Decreased Hemojuvelin Protein Levels in Mask Mice Lacking Matriptase-2-Dependent Proteolytic Activity

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Summary
Matriptase-2, a membrane protein encoded by the Tmprss6 gene, is a negative regulator of hepcidin expression. Although matriptase-2 has been proposed to cleave membrane hemojuvelin, we have recently found decreased hemojuvelin protein levels in Tmprss6-/- mice. The purpose of this study was to confirm this observation by determining hemojuvelin protein levels in another strain of mice with disrupted Tmprss6 gene, and to determine the effect of matriptase-2 deficiency on the expression of other membrane proteins participating in the bone morphogenetic protein signal transduction. Mask mice, which lack the proteolytic domain of matriptase-2, displayed decreased liver hemojuvelin protein content, while Id1 mRNA level, an indicator of hemojuvelin-dependent signal transduction, was increased. Protein levels of bone morphogenetic protein receptors Alk3 and Acvr2a were unchanged, and transferrin receptor 2 and neogenin protein levels were slightly decreased. The results confirm that the loss of matriptase-2 increases bone morphogenetic protein-dependent signaling, while paradoxically decreasing liver hemojuvelin protein content. The regulation of transferrin receptor 2 protein levels by transferrin saturation was not affected in mask mice. How the loss of matriptase-2 proteolytic activity leads to decreased hemojuvelin protein levels is at present unclear.

Key words
Hepcidin • Id1 • Tmprss6 • Hfe2 • Transferrin receptor 2 • Neogenin

Introduction
Iron-deficiency anemia is the most common anemia worldwide. Although the overwhelming majority of iron-deficiency anemia cases are caused by chronic bleeding or inadequate dietary iron intake, a minor subgroup of iron-deficiency anemias is inherited in an autosomal recessive manner. Recently, it has been demonstrated that rare cases of iron-refractory iron deficiency anemia (IRIDA) are caused by mutations of the TMPRSS6 gene (Finberg et al. 2008).

The exact function of the TMPRSS6 gene is at present unknown. The gene encodes a serine protease, matriptase-2, which is expressed mainly at the hepatocyte plasma membrane. In vitro, matriptase-2 has been convincingly demonstrated to cleave hemojuvelin (Silvestri et al. 2008), another hepatocyte plasma membrane protein, which plays an essential role in the regulation of expression of hepcidin, the key iron-regulatory hormone. Hemojuvelin (Hjv) is a central component of the bone morphogenetic protein/hemojuvelin (Bmp/Hjv) signaling pathway, which upregulates hepcidin expression in response to increased iron stores (Babitt et al. 2006). In this pathway, hemojuvelin facilitates the binding of the Bmp6 protein (Andriopoulos et al. 2009, Meynard et al. 2009) to a set of bone morphogenetic protein receptors at the extracellular side of the hepatocyte plasma membrane, leading to intracellular receptor phosphorylation, phosphorylation of the Smad1/5/8 proteins and, ultimately, to transcriptional activation of hepcidin expression. By cleaving plasma membrane hemojuvelin, matriptase-2 is thus proposed to remove an important...
component of the Bmp/hemojuvelin pathway from the membrane, resulting in diminished hepcidin expression. In accordance with this concept, lack of matriptase-2, as in IRIDA patients, leads to inappropriate high expression of hepcidin (Finberg et al. 2008), which causes a decrease in iron absorption from the intestine.

At present, three well-characterised mouse models of matriptase-2 deficiency exist: mask mice on C57BL/6 background, which harbor an ethyl nitrosourea-induced mutation a splice acceptor site upstream of exon 15 of the Tmprss6 gene, resulting in the loss of the proteolytic domain of matriptase-2 (Du et al. 2008); Tmprss6-/- mice on a mixed background, in which the expression of matriptase-2 was compromised by duplication of exons 3 to 6 (Folgueras et al. 2008), and finally Tmprss6 mutant mice on a C57BL/6 background, obtained by deletion of a part of exon 17, again resulting in the loss of a part of the protease domain of matriptase-2 (Finberg et al. 2010). The phenotype of these strains is very similar, with truncal alopecia and iron-deficiency anemia as most prominent findings. All three strains display elevated expression of hepcidin, which is in accordance with enhanced signaling through the Bmp/Hjv pathway. Despite these similarities, there are also slight differences between the phenotypes of the mutant strains, particularly with respect to the survival of offspring (Folgueras et al. 2008, Finberg et al. 2010) or expression of the Bmp6 gene (Finberg et al. 2008, Nai et al. 2012).

