The Role of Brain Imaging in the NICU: Lessons Learned & Future Directions in MRI Analysis

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FN3 Orlando, FL
Division of Newborn Medicine, MGH
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We have no financial relationships with a commercial entity producing healthcare-related products and/or services.

*photo consents have been obtained for all patient photos per MGH Partner’s guidelines
MGH: Snapshot

- Patient care from conception through adulthood (1042 beds)
- Deliveries at MGH: 4000/year
- Deliveries in MGH Network: 12000/year
- MGH NICU admissions: 800/year
- Neonatal Transport Program – Boston MedFlight
- 24 hour in-house coverage by 12 Neonatologists
- Fetal Care Program
- NICU operating suites / ECMO
- Interdisciplinary, family-centered care
- Developmental Follow-up Clinic (network-wide)

- Magnet designation from the American Nurses Credentialing Center (ANCC)
  - “Magnet achievement was a true team effort, made possible by the dedication, persistence and commitment of a wonderful team of nurses and others across the organization”
- Largest hospital-based research enterprise in US (budget ~$930M)
- Ranks #1 in NIH funding (independent hospitals)
- Infant Brain Center (MGH Neuroscience)
- Perinatal Clinical Translational Research Committee

Come visit!
Learning Objectives

• During patient case discussions, appreciate both the strengths and limitations of MRI
• Reflect upon the role of MRI in difficult diagnostic and therapeutic decisions
• Describe the technology and potential applications of machine learning algorithms in neonatal neuroimaging

Focus: HIE

Ex. HIE & NAS
Who Discovered MRI?


1950-1960’s: Erwin Hahn – spin echoes

1968: First publication of NMR signals from a living animal

1970’s: Major advancements: relaxation, diffusion, exchange of chemical water cells; different tissues. Raymond Damadian published in Science re: the differences detected between normal and abnormal (tumors) using NMR (Science, 1971)

1980’s: MR angiography

1990’s: fMRI, arterial spin labeling, FLAIR, DTI, SWI (WashU)


Neonatal MRI

• Most sensitive, noninvasive imaging modality for the documentation of neonatal brain injury

• Challenges: injuries may be over or under called
  – Rapidity of myelination and microstructure maturation of white matter, gyrification, volume, cortical thickness, differences in regional development etc
  – Many technical challenges too

• Uncommon disorders may be misdiagnosed as HIE
Normal MRI: 3 day-old FT Infant

**Axial T1**
- Normal hypointense appearance of the unmyelinated white matter
- Relative hyperintense signal in the cortical gray matter & deep gray nuclei
- High signal intensity in the PLIC & VL thalamus – early myelination

**Axial T2**
- Normal hyperintense signal of the unmyelinated white matter
- Relative hypointense signal in the cortical gray matter & deep gray nuclei
- Low signal intensity in the PLIC & VL thalamus – early myelination
Normal MRI: 3 day-old FT Infant

ADC: low SI in PLIC and VL thalamus: NORMAL. Water can’t move as freely between myelin sheaths (physiologic)
Case 1: Clinical Presentation

- 40 6/7 week male infant (3680 grams; 44th%) born via vaginal delivery to a 22 yo G1PO mother
- Maternal hx notable for GBS+, obesity, anxiety and depression (not on meds)
- Cat II fetal tracing; chorio, meconium
- Infant was non-vigorous; PPV, ETT (passive cooling commenced)
- Apgars 1, 3, 5
- UCB: (a) pH 7.0, BD 14.5
Case 1: Clinical Presentation

- Initial neuro exam: no spontaneous movement, hypotonic, absent grasp, no suck
- Full montage EEG (Diffuse voltage attenuation)
- Early MRI obtained prior to rewarming
- When do you typically perform MRI?
  - <7 days
  - >7 days
  - both
  - other
Case 1: Imaging

Imaging compliments of P. Ellen Grant, MD
Case 1: Clinical Course

- Diagnosis: Severe HIE
- Family wished to re-direct care to comfort measures
- Infant passed peacefully in mother’s arms
- Placenta 40th% - multiple infarctions
- Post mortem
  - Neuropath: extensive hypereosinophilic change in neurons throughout the brain and marked astrogliosis throughout the white matter consistent with perinatal HII
  - No infection or hemorrhage
Case 1: Take home points

- Limitations of fetal monitoring
- Maintain a broad differential for encephalopathy
- Contributions of placental and post-mortem pathology
Case 3: Clinical Presentation

