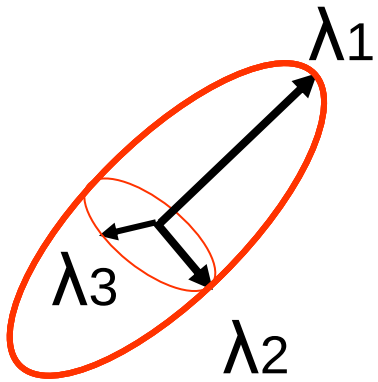
Diffusion tensor imaging: diffusivity, fractional anisotropy, tractography



unrestricted motion



restricted motion

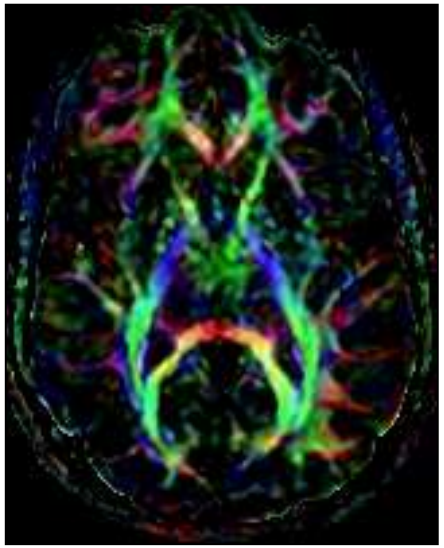


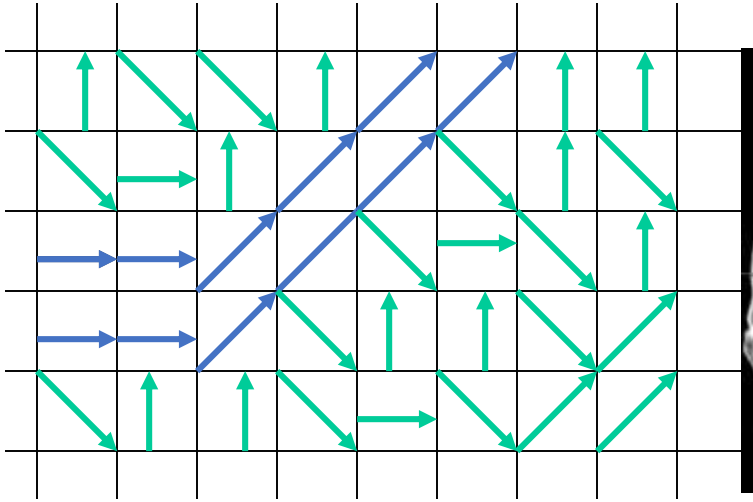
anisotropy

Quantitative DTI

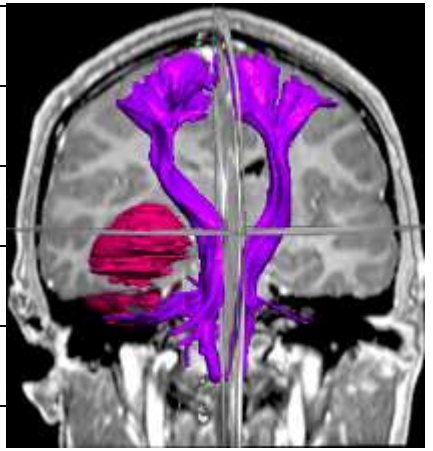
- Eigen values λ1, λ2, λ3
- Trace or total D (λ1+λ2+λ3)
- Mean (D/3) diffusivity/ADC
- *Fractional anisotropy index FA*