When recently investigating Hjv protein levels in Tmprss6-/- (Folgueras et al. 2008) mice, we surprisingly found decreased, rather than increased, levels of hemojuvelin protein (Krijt et al. 2011). This observation suggests that, in vivo, the actual function of matriptase-2 in iron metabolism regulation could be more complex than simple cleavage of plasma membrane hemojuvelin. The purpose of the present investigation was to confirm this observation by examining hemojuvelin protein levels in mask mice, and to determine the effect of matriptase-2 deficiency on the expression of other proteins participating in the bone morphogenetic protein signal transduction.

Methods

Animal experiments were approved by the Ethics Committee of the First Faculty of Medicine in Prague.

Liver samples from male mask mice, aged three to four months (Du et al. 2008), were processed to obtain either whole tissue homogenate or crude membrane fraction. For whole tissue homogenates, liver samples were homogenised in 150 mM sodium chloride, pH 7.8, containing protease inhibitors (Roche) and 1 % of Triton X-100. Homogenate was centrifuged for 15 min at 12 000 g, and 60 µg of the supernatant protein was used for electrophoresis. Crude membrane fraction was obtained by homogenisation of liver samples in 250 mM sucrose, pH 7.5, containing protease inhibitors. After low-speed centrifugation at 6000 g for 15 min, the crude membrane fraction was isolated by ultracentrifugation of the homogenate at 80 000 g for 50 min. The pellet was resuspended in Tris-buffered saline, pH 7.5, and a 60 µg protein aliquot was used for electrophoresis on 12 % polyacrylamide gels. For neogenin determinations, 6 % polyacrylamide gel was utilized. A total of four pairs of C57BL/6 and mask mouse livers, originating from age-matched mice kept on a standard laboratory diet, were used for the experiments.

Immunoblotting was performed on an Invitrogen semi-dry blotter, PVDF membrane was blocked for one hour in 5 % milk in tris-buffered saline containing 0.1 % Tween 20, and incubated overnight with the primary antibody in 5 % milk. The primary antibodies were: Goat anti-Hjv, AF 3634, R&D Systems, 1:500; rabbit anti-transferrin receptor 2 (Tfr2), Alpha Diagnostics International, 1:1000; rabbit anti-Acrv1 (Alk2), #4398, Cell Signaling Technology, 1:250; rabbit anti-Acrv1 (Alk3), ab59947, Abcam, 1:1000; rabbit anti-Acrv2a (Acrv2a), sc-130679, Santa Cruz Biotechnology, 1:200, and rabbit anti-neogenin (Neo1), sc-15337, Santa Cruz Biotechnology, 1:500. Rabbit anti-pan-cadherin, #4068, Cell Signaling Technology, 1:24 000, and rabbit anti-Actr-IIa primary antibodies were from Jackson ImmunoResearch.

RNA was isolated from samples stored at –80 °C using Qiagen RNeasy Plus Mini Kit, and reverse transcribed by RevertAid First Strand cDNA synthesis kit (Thermo Scientific). Real-time PCR was performed on a Roche Light Cycler instrument as previously described (Krijt et al. 2011), target mRNA content is expressed relative to β-actin (Actb) mRNA. Primer sequences were (forward and reverse): Actb GAC ATG GAG AAG ATC TGG CA and GGT CTT TAC GGA TGT CAA CG, Acrv1 AGG TTT ATG AGC AGG GGA AGA and CTG AGA GCA ACT CCA AGG ATG, Bmpr1l TCG AGA CCT GAA GAG CAA AAA and GAT GTA GGG CTG.
Results

Hjv protein is decreased in mask mice

As previously reported (Krijt et al. 2011), the R&D AF3634 antibody detects, under reducing conditions, two Hjv-specific bands in vivo – a major band at approximately 35 kDa, and a minor band at approximately 18 kDa. Comparison of whole liver homogenates from mask mice and their wild-type littermates showed significant downregulation of the major 35 kDa band (Fig. 1A); the minor band was barely visible. When the same samples were run under non-reducing conditions, only one band at approximately 50 kDa, probably representing a disulfide bridge-bound Hjv heterodimer (Zhang et al. 2005), was apparent. The intensity of this band was decreased in mask mice (Fig. 1B).