- 39 2/7 week male (BW 3700 grams) born via stat cesarean section due to decreased fetal movement
- Born to a 39 yo G2P1 mother with negative prenatal screens. History notable for T1DM (insulin dependent)
- Apgars 1, 6, 7
- Required several minutes of PPV
- Umbilical arterial gas 6.8, BD 17
- Passive cooling started
- Infant transferred to level III NICU
Case 2: Clinical Course

- Required CMV and iNo for PPHN
- Completed 72 hours of TH
- EEG without seizures and normal background s/p cooling
- Prolonged hospitalization
- Normal MRI
Case 2: Take home points

- A negative MRI is encouraging
  - ~ 50% will have good outcomes
  - ~ 30% will have mild outcomes
  - ~ 20% will have moderate-severe outcomes
- EEG adds additional useful information
- Don’t forget about channelopathies (e.g. KCNQ2) when HIE, metabolic, infection ruled out

Shankararan et al J of Pediatrics.2015
Case 3: Clinical presentation

- 40 4/7 week male infant born via stat c-section d/t NRFHT  
  Pre-cooling era
- 21 yo mother – no significant history; prenatal labs unremarkable
- 30 seconds of PPV; APGAR scores 5, 9
- BW 4065 grams (95th%), L 54.5 cm (95th%), HC 37 cm (95th%)
- DOL1 he was noted to be lethargic and hypotonic
- Septic work-up initiated and transferred to the NICU
- DOL3 developed apnea and seizures
Case 3: Clinical course

- Intubated
- Phenobarbital, Dilantin
- LTM
- LP, HSV PCR, gas, BMP, lactate, pyruvate, urine organic acids, serum amino acids
- Followed by pediatric neurology and metabolism
Case 3: Imaging

T1  T2  DWI  ADC

Imaging compliments of P. Ellen Grant, MD
Case 3: Clinical course

- **Metabolism**
  - Urinary sulfites present on dipstick
  - Elevation of urinary thiosulfate and s-sulfocysteine
  - Normal serum uric acid

- Diagnosis: Sulfite Oxidase Deficiency (SOD)

- X-Met, X-Cys Analog formula

- Discharged with g-tube and AEDs

- 4 month follow-up notable for: lack of visual tracking, hypertonia, myoclonic jerks, exaggerated moro reflex, bilateral up-going toes
Sulfite oxidase deficiency

Evolution

4 Days  10 Days  3 mo  3 yrs

Imaging compliments of P. Ellen Grant, MD
Case 3: Take home points

- Neurometabolic disorders – may have features similar to HIE
- Never presume an infant with encephalopathy has HIE
  - Implications for: infant care, family, OBGYN
- Delayed onset of encephalopathy consider other etiologies (metabolic, infection, stroke)
- Timing matters

Isolated SOD:
- Lips
- Philtrum
- Microcephaly
- Seizures
- Cognitive delays
Current clinical practices for analyzing the ADC maps is a visual assessment


Scoring systems:
- Barkovich (1998)
- Rutherford (2010)
- De Vries (2018)
MRI Interpretation

- Limitations, challenges, & pitfalls
- 20-50% uncertainty/errors in radiologists’ interpretation of ADC maps in neonates with HIE\(^1\)-\(^2\)
- What are the normal regional ranges of ADC variation?
- How low is too low? What about high values?
- Need for: quantifiable, precise, reproducible measurements

Improving neonatal MRI interpretation & the role of imaging informatics
Utilization of legacy health care data

Research Patient Data Registry (RPDR)
- Shawn N Murphy
- Christopher Herrick
- Mariah Mitchell
- Stacey Duey
- Laurie Bogosian
- Eugene Braunwald
- Anne Klibanski
- Henry Chueh

Medical Imaging Informatics Bench to Bedside Mi2b2
- Randy Gollub
- Christopher Herrick
- Bill Wang
- David Wang
- Kathy Andriole
- Darren Sack
- P Ellen Grant
- Nathaniel Reynolds
- Kallirroi Retzepi
- Rudolph Pienaar
- Victor Castro
- Steve Pieper
- Lilla Zollei
- Yangming Ou

Mi2b2 engine: https://www.nmr.mgh.harvard.edu/lab/mi2b2
[Murphy et al, 2015]
Efficiently reaching a larger N with lower cost

Research Patient Data Registry (RPDR) at Partners Healthcare to find patient cohorts for clinical research

