The Amazing Gene That Could solve many brain-related disorders
Purpose of this presentation

The International FOXG1 Foundation (IFF) is providing grants to scientists to understand the biology of FOXG1, with the ultimate goal of identifying innovative therapeutic strategies.

This presentation seeks to inform scientists of current research on FOXG1 and assets available.

Link to Grant Application:

Please email application to nasha.fitter@foxg1.org
International FOXG1 Foundation (IFF)

IFF exists to pioneer innovative research to find a cure while guiding and supporting families.

- Formed on October 4, 2012 by six affected FOXG1 families
- Approved for 501(c)(3) nonprofit tax exempt status
- Raised $300,000 to date with a goal of $5 million by 2018
- FOXG1 Clinics at Boston Children’s Hospital and Stanford’s Lucile Packard Children’s Hospital
- Ongoing Natural History Study with NIH Grant
- Active global parent community with 300 affected families
FOXG1 Foundation Scientific Advisory Board

**Dr. Heather Olson**, MD, MS, Children’s Hospital Boston, Assistant in Neurology, Instructor of Neurology, Harvard Medical School.

**Dr. Orrin Devinsky**, MD, NYU Langone Medical Center, Professor, Department of Neurology, Department of Neurosurgery, Department of Psychiatry, Chief of Service, NYU Epilepsy Service.

**Dr. Walter Kaufmann**, Ravenel Boykin Curry Chair in Genetic Therapeutics, Professor of Neurology, Greenwood Genetic Center.

**Elli Brimble**, MSc, MS, CGC, Lucile Packard Children’s Hospital at Stanford has joined us as the foundation’s Genetics Liaison.
Research Goals - what we are looking to fund

1. **Understand the Biological Impact of FOXG1**
   Characterize the molecular, behavioural, and functional consequences of FOXG1 disruption using patient-derived iPSC neurons and mouse models

2. **Utilize Gene Therapies for Cures**
   Exploit existing gene therapies to better understand FOXG1 function, and to develop novel treatment strategies:
   - saRNA- and AAV-Foxg1-mediated approaches to boost endogenous expression
   - CRISPR/Cas9 editing as a tool to correct FOXG1 mutations in neurons
   - RNAi as a tool to silence dysfunctional protein

3. **Target FOXG1 Symptoms**
   Promote transcriptomic and proteomic evaluations of FOXG1 to identify biological pathways that can be modulated with existing compounds
FOXG1 Science
FOXG1 is critical for brain development

- FOXG1 encodes the Forkhead box G1 protein

- FOXG1 is one of the **earliest transcription factors** that contributes to development of the telencephalon - the telencephalon is an embryonic structure that gives rise to the cerebrum

- The following pathogenic variants have been observed in FOXG1 patients: deletions, duplications, missense, truncation and frameshift variants
● All pathogenic missense mutations thought to occur in the forkhead DNA binding domain
● Deletions including cis-acting regulatory elements but not coding region result in a FOXG1 syndrome phenotype
Established transcriptional targets of FOXG1 (direct and indirect)

- FOXG1 thought to act primarily as a transcriptional repressor

- In addition to listed genes, widespread disruption of ‘ventral’ telencephalon genes with Foxg1 deletion

**With TGFβ1**

**FOXG1 shown to be enriched for in RELN promoter in NIH-3T3 cells, acting as a transcriptional repressor**
**FOXG1 syndrome phenotypes**

**Microcephaly and Structural Brain Abnormalities**
- Small head size with partial or full loss of the corpus callosum (inhibiting communication of left and right brain)

**Epilepsy/Seizures**
- Infantile spasms and life-threatening seizures resistant to drug and surgical treatments

**Gross Motor/Fine Motor Delays**
- Low muscle tone leads to inability to sit, walk, talk or use hands purposefully
- Strabismus, poor eye contact, and cortical visual impairment

**Feeding Issues**
- Low muscle tone leads to reflux, constipation
- Many individuals require feeding tube placement

**Associated Conditions & Disorders**
- Autism Spectrum Disorders (ASD)
- Sensory Processing Disorder (SPD)
- Movement disorders
FOXG1 syndrome – history and landscape

- Formerly called Congenital Rett syndrome; has since been proven that Rett Syndrome is a sister to FOXG1 Syndrome, not a parent
- FOXG1 gene discovered in 1995 by Dr. Alessandra Renieri, University of Siena, Italy
- Shown as cause of Congenital Rett/FOXG1 Syndrome in 2005
- Currently 272 cases reported worldwide.
  - This number steadily increasing as more children undergo genetic testing for Autism Spectrum Disorder (ASD), epilepsy, etc.
**FOXG1 and brain development**

**Development of the Telencephalon:**

- **FOXG1** is required for patterning the developing telencephalon, particularly for ‘ventral identity’ - ‘ventral’ denotes a region of the developing telencephalon that will become the basal ganglion.

