Questions and Answers About Myostatin, GDF11, and the Aging Heart

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Myostatin and GDF11 are highly homologous transforming growth factor (TGF-β) family members implicated in skeletal and cardiac muscle growth. Myostatin promotes muscle wasting. In contrast, GDF11 was identified as a factor that reverses aging-related cardiac hypertrophy, and in separate experiments, GDF11 supplementation was linked to the reversal of aging-associated skeletal muscle dysfunction. These initial findings have been challenged by work from others, specifically where injection of GDF11 did not replicate the original findings. Now, a new report in Circulation Research demonstrates that GDF11 delivery did produce a reduction in cardiac mass in both young and old animals.

Myostatin, a member of the TGF-β superfamily of proteins, is a negative regulator of muscle mass.1 Both naturally occurring and genetically engineered mutations that ablate or inhibit myostatin processing lead to a dramatic increase in muscle mass, an observation not lost on body builders and the pharmaceutical industry.2 Intriguingly, deletion of myostatin specifically in the heart has been shown to block muscle wasting that occurs in cardiac cachexia although others have found that body-wide myostatin deletion renders little change in this regard.3-4 GDF11 is the most closely related TGF-β superfamily member to myostatin and shows near identity in its active domain to myostatin (Figure 1). Inhibiting myostatin activity is expected to be useful to treat many muscle-wasting conditions, as well as sarcopenia with aging. Myostatin inhibition can be achieved through a variety of mechanisms including blocking peptides or neutralizing antibodies directed toward myostatin’s active domain (Figure 2). Alternative avenues to block myostatin’s effects include ligand traps like soluble receptor or follistatin, or blocking its major receptor, the activin type II receptor. The clinical efficacy of myostatin inhibition remains to be demonstrated in the human setting although its application may ultimately be useful for treating degenerative muscle diseases in children or reversing sarcopenia in the elderly.

The aging population, which includes scientists, is drawn to any capacity to reverse the steady decline of function that occurs with time. With this goal in mind, mice were joined by heterochronic parabiosis where the bodies of old and young are sutured together to learn what factors could transmit features of young to aged animals. In mice, parabiosis entails combining the fascial layers along the flanks of 2 animals, which then survive side-by-side sharing circulating factors.5 Loffredo et al6 used heterochronic parabiosis and surgically joined 23-month-old C57BL/6 animals with 2-month-old strain-matched animals for 4 weeks. This time frame was sufficient to observe reduction of heart mass/tibial length (HM/TL) in the older animals and partial improvement toward a youthful phenotype. Using an aptamer-based proteomics screen, which allowed examination of ≈1000 proteins, 13 different factors were identified that differed between young and old mouse serum. The authors focused on GDF11, a distinct member of the TGF-β family that is highly related, and indeed, nearly identical to myostatin in its active domain (Figure 2). Serum profiling of old, young, and parabiosed animals supported a reduction in GDF11 in aged animals, and older animals that had undergone parabiosis had increased serum GDF11 levels. To confirm the role of GDF11, recombinantly produced GDF11 active domain was injected intraperitoneally into old animals at 0.1 mg/kg, and this was sufficient to produce a similar magnitude of reduced HM as in the parabiosis experiments.6

A recent study by Smith et al7 did not reproduce the effect on cardiac hypertrophy seen by Loffredo et al,8 and instead they observed little effect from GDF11 injections. Using similar dosing (0.1 mg/kg) in 24-month-old C57BL/6 male mice, no decrease in HM/body mass (BM) was seen after 28 days of treatment. Similarly, when evaluating HL/TL measurements, there were no significant changes. The authors concluded that GDF11 is ineffective to reduce HM in older mice. There were several important differences between the 2 studies including the source of the mice and their sex, male versus female mice, as well as the source of recombinant GDF11 active domain used in the injections.

And yet the plot thickens. A new study, Poggioli et al,9 now provides support to the notion that GDF11 delivery can reduce HM. The authors injected recombinant active GDF11 into both young and old mice. They found that GDF11 injection at 0.5 mg/kg and 1 mg/kg daily produced a reduction of HM/TL when compared with vehicle treated after only 9 days in both young and old animals. Cardiac mass itself was reduced after 9 days of daily GDF11 injection in both young and old mice (Table 1 in the study by Poggioliin et al). These results are interesting because it was originally suggested that only older animals with reduced GDF11 were responsive to GDF11 supplementation.9 More complicated to interpret is the effect of GDF11 injections on BM. In old animals, GDF11 injections resulted in a decrease in BM at all doses although...
this was significant only at the highest doses. In young animals, a decline of BM was only seen at the highest doses, and other doses were not sufficient to overcome the rise in BM that occurs in young animals. Because GDF11 injection reduced BM, the authors focused on evaluating HM/TL as the readout. From these data, it seems that GDF11 injection has a similar effect as myostatin, that is, it decreases BM. Myostatin inhibition affects not only muscle mass but also body composition, including fat deposition. GDF11 has also been linked to anemia and vascularity. Thus, GDF11's effect on body composition and size may be through a multiorgan or systemic effect, but it seems to mimic the known effects of myostatin.

Do Serum GDF11 Levels Decrease With Age?