1) Queries for aggregate patient numbers
   - Warehouse of in & outpatient clinical data
   - 6.5 million Partners Healthcare patients
   - 2.2 billion diagnoses, medications, procedures, laboratories, & physical findings coupled to demographic & visit data
   - Authorized use by faculty status
   - Clinicians can construct complex queries
   - Queries cannot identify individuals, internally can produce identifiers for (2)

2) Returns detailed patient data
   - Start with list of specific patients, usually from (1)
   - Authorized use by IRB Protocol
   - Returns contact and PCP information, demographics, providers, visits, diagnoses, medications, procedures, laboratories, microbiology, reports (discharge, LMR, operative, radiology, pathology, cardiology, pulmonary, endoscopy), and images into a Microsoft Access database and text files.
Finding Patients with RPDR

Query items

Person who is using tool

Query construction

Results - broken down by number distinct of patients
Find “normative cases” ages 0-6 yrs
RPDR & mi2b2 Pipeline: Data Extraction Example

Accessible to & may benefit:

- Data scientists
- Data base engineers
- Medical image analysis algorithm developers
- Machine learning experts (mine in a meaningful way)
- Clinician scientists
- Image acquisition experts
- Radiology Decision Support developers
- Clinical care teams

Mi2b2 engine: https://www.nmr.mgh.harvard.edu/lab/mi2b2
[Murphy et al, 2015]
The Start of an Atlas: Finding Normative Data

- How do we know what is “normal?”
- How do we obtain images?
- Research Patient Data Registry (RPDR) used to query EHR → Medical Imaging Informatics Bench to Bedside (mi2b2) software → access identified pts from PACS at MGH

N = 100,000
- Brain MRI (MGH)

N = 2,871
- Scanned 2006-2013 with ADC maps in Siemens 3T scanner
- 0-6 years old at the time of scan
- Radiological reports suggesting free of abnormality

N = 1,648
- ADC maps found and not corrupted

N = 705
- ADC maps re-examined & confirmed to be normal by expert clinicians

N = 201
- Duplicates removed
- Still normal 3 years after the initial visit
Basic pipeline for analyzing structural images

Infant T1w/T2w MR images

- Image Preprocessing
- Tissue Segmentation
- Image Registration
- ROI Labeling

- Topology Correction
  - Surface Reconstruction
  - Surface Registration
  - Surface Parcellation

Volumetric Atlas Construction
Volume-based Measurement

Surface-based Measurement
Surface Atlas Construction

Volume-based Analysis
Surface-based Analysis

• 1. Field of View Normalization
• 2. Skull Stripping
• 3. Automatic Structural Segmentation
• 4. Multi-modal/channel Fusion
• 5. Tissue Density and Morphometry
• 6. Atlas Construction
• 7. Lesion Detection
• 8. Longitudinal Change Quantification
• 9. Machine learning to predict clinical variables

Based on DRAMMS Registration (2, 3, 4, 5D) [Ou’11, ‘12, ‘14a,b, ‘15]
Based on BEFI Machine Learning [Ou’09, ’17 (u.r.)]
Data Analysis – Atlas Construction

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<td>5</td>
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<td>17</td>
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* Ou et al, MedIA, 2011 (Most Cited Articles)
* Ou et al, IEEE TMI (Most Popular Articles)
* Ou et al, OHBM, 2014, 2015, 2017
* Ou et al, NeuroImage, 2015
* Ou et al, HBM, 2017

[Atlases released] https://www.nitrc.org/projects/mgh_adcatlases
Validation – are the atlases right?

Whole-brain volume and ADC values, and changes

[Atlases released] https://www.nitrc.org/projects/mgh_adcatlases
Abnormality detected as outliers to the characterized normal ranges of ADC values

Quantitative comparison of patient’s ADC values to the population mean and stdev, at the voxel level

How to detect HIE lesions automatically and accurately?

- Done: created normative ADC atlases for abnormality detection

Problem in Detecting HIE Injury

- Gold Standard: Apparent Diffusion Coefficient (ADC) maps
- Abnormally low ADC values => restricted diffusion => lack of oxygen/blood
- Q: How low is too low? How low is within normal variation?