To enhance the visualisation of the 35 kDa band, crude liver membrane fraction was prepared by ultracentrifugation. Hjv signal from the crude membrane fraction was stronger as compared to the whole homogenate; the intensity of both the 35 and 18 kDa bands (Fig. 1C, reducing conditions), as well as the single 50 kDa band (Fig. 1D, non-reducing conditions), reproducibly decreased in mask mice. These results confirm that the disruption of Tmprss6 gene significantly decreases hemojuvelin protein content.

Matriptase-2 does not decrease membrane Tfr2, Alk3, Acvr2a and neogenin protein content

Since matriptase-2 is a hepatocyte membrane protein, it was of interest to determine whether disruption of the Tmprss6 gene will affect the content of other membrane proteins participating in iron homeostasis. Of these, transferrin receptor 2 (Tfr2) is of particular interest, since it is also selectively expressed in the hepatocyte (Fleming et al. 2000), and therefore represents a potential target for matriptase-2 activity. As can be seen in Figure 3A, the levels of transferrin receptor 2 slightly decreased in mask mice, as compared to wild-type littersmates. To confirm that the antibody indeed allows reliable detection of Tfr2 protein, we determined Tfr2 protein levels in two female C57BL/6 mice fed an iron-deficient diet (Altromin C 1038, iron content 10 mg/kg) for three weeks since weaning, as well as in two three months old female C57BL/6 mice treated with a single intraperitoneal dose of iron dextran (200 mg iron/kg). In addition, we also determined Tfr2 protein in two male Hjv-/- mice. In all cases, Tfr2 protein levels reacted to the changes in body iron levels (Fig. 2), which is in accordance with published data (Johnson and Enns 2004).
detected protein bands corresponding to Alk3 and Acvr2a. The expression of these proteins was not significantly changed in mask mice (Fig. 3A). The Alk2 antibody produced only very weak bands at the expected band size of 60 kDa, although, as stated by the manufacturer, it showed strong bands of unknown origin at 95 kDa (Fig. 3A).

Several groups have reported that iron metabolism is influenced by neogenin (Zhang et al. 2005, Lee et al. 2010). In liver crude membrane preparations from mask mice, we detected slightly decreased membrane neogenin protein levels (Fig. 3A). Overall, these results suggest that Alk3, Acvr2a and neogenin are not physiological substrates of matriptase-2.

The decrease in Hjv protein occurs posttranscriptionally

To verify that the observed changes in Hjv protein occur posttranscriptionally, levels of Hfe2 mRNA, coding the Hjv protein, were determined by real-time PCR. Hfe2 mRNA content was unchanged in mask mice (Fig. 3A). In addition, no changes were observed in Acvr1, Bmpr1a and Neo1 mRNA, encoding the Alk2, Alk3 and neogenin proteins (results not shown).

Id1 mRNA levels in mask mice confirm upregulation of Bmp-dependent signal transduction, despite decreased Hjv protein levels

Liver Id1 mRNA levels are often used to monitor Bmp6-dependent signaling. In iron-deficient C57BL mice, liver Id1 mRNA levels are decreased in comparison with control mice (Kautz et al. 2008).

Despite low liver iron levels (Du et al. 2008) and low liver Hjv protein (Fig. 1), liver Id1 mRNA levels were increased in mask mice (Fig. 3B). These results are in accordance with data previously reported for other mice with disrupted Tmprss6 gene (Finberg et al. 2010, Nai et al. 2012), confirming the positive effect of Tmprss6 gene disruption on the activity of the Bmp6/Hjv pathway.

Discussion

During the past decade, the iron regulatory hormone hepcidin has emerged as the key factor which
controls iron metabolism in mammals (Andrews 2008, Ganz 2011). Consequently, the signaling pathways which regulate hepcidin expression in the hepatocyte represent a subject of intensive research. Hepcidin expression is influenced by several proteins present at the hepatocyte plasma membrane: Hemojuvelin, Tfr2, the Hfe protein and neogenin (Lee et al. 2010). Disruption of any of these proteins leads to decreased hepcidin expression and iron overload. Recently, another hepatocyte membrane protein, the serine protease matriptase-2, has been identified as the only known negative regulator of hepcidin expression. Mutations in the Tmprss6 gene cause inappropriately high expression of hepcidin, resulting in IRIDA (Finberg et al. 2008). The currently accepted model of matriptase-2 function proposes that matriptase-2 cleaves hemojuvelin (Silvestri et al. 2008), a GPI-bound protein which serves as a coreceptor for the Bmp6 molecule. However, in vivo evidence for this mode of action of matriptase-2 is still lacking. Moreover, the possible discrepancy between the in vivo and in vitro effects of Tmprss6--/-- mutations has also recently been highlighted by the observation that, in vitro, hepcidin expression is repressed even by those Tmprss6--/- mutant constructs which lack protease activity (Guillen et al. 2012). Therefore, it is still of importance to determine the effect of in vivo loss of matriptase-2 proteolytic activity on proteins participating in the regulation of hepcidin expression.