- The pattern of **FOXG1** expression in the developing telencephalon is a gradient - an abnormal ‘ventral’ region leads to corresponding defects in the opposite ‘dorsal’ region.

- Mice engineered to lack **Foxg1** expression show gross malformations of the cerebral cortex, with a smaller, irregularly shaped cortex, and nearly absent ventral telencephalon.

**Neurogenesis and Cell Proliferation:**

- **Foxg1** plays a role in the timing of neurogenesis and patterning of the cerebral cortex:
  - **Foxg1** suppresses early-neuronal cell types - allows for switch to neurons that reside in deeper layers of the cerebral cortex.

- Several publications support a role for **Foxg1** in improving survival of neuronal progenitor cells (early cell types that give rise to neurons):
  - Some evidence to suggest that this does **NOT** require the DNA-binding activity of **FOXG1**
  - Possible avenue to explore genotype-phenotype correlations.
Unlocking the mysteries of common neurodevelopmental disorders via FOXG1

**Autism spectrum disorders: Proportion Monogenic - 15-34%**
- FOXG1 variant identified in an individual with ASD and his similarly affected mother
- FOXG1 gene dose associated with ASD diagnosis

**Epilepsy: Proportion Monogenic - >40% in epileptic encephalopathies**
- ~87% of individuals with a FOXG1 mutation are diagnosed with epilepsy
- Age of onset, seizure type, response to medication variable

**Schizophrenia: Proportion Monogenic ??; heritability 70-80%**
- A schizophrenia-associated loci was shown to physically interact with and regulate FOXG1 expression
- Expression of schizophrenia-associated gene, GRID1, found to be significantly elevated in FOXG1 patient-derived iPSC neurons and Foxg1+/- fetal mouse brain

A role for FOXG1 in autism spectrum disorders?

Mariani J, et al. show...

- iPSC neurons derived from patients with an autism spectrum disorder + macrocephaly (larger head size) show:
  - Overproduction of GABAergic progenitors and neurons (principle inhibitory neurons in adult brain)
  - Disrupted balance of inhibitory and excitatory neurons
  - Increased FOXG1 expression

- Normalizing FOXG1 expression using RNAi corrects for these findings, implicating FOXG1 in ASD pathogenesis

- FOXG1 expression significantly correlated with head circumference in this population, a marker of severity in ASDs (↑head circumference = ↑severity)

FOXG1 Assets for Scientists
FOXG1 promising for research investment

We know:

- Affected Gene
- Emerging genotype-phenotype correlation, with patients sharing strong similarities
- Strong research connecting FOXG1 to prevalent neuropsychiatric disorders
- How to safely deliver drug/gene therapies to the brain
Current assets for investigators

- Publicly available *Foxg1* deletion **mouse models** and **iPSC lines** for molecular/behavioural research and preclinical trials

- *FOXG1* clinics at Boston Children’s Hospital and Stanford Children’s Health to accumulate accurate clinical data

- Rett-associated Natural History Study to characterize outcomes across patients lifespan, and to explore possible genotype-phenotype correlations

- Active social network of affected families that can be reached immediately

- Development of a public-facing clinical and patient derived database
Existing *Foxg1* ‘knock-out’ models

**Foxg1-Lacz Model**
- *Foxg1* replaced by a LacZ + PGK/Neo cassette
  - Homozygotes die shortly after birth
  - Cerebral hemispheres reduced by 95% in homozygotes
  - Almost all telencephalon expresses dorsal markers (no ventral structures)

Xuan S, *et al.* 1995

**Foxg1-Cre Model**
- *Foxg1* replaced by a Cre/Neo cassette
  - In heterozygotes:
    - Significant reduction in volume of adult forebrain and thalamus
    - Significant reduction in cortical thickness (could be due to Cre transgene)
    - Expression analysis: ↑ oxytocin, ↑ arginine vasopressin, ↑ neuronatin

Hébert JM & McConnell SK. 2000

**Foxg1-tTA Model**
- *Foxg1* replaced by a tTA + PGK/Neo cassette
  - Significant reduction in volume of adult forebrain in heterozygotes
  - Heterozygotes show hyperactivity and impaired contextual fear conditioning

Hanashima C, *et al.* 2002
Other Foxg1 Mouse Models

**Conditional Foxg1 Knockout**

- Endogenous Foxg1 expression absent; replaced with Foxg1 transgene that can be ‘turned off’ with doxycycline treatment

Hanashima C, et al. 2007

**DNA-Binding Defective Foxg1**

- Endogenous Foxg1 expression absent; replaced with Foxg1 transgene that cannot bind DNA
- Enhanced growth of telencephalon compared to knockouts

Hanashima C, et al. 2002
Newly developed Foundation-sponsored model

- Mouse model can generate:
  - Conditional knock-out (stop codon prevents Foxg1 transcription)
  - Expression of 3xHA-tagged FOXG1 protein
iPSC lines available in Biobank