The articles by Loffredo et al and Poggioli et al emphatically take this view. These authors suggest that a commercial anti-GDF11 antibody crossreacts not only to myostatin/GDF8 but also to serum immunoglobulin. They assert that it is this nonspecificity that accounts for observations that GDF11 levels do not decline with age. Given the tight homology between these proteins in their active domains, it is unlikely that any immunoreagent can reliably detect myostatin versus GDF11 in a manner that is not concentration dependent. The Abcam antibody used in immunoblotting is currently labeled as detecting both GDF11 and myostatin. However, it was an R&D antibody used in immunoassays of human serum that showed no significant decline of GDF11 levels. R&D lists this antibody as being specific to GDF11. The R&D anti-GDF11 antibody was raised to the entire active domain, and data are not provided that this antibody specifically recognizes amino acid residues 353 to 350, as this region may be sufficient to distinguish between GDF11 and myostatin (Figure 1, underlined region). There is a substantial literature with vastly conflicting reports of serum levels in human. It would seems that GDF11 levels have similar challenges for serum detection.

Perhaps far more relevant than serum levels, it may be the local concentration of these molecules and their relative bioavailability that is most related to function. TGF-β superfamily members undergo strict processing and regulation where they are held inactive by both small and large latent complexes. Only once released from these layers of latent complexes can the active domains engage local cell surface receptors. Myostatin has been considered a chalone, which are proteins secreted by and responsible for growth of specific organs. That deletion of myostatin in heart blocks cardiac cachexia implies that these proteins can exert effect beyond the targeted organ. Whether serum levels have bearing on local tissue levels and availability is an area that needs more investigation. The greatest sequence differences between GDF11 and GDF8/myostatin reside in the prodomains, and these areas play an essential role in differential regulation and availability. Because immunoreagents cannot reliably distinguish between active GDF11 and GDF8/myostatin, most
investigators have relied on measuring mRNA levels, which may only partly reflect protein levels. Examining 3-month-old mice, Loffredo et al⁶ reported that GDF11 mRNA levels were greatest in spleen with lower levels in muscle and even lower in heart.⁴ How GDF11 levels change with age and disease status will need careful study. Egerman et al¹¹ found a decrease in GDF11 levels in spleen and kidney mRNA levels with age in rat muscle, whereas Poggioli et al⁸ reported an increase in GDF11 and a decrease in myostatin and circulating levels even lower in heart.⁶ How GDF11 levels change with age in mice, Loffredo et al⁶ reported that GDF11 mRNA levels are greatest in spleen with lower levels in muscle and likely the same receptors. Answer: Given the high homology between the active domains of GDF11 and myostatin, most immunoreagents can be expected to detect both GDF11 and myostatin. Mass spectrometry methods targeting peptides where myostatin and GDF11 differ should be a more reliable means to achieve specificity.

**Does Injection of GDF11’s Active Domain Affect BM?**

Smith et al’ did not observe a reduction in BM after 28 days of intraperitoneal injections of GDF11: whereas the study by Poggioli et al⁸ did see trends or significantly reduced BM in older animals after only 9 days of dosing. Although both studies used C57Bl/6 mice, the mice were derived from different colonies and perhaps from different sub-strains. Genetic drift is known to occur in all mice including C57Bl/6 strains, and this genetic drift can alter genes important for metabolism like the Nnt gene.¹³ The study by Smith et al’, where no decrease in mass was seen after GDF11, used mice that were considerably leaner than in the study by Poggioli et al⁸ (34.19±3.73 compared with 39.42±5.63 g). Moreover, animals were housed in distinct caging and environments. It is fair to assume that the diets fed to these animals during aging and even during the course of GDF11 injections were not identical.

Answer: Injection of GDF11 active domain seems to reduce BM in mice, but this result depends on initial body composition, age, genetic modifiers, sex, and diet.

**Does Cardiac Pathological Hypertrophy Occur With Age?**

The article by Smith et al⁷ also raised a series of important points on the nature of pathological cardiac hypertrophy as it occurs in aging. These authors compared HM/BM in young and old male mice and did not find any significant increase in this ratio with age (4.75±0.21 young versus 4.70±0.38 old). However, when the authors calculated HM relative to TL (HM/TL), they did observe an increase with age (6.64±0.43 versus 8.87±0.75 comparing 8-week male mice to 24-month male mice.) Interestingly, the Loffredo et al⁶ reported the basal HM/TL measurements in aged animals similar to those reported by Smith et al’ (=9 versus 8.87).

Answer: HM increases relative to TL with age in mice, but HM to BM seems not to change. BM may better reflect the physiological demands on the heart.

**What Is the Potential for GDF11 as a Fountain of Youth?**

The ability to reverse any aspect of aging and finding the fountain (or infusion) of youth has drawn Juan Ponce de León and many others to Florida. Yet the fountain of youth remains as elusive as sunshine in the Chicago winter. Whether infusion of GDF11 active domain is useful requires further study. It is known that there is a remarkably high degree of identity between myostatin/GDF8 and GDF11 active domains, and that these 2 proteins use the same intracellular signaling pathways and likely the same receptors.

Answer: Dosing and especially local concentration and regulation may be keys to unlocking the secrets of these GDFs, and systemic dosing of these agents may not be ideal to achieve this local specificity.

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**References**


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