Atlas-based Abnormality Detection

- A naïve but intuitive approach

Accuracy of Z-map Approach

- Compare with expert annotations
- Machine-vs-Man =? Man-vs-Man

Data Analysis – Atlas Construction

- N=100,000
- Brain MRI in MNI
- N=2,871
- Scanned 2006-2013 with ADC maps in Siemens 3T scanner
- 24-year-old at the time of scan
- Radiological reports suggesting free of abnormality
- N=1,648
- ADC Maps found and not corrupted
- N=705
- ADC maps re-examined & confirmed to be normal by a board radiologist (Dr. Cobb) and a neurologist (Dr. Dales)

[Publications]
- Ou et al, MedIA, 2011 (Most Cited Articles)
- Ou et al, IEEE TMI, 2014 (Most Popular Articles)
- Ou et al, OHBM, 2014, 2015, 2017
- Ou et al, NeuroImage, 2015
- Ou et al, HBM, 2017
- Ou et al, Neuroinformatics, 2018

[Software for Atlas Construction]
- Ou et al, https://www.nitrc.org/projects/popdramms

[Atlases released]
- Ou et al, https://www.nitrc.org/projects/mgh_adcatlases
Machine Learning:

- Computer aided patterns/maps
- Learned models & the application to medical images
- Algorithm development:
  - Lesion detection
  - Outcome prediction

Proposed Framework Example: Unpublished Work

A-D. Characterizing A Patient by Features

A. Multi-Parametric MRI
- ADC
- FA
- T2w
- T1w
- MRS

B. Z_{ADC} Map

C. Lesion Detection (via DL)

D. Feature Extraction
- I. Morphometry Features (T1w/T2w)
- II. Diffusion Features (ADC/FA)
- III. Z_{ADC} Features
- IV. MR Spectroscopy Features
- V. Lesion Geometry
- VI. Intra-Lesion Signal Heterogeneity

E. Outcome Prediction (via SVM)

Training Phase
- Normal
- Adverse

Testing Phase
- ?
Data-Driven Outcome Prediction

- Lesion-Symptom

- Radiomics without lesion segmentation

(feature histogram analyses, heterogeneities, volume, geometry... of each of 62 structures)

Features selected by our algorithm

For Cerebral Palsy
- AnteriorLimbicLeft_ADC_p0
- Motor Imp (n=10)
- Speech delay (n=15)

For Visual Impairment
- ParietalLateralGMRight_ADC_p25
- PLICLeft_ADC_stdev

For Dev. Delay
- aed_discharge_2
- aed_discharge_1

For Hearing Impairment
- TemporalInferiorGMRight_ADC_p0
- Vermis_ADC_mean
- AnteriorLimbICleft_ADC_p25
- RightInsula_ADC_p100
- OccipitalMedialGMLLeft_ADC_stdev

Honorable Mention; Pilot Funding Finalist
MGHfC Research Day, 2018
What about Other Locations?

Our preliminary results show
a) vulnerability throughout the brain
b) vulnerability varying from voxel by voxel

Voxel-wise Liebermeister test
\( P<0.05 \) after 10000 permutations and multi-comparison correction
Controlling for covariates (age, sex at MRI, treatment, lesion volume)
Data-Driven Outcome Prediction Example

- Can an early MRI (first 1-2 weeks of life) predict which infants will be diagnosed with CP?

<table>
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<th>Outcome</th>
<th>Accuracy</th>
<th>AUC</th>
<th>Sensitivity</th>
<th>Specificity</th>
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<td>Cerebral Palsy</td>
<td>0.952</td>
<td>0.974</td>
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</table>

- The accuracy of predicting outcomes at age 2 years was 68% for developmental delay (sensitivity 0.9, specificity 0.5) and 95% for CP (sensitivity 1, specificity ~0.95).
Can these methodologies be applied to other “high-risk,” complex neonatal cohorts (e.g. Opioid exposure)???
MRI imaging pipelines are being developed to better identify infants in these cohorts and detect abnormalities with the ultimate goal to improve outcomes.
Opioid use during pregnancy can result in a drug withdrawal syndrome in newborns called **neonatal abstinence syndrome**, or **neonatal opioid withdrawal syndrome** (NAS/NOWS), which causes **costly** hospital stays. A recent analysis showed that an estimated **32,000** babies were born with this syndrome in the United States in 2014, a more than **5-fold increase** since 2004.

**EVERY ~ 15 MINUTES, A BABY IS BORN SUFFERING FROM OPIOID WITHDRAWAL.**

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**NAS/NOWS and Maternal Opioid Use Disorder on the Rise**

Rates per 1,000 Hospital Births

- NAS/NOWS: 1.5, 1.9, 2.2, 2.2, 2.2, 2.7, 3.4, 4.8, 5.0, 5.9, 7.0, 8.0
- OUD: 1.4, 1.6, 2.1, 2.1, 2.4, 2.9, 3.9, 4.9, 5.7, 6.5

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**Growing Hospital Costs for Treatment of NAS/NOWS**

Inflation-Adjusted U.S. Dollars (millions)

- 2006: $90.9
- 2010: $122.1
- 2014: $563

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**NIH**

**National Institute on Drug Abuse**

**DRUGABUSE.GOV**
Prevalence of NAS/SEN in the Commonwealth

- The rate of reported prenatal opiate exposure in Massachusetts rose from 2.6 per 1,000 hospital births in 2004 to 14.7 in 2013, an increase of more than 500%

- However, based on hospitalization figures, researchers estimated a higher rate: that more than 1,300 Massachusetts babies or about 17.5 per 1,000 hospital births were born with heroin and other opioids in their system in 2013.

