Differential tissue response to growth hormone in mice

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Growth hormone (GH), produced in the anterior pituitary, plays a major role in both longitudinal growth and metabolism [1,2]. Dysregulation in GH signaling, either increased in acromegaly and gigantism [3] or decreased in short stature or dwarfism, has profound consequences on growth and development [4,5]. GH also impacts life span; GH excess is associated with increased morbidity and premature mortality [6], while GH deficiency promotes longevity [7]. GH binds cell surface receptors (GH receptor; GHR) on target cells, resulting in GHR-associated Janus kinase 2 (JAK2) autophosphorylation and subsequent phosphorylation of GHR intracellular domain tyrosine residues [8–13]. Signal transducer and activator of transcription 5 (STAT5) docks at the phosphorylated GHR and is phosphorylated by JAK2. pSTAT5 dimers translocate to the nucleus to influence transcription of genes including insulin-like growth factor (IGF)-1 [14–16]: GH’s metabolic and somatogenic effects are related to its influence on target cell gene expression.

Assessing acute GH effects in different key metabolic tissues may have once been considered an irrelevant question. Classically, GH was thought to exclusively target the liver, which would then produce IGF-1 (aka somatomedin C) [17]. IGF-1 would subsequently act in an endocrine manner, modulating growth/metabolism in extrahepatic tissues. This is the somatomedin hypothesis of GH action [18]. Later, D’Ercole et al. [19] showed that IGF-1 is also produced locally by extrahepatic tissues in response to...
GH and that the level of IGF-1 produced after GH administration differs between tissues. Further, Skot-
tner et al. [20] demonstrated that administration of IGF-1 did not affect longitudinal growth in hypoph-
sectomized rats, except at very high concentrations, whereas GH administration induced significant
growth. These pioneering studies suggested that IGF-1 might be produced and act locally within target tis-
ues, in contrast to the somatomedin hypothesis. Cons-
istent with these observations, liver-specific IGF-1
knockout mice grow and develop normally, despite
diminished circulating IGF-1 [21–23]. As such, a
revised hypothesis suggests that circulating (hepatic-
derived) IGF-1 is responsible for negatively regulating
GH secretion, whereas local (extrahepatic) IGF-1 plays
a primary role in longitudinal growth [24].

Despite interest in extrahepatic actions of GH and
IGF-1, little information is available that compares
GH signaling among organs in intact animals. Because
of the distinct roles of GH signaling in the liver com-
pared to other metabolic tissues, we hypothesized that
GH sensitivity and responsiveness would differ in hep-
atic versus extrahepatic tissues. Herein, we compare
acute vs extrahepatic tissues. Herein, we compare
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atic versus extrahepatic tissues. The revision suggests that circulating (hepatic-
derived) IGF-1 is responsible for negatively regulating
GH secretion, whereas local (extrahepatic) IGF-1 plays
a primary role in longitudinal growth [24].

Materials and methods

Unless otherwise stated, reagents were obtained from
Sigma (St. Louis, MO).

Animals

All animal husbandry and experimental protocols were car-
ried out according to the Guide for the Care and Use of
Laboratory Animals [1996 (7th ed.), Washington, DC: Na-
tional Research Council, National Academies Press] and
in compliance with the local IACUC standards. At
15 weeks of age (± 3 days), male C57B6J mice (Jackson
Laboratories; Cat. # 000664) were individually housed in
standard conditions under a 12-h :12-h light:dark cycle and had ad libitum access to standard rodent chow and
water. After acclimatization to single housing, mice were
placed in wire-bottom cages without food at the beginning of
the light cycle. Growth hormone challenge was per-
formed in 6-h fasted mice in a manner that is essentially
identical to that described previously [25]. Briefly, either
saline (control) or human recombinant GH (2, 4, 8, 12.5,
20, 50, 80, 120, 200 ng/g bw; gift from Eli Lilly Co, Indi-
anapolis, IN) was injected (i.v.) in anesthetized mice; 5 min
thereafter, heart, liver, kidney, eWAT, and gastroc were
rapidly excised in that order and flash-frozen in liquid
nitrogen prior to biochemical analysis. Total time of tissue
extraction for each animal was 3–4 min. The duration of
GH exposure was selected so as to capture only acute (and
not secondary) effects of GH stimulation and thus most
cleanly address the question of GH sensitivity.

Liver samples for PRLR mRNA positive control were
harvested from female C56Bl6/J mice that were ad libitum
fed and age-matched, age 2–3 months. Pregnant samples
were harvested at gestational day 16.5.