The following iPSC lines are available for research purposes by Dr Renieri:

- Line ID 146/#14: p.Trp255*
- Line ID 611/#2013: p.Glu154Glyfs*301
- Line ID 968/#18: p.Ser323fs*325
- Line ID 2362/#5: hg19 chr14:g.28552714_29655318del (whole gene deletion)

Instructions to access lines:
- Go to the web site http://biobanknetwork.telethon.it
- Select “login” option (on the lower left corner) and then “register”.
- Fill in the form fields (mandatory), and then confirm the registration. You will receive immediately username and password by email.
- Once you receive username and password you can log in and place your request:
  - Select “Catalogue” and then “Request submission form”.
  - You will be redirected to a page. Indicate title, granting agency and Grant number (if you have funded project, otherwise you can write “no grant”) and a brief description of the research project for which the sample/samples will be employed. At the end of the description you have to add the following sentence to specify the samples you need: “I request FOXG1 iPSCs from patients with mutations in FOXG1 gene. The samples are present in the Biobank in Siena directed by Prof. Alessandra Renieri.”
We chose to administer miR-αFoxg1.1694 to the living brain through AAV9-pseudotyped, self-complementary AAV2-derivative, adeno-associated viral vectors.

“Remarkably, Foxg1 was upregulated by 1.66 ± 0.30 folds”

“Based on results reported above, RNAa might be a simple and scalable approach for fixing this class of problems”

RNA activation of haploinsufficient Foxg1 gene in murine neocortex, Cristina Fimiani, Elisa Goina, Qin Su, Guangping Gao & Antonello Mallamaci, Scientific Reports 6, Article number: 39311 (2016)
Lessons from other genetic neurodevelopmental disorders
Gene therapy stabilizes/improves symptoms in Rett syndrome mouse model

$\text{Mecp2}^{\text{stop/y}}$
- 4-8 weeks
- $+ \text{scAAV9/cre}$
  - Improved survival
  - Robust behavioural recovery

$\text{Mecp2}^{\text{stop/+}}$
- 7-10 months
- $+ \text{scAAV9/cre}$
  - Symptom severity stabilized
  - No seizures
  - ↑ brain size and cognition

$\text{Mecp2}^{\text{null/y}}$
- 4-8 weeks
- $+ \text{scAAV9/Mecp2}$
  - Physiologic expression levels
  - Improved survival
  - Phenotype stabilized

$\text{Mecp2}^{\text{null/+}}$
- 10-12 months
- $+ \text{scAAV9/Mecp2}$
  - Symptom severity improved
  - No seizures
  - ↑ cognition

Human recombinant IGF-1 in Rett and Fragile X syndromes

IGF-1 impacts CNS via two pathways:
- PI3K-Akt-MTOR
- RAS-MAPK-ERK

AKT implicated in functional regulation of FOX transcription factors

## Ongoing FOXG1 research projects

### Understand the Biological Impact of FOXG1

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<tr>
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<th>Role</th>
<th>Activities</th>
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<tbody>
<tr>
<td>Boston Children’s Hospital</td>
<td>Professor, Univ of California, San Diego</td>
<td>Develop patient-derived iPS neurons to characterize impact of FOXG1 disruption, and to provide a substrate for drug screening</td>
</tr>
<tr>
<td>Guangping Gao, PhD</td>
<td>Professor, Univ of Mass. Medical School</td>
<td>Develop saRNA + AAV-mediated gene therapies for neurodevelopmental disorders, including FOXG1</td>
</tr>
<tr>
<td>Jeffrey Neul, MD, PhD</td>
<td>Professor, Univ of California, San Diego</td>
<td>Generate a Foxg1-deletion mouse model to characterize molecular, developmental, and behavioral outcomes of Foxg1 disruption and subsequent correction</td>
</tr>
<tr>
<td>Alessandra Renieri, MD, PhD</td>
<td>Professor, Univ of Siena</td>
<td>Employ CRISPR/Cas9-mediated approach to correct FOXG1 mutations in iPS neurons and animal models, and characterize outcomes</td>
</tr>
<tr>
<td>Flora Vaccarino, MD</td>
<td>Professor, Yale School of Medicine</td>
<td>iPS neurons to model neurodevelopmental disorders; FOXG1 in the pathogenesis of autism spectrum disorders and head circumference</td>
</tr>
<tr>
<td>Antonello Mallamaci, PhD</td>
<td>Associate Professor, SISSA</td>
<td>Generate patient-derived iPS cortical neurons to model morphologic and electrophysiologic sequelae of FOXG1 disruption, with special interest in cortical development</td>
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### Utilize Gene Therapies for Cures

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<td>Sandra Acosta-Verdugo, PhD</td>
<td>Post-Doctoral Fellow, Northwestern University</td>
<td>Functional characterization of FOXG1 regulatory elements to identify possible therapeutic targets</td>
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### Improve FOXG1 Symptoms

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