FA map





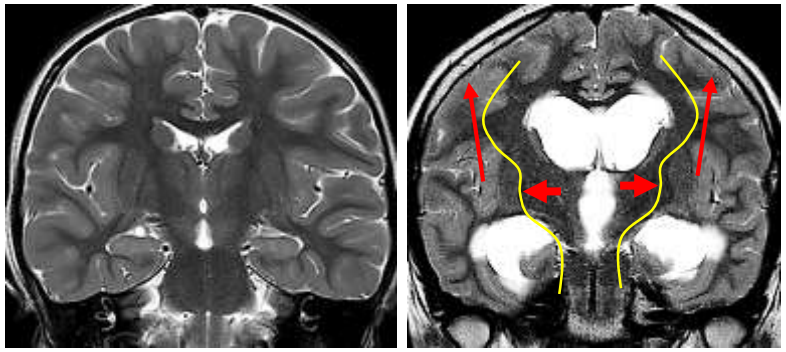
voxel-by-voxel FA mapping



tractography

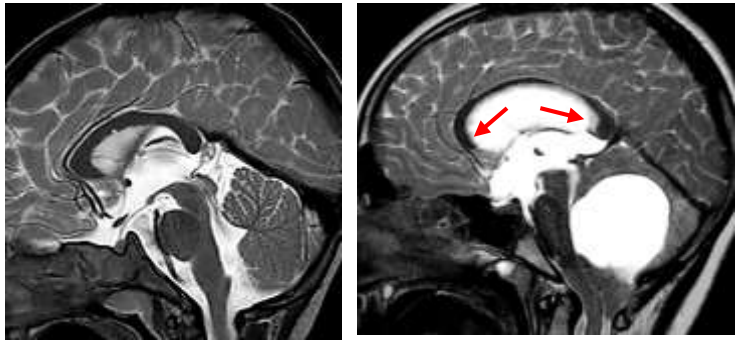
DTI: diffusivity studies

- Pathology: increased extra-cellular spaces with loss of myelin and axons, hyperhydration, microglial infiltration
- Internal capsule/corona radiata vs callosum [Assaf et al 2006, Yuan et al 2009, 2013; Mangano et al 2016]
  - increased FA in IC/CR (increased Dax, decreased Drad)
  - decreased FA in CC (decreased Dax, increased Drad)
  - congenital hydrocephalus: CC changes persist > 12m, IC repaired < 3m
- Selective vulnerability vs mechanical effect



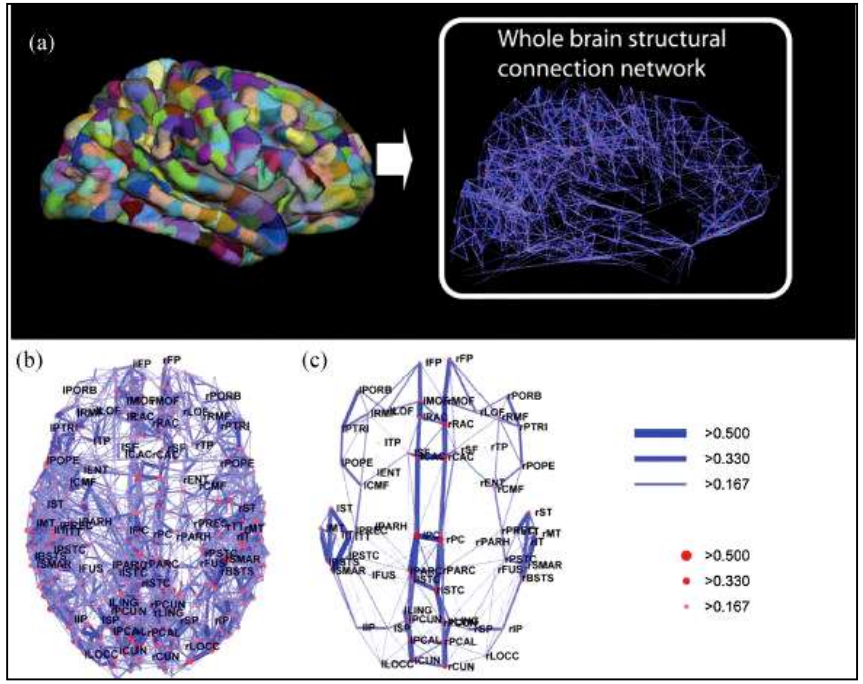
IC/CR mostly compressed
and stretched longitudinally

CC mostly stretched
perpendicular to fibers



Connectivity studies

- Structural connectivity (graph theory): preliminary reports in hydrocephalic children show abnormalities [Yuan et al 2015]
- Functional connectivity: very few studies, NPH and Chiari 2 only [Behrens et al. 2003; Hagmann et al. 2008;Lazar, 2010]



Advanced Imaging in pediatric hydrocephalus: conclusions

- Assessment of effects of hydrocephalus in individual patients
  - mostly research
  - intended to eventually provide biomarkers of prognosis
- Most studies address effects of hydrocephalus itself, but disregard the specific impact of specific etiologies
- Generalization from particular classes of hydrocephalus, all complex
  - high ICP tumoral hydrocephalus
  - post-hemorrhagic hydrocephalus of the premature
  - congenital hydrocephalus
  - Chiari 2 hydrocephalus
  - adult-type normal pressure hydrocephalus