This study protocol was approved by the University of
Alabama at Birmingham Institutional Animal Care and
Use Committee.

Immunoblotting

Protein lysates were prepared from tissues crushed to pow-
der under liquid nitrogen (~ 20 mg) using 300 μL of tissue
lysis buffer (50 mM Tris 7.3, 150 mM NaCl, 1 mM EDTA
pH 8.1, 1.5 mM MgCl2, 10% glycerol, 1% Triton X-100,
10 mM Na2P2O7, 100 mM NaF, 1 mM Na3VO4, 1 mM
phenylmethanesulfonyl fluoride, 5 μg·mL−1 aprotinin, and
5 μg·mL−1 leupeptin). Lysates were resolved under reducing
conditions by SDS/PAGE and transferred to nitrocellulose
membranes (Amersham Biosciences), followed by blocking
with 2% BSA. Membranes were immunoblotted (Table 1)
with anti-phospho-STAT5 antibody (Y694; Cell Signaling;
9351L) (1 : 1000), which reacts with both phosphorylated
Y694 in STAT5A and Y699 in STAT5B; anti-STAT5
antibody (Santa Cruz Biotechnology; sc-835) (1 : 1000);
anti-GHR (polyclonal anti-GHRcytAL-47; against the intracellu-
lar domain of GHR) [26] (1 : 1000); anti-PRLR (anti-
PRLRcytAL-84; against the human PRLR ICD) [27]
(1 : 1000); anti-PRL-R (H-300) (Santa Cruz Biotechnology;
sc-20992); and anti-JAK2 (anti-JAK2AL-33) [28] (1 : 1000).
Densitometry was performed using UVP Software 8.0.

Curve-fitting and statistical analysis

Dose–response curve data were fit to the sigmoidal dose–
response curve (with variable slope): [Y = BOTTOM +
(TOP–BOTTOM)/(1 + 10^((LogEC50–X)*HillSlope))];
Y = response; X = log[dose]; HillSlope = slope of linear section of
the dose–response curve; TOP = point in the dose–
response curve at which an increase in ‘Y’ yields little to no
increase in ‘Y’; and EC50 = the effective concentration (or
dose) at which 50% of the MAX response is achieved [29].
This analysis was performed using GraphPad Prism version
4.00 for Windows (GraphPad Software, San Diego, Califor-
nia, USA, www.graphpad.com). Sensitivity was defined by
the value EC50. Responsiveness was defined by the TOP
value, herein referred to as the MAX response. During the
constrained fit, the TOP and BOTTOM parameters were fixed at 100 and 0, respectively. Tissue-specific differences in protein abundances were assessed via one-way ANOVA using SPSS followed by post hoc analysis via Tukey’s test. Regression analysis to assess the correlation between STAT5 abundance and MAX response was performed using Excel.

### Gene analysis

mRNA was isolated from mouse tissues using either a QIAGEN RNeasy Mini Kit (Cat. No. 74104) or TRIzol RNA isolation reagent according to the manufacturer’s recommended protocol for RNA isolation. Reverse transcription was performed using the High-Capacity cDNA RT Kit (Cat. No. 4368814) from Thermo Fisher. qPCR measurements were carried out using the mPRLR TaqMan Gene Exp. Assay (Assay ID Mm04336676_m1, Cat. No. 4351372) from Thermo Fisher.

### Data display

Due to differences in normalizing proteins across tissues, densitometry data are normalized to total protein loaded on the gel except in Fig. 2 where pSTAT5 is normalized to STAT5 as a loading control; tissue differences in STAT5 abundance do not influence sensitivity. To reduce positional bias during the immunoblot transfer procedure, samples were loaded on gels in randomized order; where possible, \( n = 1 \) for each GH dose was included on each gel. Densitometry was performed on nonmanipulated blots. For clarity, representative blots presented were constructed as follows: A single gel was chosen for each tissue, after which lanes were rearranged such that GH doses were displayed in ascending order.

### Results

**Murine peripheral tissues display differential sensitivity and MAX response to GH**

Although they varied greatly in responsiveness, with kidney being the least maximally responsive, all tissues examined displayed dose-dependent GH effects on STAT5 phosphorylation (Figs 1A and 2). Calculation of EC\(_{50}\) values (see the Methods section for details) revealed tissue-specific differences in GH sensitivity (Fig. 1B, Table 2). EC\(_{50}\) values for liver and kidney did...
not differ significantly, although both were substantially lower (i.e., greater sensitivity) than eWAT, heart, and gastrocnemius. Differences were likewise observed in tissue responsiveness (Fig. 1B, Table 2). Gastrocnemius had the greatest (extrapolated) MAX GH response, followed by heart, liver, eWAT, and kidney (Fig. 1B, Table 2). There was large variability (i.e., confidence intervals) in the EC50 and MAX values for gastrocnemius, heart, and eWAT because the predicted MAX value was not defined by experimental data points (as predicted GH doses required for MAX response were too high). Therefore, as a secondary analysis we normalized the data for each curve such that the highest experimental data point was 100 while the lowest was 0, and fit the data to the sigmoidal dose–response curve using the constraints TOP = 100 and BOTTOM = 0.

