One Man’s View of One Health
Translational Lessons Learned from a Canine Model of Duchenne Muscular Dystrophy

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Veterinary Medicine and Human Health
Calvin Schwabé

- *1st Edition* (1964) had sections on population medicine, epidemiology, and food and hygiene.
- *2nd Edition* (1969) included, under Epidemiology, a subsection on “Comparative Approaches to Diseases of Unknown Etiology” in which cardiovascular disease and cancer were discussed.
“My second fixed idea is the uselessness of men above sixty years of age, and the incalculable benefit it would be in commercial, political, and in professional life, if as a matter of course, men stopped work at this age.”

William Osler – The Father of Modern Medicine
(Vol. I, Ch. 24 : The Fixed Period – The Life of Sir William Osler; 1925)
Biomedical Models
National Research Council (1985, 1998)

• “A surrogate for a human being, or a human biologic system, that can be used to understand normal and abnormal function from gene to phenotype and to provide a basis for preventive or therapeutic intervention in human diseases.”

• “Can be many types – from animal models of human diseases to animal, in vitro, or modeling systems for studying any aspect of human biology or disease.”
Muscular Dystrophy

• Group of inherited, progressive myopathies in which major signs relate primarily to skeletal muscle.

• Originally classified based on clinical features (pattern of inheritance, age at onset, and muscles involved).

• Classification system has been revised based on molecular testing.

• Duchenne muscular dystrophy (DMD) – proximal distribution.

Dystrophin-Glycoprotein Complex

- **Muscular dystrophies** tied to proteins in a complex that spans the muscle cell membrane.
- Major components include **dystrophin**, **α and β dystroglycans**, and **α, β, γ, and δ sarcoglycans**.
- **Dystrophin** protein is coded by the **DMD** gene and connects cytoskeleton to the extracellular matrix via a transmembrane complex.

Duchenne Muscular Dystrophy

- X-linked; males affected, females are carriers.
- ~1 in 5,000 live male births.
- Boys in wheelchairs by teens; most die by early 20s.
- Cardiomyopathy; respiratory.

- Spinal lordosis.
- Pseudohypertrophy of the calf muscles.
- Selective muscle sparing.
- Agonist-antagonist imbalance contributes to contractures.

Sartorius
Gracilis

Spondylosis
Pseudohypertrophy of the calf muscles
Selective muscle sparing
Agonist-antagonist imbalance contributes to contractures
Mammalian Animal Models of DMD

- **Mdx mouse** – a nonsense point mutation causes premature termination of translation within exon 23. Mild phenotype.
- **Feline hypertrophic muscular dystrophy** – deletion of the dystrophin muscle and cerebellar Purkinje cell promoters in one case.
- **GRMD** – splice site mutation in intron 6 causes exon 7 to be skipped in transcription and a stop codon; multiple other dog breeds.
GRMD Colony Development

• 1982 – Rusty and Dusty transferred to NC State.
• 1985 – GRMD dog (Rusty) first seen at UGA provided to Barry Cooper at Cornell to develop colony.
• 1987 – GRMD dog and carriers provided to NCSU for second colony.
• 1994 – NCSU colony to Missouri.
• 2007 – Missouri colony to UNC-CH.
• 2012 – UNC-CH colony to Texas A&M.
• Colonies in Australia (closed), France, Japan, Brazil, the Netherlands, Missouri, and at the Fred Hutchinson Cancer Center (Seattle).
The Role of Animal Models in Treatment Development for DMD

- *In vitro* studies (cell culture, etc).
- *In vivo* systems not involving specific X-linked animal models.
- Mdx mouse; mdx/utrophin DKO mouse.
- GRMD dog and/or primate.
- DMD patients.

A balancing act – should the dog be driving the bus (tricycle)?

Predictive value of animal models. Will the mdx or GRMD model better predict outcome in DMD?
GRMD – General Features

- Progressive disease
- Postural instability/contractures
- Muscle atrophy and hypertrophy
- Kyphosis/lordosis
- Respiratory
- Cardiomyopathy

Phenotypic Variation: Species, Individual, and Muscle (confounds preclinical trials but offers insight on disease pathogenesis).