The Bmp6/hemojuvelin signaling pathway, which controls hepcidin expression in response to iron levels, has to a significant extent been elucidated. Iron overload transcriptionally increases the synthesis of Bmp6, which then binds at the extracellular side of the hepatocyte plasma membrane to a set of bone morphogenetic protein receptors. The bone morphogenetic proteins responsible for Bmp6 binding have recently been identified as Alk2 and Alk3 (Steinbicker et al. 2011), both type 1 Bmp receptors. Type 1 Bmp receptors dimerize with type 2 receptors, of which Acvr2a is abundantly expressed in human liver (Xia et al. 2008). Theoretically, all these proteins – Hvj, Alk2, Alk3, the type 2 Bmp receptors, as well as matriptase-2 – should interact at the hepatocyte plasma membrane in order to regulate hepcidin expression. Intriguingly, Hvj protein level was significantly decreased in mask mice. In this respect, the presented results confirm our data previously obtained in another mouse model with Tmprss6 gene disruption (Krijt et al. 2011). Although the results from both studies do not directly support hemojuvelin cleavage by matriptase-2, they nevertheless apparently confirm a specific interaction between matriptase-2 and hemojuvelin.

Immunoblotting of liver crude membrane fraction from mask mice has demonstrated a slight decrease in Tfr2 and neogenin protein levels. Tfr2 is known to positively modulate hepcidin expression (Nemeth et al. 2005), but the exact mode of its signal transduction, as well as its possible participation in the Bmp6/hemojuvelin pathway, has not yet been fully elucidated (Chen and Enns 2012, D’Alessio et al. 2012). Tfr2 protein levels are known to respond to plasma iron concentration (Johnson and Enns 2004). Since mask mice are known to display low liver iron levels and plasma iron levels (Du et al. 2008), it is plausible that the observed decrease in Tfr2 protein is caused by iron deficiency, rather than by an interaction between matriptase-2 and Tfr2. This conclusion is in accordance with the recently published finding that Tfr2 is not a substrate for matriptase-2 (Lee et al. 2012).

Neogenin is a ubiquitously expressed protein, which has been demonstrated to interact with hemojuvelin (Zhang et al. 2005). Disruption of the Neol gene in mice has been reported to diminish Bmp-dependent signaling and to decrease hepcidin expression, resulting in massive iron overload (Lee et al. 2010). Therefore, matriptase-2 could theoretically exert its effect on iron metabolism by cleaving membrane neogenin. However, as can be seen in Figure 3, liver membrane neogenin protein content was actually slightly decreased in mask mice, confirming the recently published observation that neogenin is not cleaved by matriptase-2 (Enns et al. 2012).

Levels of Id1 mRNA were increased in mask mice. Id1 is a sensitive indicator of Bmp6-dependent signaling (Kautz et al. 2008), and the observed increase in Id1 mRNA thus confirms the concept that matriptase-2 blocks Bmp6/hemojuvelin-dependent signaling (Silvestri et al. 2008). How this interference with the Bmp6/Hvj pathway would decrease total Hvj protein levels is at present unclear. Lack of matriptase-2 proteolytic activity could significantly change the ratio of hemojuvelin to other components of the Bmp6/hemojuvelin pathway, and this imbalance could then affect hemojuvelin protein levels as a compensatory mechanism. It is also possible that matriptase-2 selectively influences the ratio of the various hemojuvelin forms (Maxson et al. 2009) present at the membrane. As matriptase-2 represents the most recently identified component participating in the complex regulation of hepcidin gene expression, it is
obvious that more research will be necessary to define its exact function in vivo.

In conclusion, the presented study confirmed decreased expression of hemojuvelin in mice with a mutation in matriptase-2 gene, while the overall activity of the Bmp6/Hjv pathway, as determined by the Id1 gene expression, was increased. The regulation of Tfr2 protein levels by iron was apparently unaffected. The obtained results confirm the inhibitory effect of matriptase-2 on the Bmp6/hemojuvelin dependent signaling pathway, and suggest a complex relationship between matriptase-2 expression and hemojuvelin protein levels.

**Conflict of Interest**

There is no conflict of interest.

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