Differential abundance of GH signaling proteins among tissues

The factors that influence tissue sensitivity to a hormone often reside at the level of the receptor. Accordingly, we assessed GHR abundance by immunoblotting with an antibody against the GHR intracellular domain, which revealed highest abundance in eWAT (2.05 A.U.), followed by liver (1.00 A.U.), heart (0.61 A.U.), kidney (0.29 A.U.), and gastrocnemius (0.28 A.U.) (Fig. 3A,E). This study utilized human GH, which can also induce STAT5 phosphorylation via the prolactin receptor (PRLR) [30–32]. We compared PRLR-expressing MIN6 cells to the relevant mouse tissues by immunoblotting with two distinct anti-PRLR sera (anti-PRLRcytAL-84 and anti-PRL-R (H-300); Fig. 4A,B, respectively). No bands in common were detected by these sera in the mouse tissues, but a common PRLR band was detected by both in the MIN6 positive control. Analysis of prlr mRNA levels validated the conclusion that little or no expression was detected in the mouse tissues tested (Fig. 5). Thus, analyses of GHR and PRLR abundance did not readily explain observed tissue-specific differences in GH sensitivity (although relatively high GHR expression in the liver may contribute to elevated GH sensitivity in this tissue).

In contrast to hormone sensitivity, the responsiveness of a tissue to a hormone is influenced by factors downstream of the receptor, including abundance of downstream signaling molecules. To this end, we assessed JAK2 and STAT5 abundance by immunoblotting. Relatively modest differences were observed in JAK2 abundance, with lowest levels in gastrocnemius and highest levels in kidney (Fig. 3B,F). STAT5 abundance did not differ between liver, gastrocnemius, and heart, but was significantly lower in eWAT and kidney (Fig. 3C,G). Regression analysis revealed a correlation (correlation coefficient: + 0.8296) between the STAT5 abundance in a tissue and its MAX response (P = 0.082) (Fig. 3D).

Table 2. Curve fit parameters: from fitting dose–response data from Fig. 1B to the Hill equation without constraints (free fit), and from Fig. 2 using fit constraints (constrained fit).

|          | Liver | Kidney | eWAT   | Heart | Gastroc |
|----------|-------|--------|--------|-------|---------|
| Free fit |       |        |        |       |         |
| EC50 (ng/gbw) | 10   | 14     | 1248   | 4901  | 1642    |
| MAX response (A.U.) | 104.3 | 1.8    | 53.6   | 296.1 | 615.2   |
| R²       | 0.6822 | 0.65   | 0.6343 | 0.6928 | 0.7379  |
| Constrained fit |       |        |        |       |         |
| EC50 (ng/gbw) | 11   | 14     | 46     | 63    | 82      |
| EC50 (ng/gbw) 95% CI | 7.7–16.9 | 9.2–20.9 | 30.9–67.1 | 47.0–83.9 | 65.0–103.5 |
| R²       | 0.7344 | 0.6744 | 0.6288 | 0.722 | 0.7241  |

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Discussion

The purpose of the current study was to define tissue-specific differences in GH sensitivity and MAX responsiveness to GH. Here, we report that the order of GH sensitivity was liver = kidney > eWAT = heart = gastrocnemius, while the order of GH MAX responsiveness was gastrocnemius > heart > liver > eWAT > kidney and roughly correlated with STAT5 protein abundance. Such observations lead to questions with regard to physiologic significance. While the MAX response predicted from the free curve fitting in gastrocnemius and heart was much greater than in the other tissues, the levels of GH required to attain that MAX stimulation are far
Beyond physiologic levels. However, despite the error in these predicted values being large, the fact that there was a near-significant correlation between STAT5 and MAX response supports the idea that these values are good estimates. The liver and kidney exhibit the highest level of GH sensitivity (relative to other tissues investigated), and the other three tissues were indistinguishable statistically. That this general relationship holds true regardless of whether constraints were used supports the idea that the liver and kidney respond to GH at much lower concentrations than eWAT, heart, and gastrocnemius.