Primary vs. Secondary Effects of Dystrophin Deficiency and Identification of Modifier Genes as Druggable Targets
Therapeutic Approaches

- **Gene Therapy**
  - Viral Vectors
  - Plasmid DNA
  - Antisense oligos

- **Cell Therapy**
  - Myoblasts
  - Stem cells

- **Pharmacologic**
  - Prednisone (Std of Care for DMD)
  - \( \uparrow \) utrophin (surrogates)
  - NF-\( \kappa \)B inhibitors
  - Calpain inhibitors
  - Membrane sealants
  - Myostatin (GDF-8) inhibition

**AAV-minidystrophin, Neonatal Intravenous**

**Dog helps find cure for fatal muscle disease**

**Mesoangioblast Therapy in GRMD**

- Golden retrievers are often used in research because of their large muscle mass.
- There are no effective treatments for muscular dystrophy, a disease caused by a gene that affects muscle function.
- An Italian team has been testing experiments on the disease after Duchenne muscular dystrophy was identified as the cause of the muscular dystrophy in humans.
- In experiments on Golden retrievers with muscular dystrophy, the researchers injected minidystrophin with the AAV vector.
- Injections were administered using a catheter.
- The researchers measured the expression of utrophin in the muscle. There was a significant expression of utrophin in a dose-dependent manner. The researchers also measured the expression of utrophin in the muscle 6 months after injection with the AAV vector.
Myostatin inhibition

- Myostatin (Growth/differentiation factor 8; GDF-8). Negative regulator of muscle growth; mutations lead to muscle hypertrophy (double muscled cattle; human; sheep; whippets).
- Knocking out myostatin improves function in mdx mice BUT...
- Adult dystrophy myostatin-inhibition (MYO-29) trial ambiguous
- Murine models of LGMD and CMD either did not improve or had differential effects in young vs. old mice and/or muscles.
Hypertrophy of the GRMD Cranial Sartorius (and Other Flexor Muscles) May Have Deleterious Effects.

GRMD – Postural Changes


• GRMD data suggest muscle hypertrophy can be harmful, BUT....
• Whippet dogs that are heterozygous for myostatin are better athletes; homozygous-null dogs have gross muscle hypertrophy, i.e. so-called *bully whippets*.
• Transgenic/knockout technology in dogs is not widely utilized.
• Potential to cross breed GRMD and heterozygous myostatin whippet dogs (*GRippets*).
Myostatin-Heterozygous (\(Mstn^{+/-}\))
GRMD Dogs; \textit{GRippets}

- Collaboration with Kathryn Wagner and Se-Jin Lee of Johns Hopkins.
- First litter – GRMD carrier bred to sire (\(Mstn^{+/-}\)) of “Bully Whippet” (\(Mstn^{-/-}\)).
- Second litter – GRMD male bred to \textit{Speedy} (double mutation).

\begin{table}
\centering
\begin{tabular}{|c|c|c|c|}
\hline
Dog Name & Gender & GRMD Status & Myostatin Status \\
\hline
\multicolumn{4}{|c|}{First Litter (“Racing”)} \\
\hline
Racer & Male & Normal & Normal \\
\hline
Flash & Male & Affected & Normal \\
\hline
Dash & Male & Affected & Heterozygote \\
\hline
Speedy & Female & Carrier & Heterozygote \\
\hline
Lightning & Female & Carrier & Normal \\
\hline
Zippy & Female & Normal & Heterozygote \\
\hline
\multicolumn{4}{|c|}{Second Litter (“Bewitched”)} \\
\hline
Endora & Female & Carrier & Normal \\
\hline
Esmerelda & Female & Carrier & Heterozygote \\
\hline
Samantha & Female & Affected & Normal \\
\hline
Hagatha & Female & Affected & Normal \\
\hline
Tabitha & Female & Affected & Heterozygote \\
\hline
Derrwood & Male & Affected & Heterozygote \\
\hline
Abner & Male & Affected & Heterozygote \\
\hline
\end{tabular}
\end{table}