- Nationally, the figure is five babies out of every 1,000 births

- The New England region (of which Massachusetts is the most populous) has the second highest rate of prenatal exposure in the nation (13.7 per 1,000), after the East/South Central region

- The average length of stay in Massachusetts for an infant requiring treatment for NAS is 19 days, with an average cost (2013) of $30,000

Franca et al. 2016, ibid.
In-utero exposure to opioids

Studies have shown in-utero exposure to opioids and consequent NAS is associated with long-lasting neurocognitive impairment (heterogenous cohort; many challenges)

Volumetric cerebral characteristics of children exposed to opiates and other substances in utero

K.B. Walhovd, a,*, V. Moe, a K. Slinning, b P. Due-Tønnessen, c A. Bjørnerud, c A.M. Dale, d, e A. van der Kouwe, e B.T. Quinn, f B. Kosofsky, f D. Greve, e and B. Fischl e, g

Neonatal Abstinence Syndrome and High School Performance

Potential mechanisms for abnormal fetal brain development are complex and multifactorial

- Genetics
- Maternal health
- Placenta
- Environmental exposures
- Prescribed and illicit drugs
- Nutrition
- Tobacco
- Combinations of all of the above….
Timing

- Fetal effects of exposures during pregnancy
- Timing of initial exposure
- Dose; Length of exposure
- Ex FASD, SSRI, anti-epileptics etc.

Lewis Ball Holmes, MD
- Emeritus Unit Chief, Medical Genetics, Pediatric Service
- Emeritus Director, Genetic Counseling & Screening Services,
  Perinatal Diagnostic Unit, Obstetrics Program
Can these methodologies be applied to other “high-risk,” complex neonatal cohorts (e.g. Opioid exposure)??

K12 Career Development Program in Substance Use and Addiction Medicine (MGH)

Maternal Infant NeuroDevelopment Study (MINDS)

Research reported in this portion of the talk] was supported by The National Institute of Drug Abuse of the National Institutes of Health under award number K12 DA043490-01. The content is solely the responsibility of the authors and does not necessarily represent the official views of the National Institutes of Health.
Abbreviated Specific Aims

• Aim 1: Characterize regional brain volumes and structural/functional connectivity patterns in opioid-exposed neonates compared to age- and sex-matched healthy control infants.

• Aim 2: Characterize the relationship between imaging findings and neurodevelopmental outcomes assessed with the Bayley-III Scale in opioid-exposed neonates between 18 and 24 months.

• Can we create a research imaging pipeline at MGH for infants with in-utero drug exposure(s)?

• Maintain our practices of: reducing stigma, partnering with parents, & advocating to maximize brain health for all of our patients
# Team Effort

<table>
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<th>Role in Study</th>
<th>Department or Division</th>
<th>Phone Number</th>
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<th>Notes</th>
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<td>Principal Investigator</td>
<td>Newborn Medicine</td>
<td>W: 617-734-9040; M: 617-663-7472</td>
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# Inclusion & Exclusion Criteria

## Inclusion

### Exposed Infants:
- Newborns \( \geq 35 \) weeks gestational age
- Known in-utero exposure to opiates (e.g. mother has been in recovery and on medication assisted therapy (MAT) during pregnancy and/or is using illicit opiates). This information will be extracted from the EHR. In the event any clarification is required, the PI will contact the primary OBGYN for additional information.
- Postnatal diagnosis of NAS, NOWS, or drug withdrawal syndrome

### Control Infants:
- Newborns \( \geq 35 \) weeks gestational age born at MGH
- No diagnosis of NAS, NOWS, drug withdrawal syndrome, or history of in-utero exposure to drugs.
- No maternal history notable for OUD and/or a negative toxicology screen
- No maternal history of any of the following prescribed or illicit exposures during pregnancy: opioids (prior to the onset of labor), anti-epileptics, alcohol consumption, tobacco or marijuana use. This information will be abstracted from the EHR.