Growth hormone plays a number of important roles in the liver, including generation of circulating IGF-1 (which acts in a negative feedback manner on GH secretion) and hepatic metabolism. In the latter case, GH effects generally oppose those of insulin; specifically, these effects suppress glycolysis in favor of fatty acid oxidation and promote glycogenolysis and in prolonged fasting conditions promote gluconeogenesis [1,33–36]. Thus, increased GH secretion during sleep likely plays an important role in maintenance of blood glucose levels via multiple mechanisms. Interestingly, the kidney is also a gluconeogenic tissue, contributing up to 50% of endogenous glucose production in the starved state [37]. GH signaling in the kidney is also important for normal sodium and water retention; GH deficiency leads to renal insufficiency, while excess leads to hypertension, renal hypertrophy, and failure [37].

Thus, our observation that the kidney is relatively GH-sensitive (similar to the liver) is consistent with essential GH actions in this tissue. GH signaling is also important in eWAT, as this endocrine factor shifts metabolism from glucose utilization toward lipolysis and fatty acid oxidation, thereby minimizing reliance on muscle protein catabolism during periods of fasting (such as the sleep period) [1,38–40]. In contrast, GH signaling in the adult heart must be closely regulated, thus preventing excessive growth (e.g., in acromegaly) and subsequent contractile dysfunction [41]. Similar to the heart, GH signaling in skeletal muscle mainly influences muscle size, but not contractile force [38,40,42]. Our observation that skeletal muscle has decreased responsiveness to circulating GH may be explained by the existence of mechano growth factor (MGF), an alternative splice variant of the igf-1 gene. MGF expression is increased in response to muscle stretch and exercise [43]. Even hypophysectomized mice retain the ability to upregulate MGF in response to exercise [43,44]. The low GH sensitivity of gastrocnemius muscle may suggest that skeletal muscle growth in an adult mouse, in response to exercise, for example, may be through GH-independent mechanisms.

Subsequent interrogation of known GH signaling components provided potential mechanistic insights with regard to tissue-specific differences in GH responsiveness/sensitivity. For example, STAT5 levels were consistent with high GH sensitivity. Our findings are consistent with those of Walker et al. [45], who reported that GHR mRNA in the rat kidney was roughly 33% that of liver. Additional studies are required to elucidate fully the mechanisms mediating tissue-specific differences in GH sensitivity/responsiveness.

The current study focused on a particular acute signaling response of various tissues to exogenously administered GH (namely STAT5 phosphorylation). This approach has benefits and drawbacks. Although we did not assess the long-term response to endogenous GH pulses, this approach allowed us to directly compare acute responses to GH in multiple tissues simultaneously. As STAT5 is a critical mediator of acute GH action, we were able to observe direct GH effects, rather than compensatory effects over longer periods. Nonetheless, we acknowledge that our studies do not discriminate between the STAT5A and STAT5B isoforms of STAT5. As different tissues may express varying ratios of these isoforms, our conclusions concerning maximum responsiveness based on STAT5 abundance should be interpreted with caution.

As noted above, GH stimulates glycogenolysis in liver and kidney during fasting [35,36]. The mice in this study were fasted for 6 h prior to GH treatment. Therefore, it is possible that we would have observed a different relationship among tissues of GH sensitivity in mice if food had not been withdrawn in the 6 h...
leading up to GH treatment. However, the period of fasting corresponded to the first 6 h of the rest phase, during which food consumption is generally reduced (relative fasting), compared to the active period [46]. Thus, the relative physiologic effects of the strict fast are likely limited. We are mindful, however, that GH sensitivity and MAX response were only assessed at one time of day in our study. Because the circadian clock may control both secretion and sensitivity to hormones [47], it is possible that relative tissue sensitivity to GH may vary depending on the time of day.

In summary, the current study reveals a correlation between STAT5 abundance and the MAX GH response in these tissues, while GH sensitivity is not correlated with GHR. Thus, an important determinant of MAX GH response appears to be STAT5 abundance, while the determinants of in vivo GH sensitivity are more complex. We speculate that in pathological states, GH action may be influenced by alterations in GH sensitivity and/or responsiveness, not solely by changes in circulating GH levels. Our data from wild-type mice will serve as a template for analyzing such changes in disease states.

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Author contributions

RDB, MEY, and SJF conceived and designed the project, analyzed and interpreted the data, and wrote the manuscript. RDB, RRB, and GRM acquired the data.

Conflict of interest

The authors declare no conflict of interest.

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