Myostatin-Heterozygote ($Mstn^{+/−}$) GRMD (Litter 1 – “Racing”)

- Similar phenotype for *Flash* and *Dash* until ~ 4.5 mos.
- *Dash* developed contractures.
- Hypertrophy of the cranial sartorius, semitendinosus, and semimembranosus muscles.
- *Dash* had features of a severe GRMD phenotype.
- Contractures – unbalanced agonist/antagonist muscles.
- Bigger is not necessarily better.
• Overall body-weight-corrected (mm$^3$/kg) muscle mass comparable among the three groups of dogs.

• Marked variation among muscles; trend whereby relative lack of myostatin exaggerates pre-existing trends for muscle atrophy/hypertrophy.

The Realities of Drug Development

• The success rate for Phase II human clinical trials fell from 28% in 2006-2007 to 18% for 2008-2009 (Arrowsmith 2011).

• Over half (51%) of 108 reported Phase II failures occurred due to insufficient efficacy, even though most drugs were assessed in animal models (Plenge et al. 2013).

• Only 28 of 76 (37%) of highly-cited studies that investigated a preventive or therapeutic intervention in an in vivo animal model over the 1980-2000 period were replicated in human randomized trials (Hackam and Redelmeier 2006).
Lost in Translation
(Ergorul and Levin 2013)

• The *Butterfly Effect* (chaotic behavior whereby small differences in the animal model lead to substantial differences in clinical results);

• The *Princess and the Pea* problem based in variability of effect size when progressing from biochemical findings through tissue culture and animal and human studies (the pea does not indent the mattress to the same degree as the princess);

• The *Two Cultures* problem evident in preclinical and clinical research (need for more rigorous experimental design in preclinical studies).
Biomedical Models
National Research Council (1985, 1998)

• Biological (animal) models can be based in analogy or homology.
  - Analogy implies a point-by-point relationship.
  - Homology implies a shared evolutionary history and DNA makeup.

To be functionally useful, homologous models must be good models by analogy.

• Models may be one-to-one (disease in humans and a species that share the same clinical features) or many-to-many (findings from more than one species or organ system model disease features).
GRMD – General Features

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- Cardiomyopathy

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Primary vs. Secondary Effects of Dystrophin Deficiency and Identification of Modifier Genes as Druggable Targets
Traditional Drug Targeting – Histopathologic Lesions and Presumed Pathogenetic Mechanisms

A New Model – Targeting Genetic Mechanisms such as Modifier Genes through mRNA Array and GWAS Studies

Phenotypic Data from GRMD Dogs Assessed with mRNA Microarrays

- Collaboration with Scott Schatzberg and Peter Nghiem at UGA and Eric Hoffman at Children’s National Medical Center in Washington, DC.
- 8 GRMD and 4 normal dogs with muscle biopsies at 8 wks and 6 months.
- Biopsies from the vastus lateralis, cranial sartorius, and long digital extensor muscles.