## Exclusion

### Exposed and Control Infants:
- Known chromosomal or major congenital abnormalities
- Suspected in-born error of metabolism
- Brain insult or injury (e.g. Hypoxic ischemic encephalopathy, perinatal stroke)
- Sepsis
- Respiratory distress or failure requiring mechanical ventilator support
- Presence of electrically, magnetically, or mechanically activated medical implants (such as cardiac pacemakers)
- Maternal history of major neuropsychiatric illness such as psychosis, bipolar or schizophrenia
- In the opinion of the PI, not able to safely participate in this study
General Study Overview

• Clinical data collected from EHR:
  • Mom
  • Infant
  • Placenta

• REDCap

Pregnant mothers will be identified through collaboration with the OB and Neonatology teams

Consent AFTER infant is delivered

Enrolled infants meeting all inclusion criteria are scanned within the first 3 weeks of life

Bayley 3 Scales of Toddler and Infant Development obtained in follow-up clinic at 12 and 24 months of age PER CLINICAL ROUTINE

The HOPE Clinic (Harnessing support for Opioid and substance use disorders in Pregnancy and Early childhood) at Massachusetts General Hospital
3T Scanner
# MINDS imaging protocol (~45 minutes)

<table>
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<th>Sequence</th>
<th>Average Time (minutes)</th>
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<td>Localizer</td>
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<td>mocoMEMPRAGE (T1w with prospective motion correction)</td>
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<td>SMS diffusion weighted imaging with two b shells, and bmax = 2000</td>
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<td>Sagittal T2</td>
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<td>Spectroscopy</td>
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<td>SMS resting state fMRI (BOLD)</td>
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<td>Axial T2</td>
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Processing Workflow Overview

DICOM Review
- Remove images with motion artifact

Transfer to cluster
- Preprocessing

Data Analysis
- Structural
- Resting state
- Diffusion/Tractography

MINDS_001: MPRAGE with motion artifact (left) and without (right)

- Renaming/organizing files
- mri_convert dicom → niftii


Fig. 1. (Left) Cortical and subcortical segmentation labels displayed on the structural MRI of an infant. (Right) Manually annotated tracts of a sample subject: CST (light blue), FMIN (green), FMN (bright green), IFN (beige), ILF (purple), UF (red) and SLF (light brown).
Detailed DTI pre-processing workflow

- Convert DICOM to Nifti (dcm2nii)
- Skull stripping (dramms)
- Skull strip DTI (dramms)
- fslsplit 4D DTI image into individual 3D images
- Register MPRAGE to b0
- Warp MPRAGE brain mask to create b0 brain mask
- Fslmaths to apply brain mask to each 3D image + fslmerge to create new 4D image
- FSL Preprocessing
- Eddy current correction
- DTI Fit

*Currently processing initial group of patients; unpublished data
40 Years Later…

Indomitable

MRI compatible isoolette (early example)

Embrace: Aspect Imaging

Neuro Optics: NIRS + DCS

Baby Connectome

NIH: Human placenta project

Optimization of acquisition and processing

fMRI (stim, resting state)

*So many more amazing scientific discoveries and technological advances…far to many to list

Fetal-Neonatal Neuroimaging Developmental Science Center
Future Directions

• Despite limitations, the machine learning algorithms presented provide promising first steps in both detecting lesions and predicting outcomes
• Increasing our inputs/features $\rightarrow$ clues $\rightarrow$ improved learning/outputs
• Continue to explore mechanisms
• Integration of clinical data (ongoing)
• Continue to build collaborative, multi-site, multidisciplinary research teams
Learning Objectives

• During patient case discussions, appreciate both the strengths and limitations of MRI
• Reflect upon the role of MRI in difficult diagnostic and therapeutic decisions
• Describe the technology and potential applications of machine learning algorithms in neonatal neuroimaging
# Acknowledgments

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<tr>
<th>MGH/Martinos Center:</th>
<th>Nancy Rigotti, MD</th>
<th>Wayne State University:</th>
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<td>Karen Buch, MD</td>
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Special thanks to the patients & families we have the privilege of caring for
Contacts & Image Processing Links

Additional questions, comments, ideas about potential collaborations???
Please reach out; we’d love to hear from you!

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  Image processing & algorithm development

  - https://www.nitrc.org/projects/normalizefov
  - https://www.nitrc.org/projects/picasso
  - https://www.cbica.upenn.edu/sbia/software/MUSE
  - https://www.nitrc.org/projects/dramms
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