<table>
<thead>
<tr>
<th>GRMD Dogs (6 mos)</th>
<th>Left TTJ Angle (degrees)</th>
<th>Tetanic Extensor Force (N/kg)</th>
<th>Tetanic Flexor Force (N/kg)</th>
<th>Body Weight (kg)</th>
<th>CS Circumference (mm/kg)</th>
<th>Overall Rank (1= least severe, 8= most severe phenotype)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tico</td>
<td>159</td>
<td>3.138</td>
<td>0.296</td>
<td>15.2</td>
<td>2.303</td>
<td>1</td>
</tr>
<tr>
<td>Joker</td>
<td>155</td>
<td>2.135</td>
<td>0.331</td>
<td>16.3</td>
<td>2.653</td>
<td>2</td>
</tr>
<tr>
<td>Peggy</td>
<td>155</td>
<td>2.109</td>
<td>0.489</td>
<td>13.1</td>
<td>2.774</td>
<td>3</td>
</tr>
<tr>
<td>Jeannette</td>
<td>151</td>
<td>1.669</td>
<td>0.489</td>
<td>13.2</td>
<td>3.102</td>
<td>4</td>
</tr>
<tr>
<td>Huckleberry</td>
<td>141</td>
<td>1.144</td>
<td>0.508</td>
<td>13.2</td>
<td>3.298</td>
<td>5</td>
</tr>
<tr>
<td>Porsche</td>
<td>130</td>
<td>1.041</td>
<td>0.575</td>
<td>14.6</td>
<td>3.493</td>
<td>6</td>
</tr>
<tr>
<td>Janet</td>
<td>142</td>
<td>1.583</td>
<td>0.667</td>
<td>12.6</td>
<td>3.598</td>
<td>7</td>
</tr>
<tr>
<td>Betty</td>
<td>102</td>
<td>2.29</td>
<td>0.72</td>
<td>9.3</td>
<td>6.156</td>
<td>8</td>
</tr>
</tbody>
</table>
Supervised hierarchical clustering of **250 genes** from cranial sartorius (CS) array correlated to CS size \(p = 0.001; r > 0.94\) in CS profiles of normal and GRMD at 4-9 Wk and 6 Mo **Red = up-regulated; Green = down-regulated**
Ingenuity Pathway Analysis (IPA) of 250 genes associated with CS hypertrophy generated the top-ranked network, DAG1 & LARGE.

Diagram showing the relationship between Q-PCR and CS Circumference at 6M, comparing DAG1 and LARGE expression levels. The correlation coefficients are as follows:

- DAG1: $r^2 = 0.5$, $r = 0.71$, $p < 0.03$
- LARGE: $r^2 = 0.68$, $r = 0.83$, $p < 0.005$

Additional Studies

Table 2. Total Spectral Counts for Spectrin, Myotrophin, and Laminin-α2 from Proteomic Profiling Results

<table>
<thead>
<tr>
<th>Genotype</th>
<th>Age</th>
<th>SPTAN1</th>
<th>SPTBN1</th>
<th>MTPN</th>
<th>LAMA2</th>
</tr>
</thead>
<tbody>
<tr>
<td>Normal</td>
<td>4-9 wks</td>
<td>43</td>
<td>7</td>
<td>7</td>
<td>54</td>
</tr>
<tr>
<td></td>
<td>6 mos</td>
<td>36</td>
<td>1</td>
<td>5</td>
<td>3</td>
</tr>
<tr>
<td>GRMD</td>
<td>4-9 wks</td>
<td>65</td>
<td>19</td>
<td>12</td>
<td>12</td>
</tr>
</tbody>
</table>

Sum of spectral counts for each group is shown. There are n = 3 profiles for normal and GRMD at 4 to 9 weeks and at 6 months (12 total profiles). LAMA2, laminin-α2; MTPN, myotrophin; SPTAN1, α-spectrin; SPTBN1, β-spectrin.

• Proteomic profiling (mass spectrometry) was done to identify additional dystrophin surrogates and/or hypertrophic factors.
• Membrane proteins α- and β-spectrin, as well as the muscle growth factor, myotrophin, were selectively upregulated in the CS (Confirmed by IHC and/or Western blots).

What about Myostatin?

- Myostatin was **downregulated** on qPCR in all GRMD muscles but especially in the CS.
- Myostain mRNA levels were inversely correlated with CS muscle circumference at 6 mos.

Overall Conclusion: Cranial sartorius hypertrophy in the GRMD model is driven and supported by a complex set of genes whose manipulation could have (favorable or deleterious) clinical significance.
Animal models are a powerful example of the *one medicine* concept.

Preclinical studies often do not translate to humans.

*Homologous* genetic models are not necessarily *analogous*.

Genetic studies, including mRNA analysis, offer an additional tool to identify potential drug targets, especially if coupled with phenotypic data.
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QUESTIONS?