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Ultrastructural Localization of Histidine-rich Glycoprotein in Skeletal Muscle Fibers: Colocalization With AMP Deaminase

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Summary

Histidine-rich glycoprotein (HRG) is a plasma protein synthesized by the liver. We have given the first evidence of a tissue localization of HRG demonstrating its presence in skeletal muscle, associated with the zinc enzyme AMP deaminase (AMPD1). Moreover, we have shown that muscle cells do not synthesize HRG, but they can internalize it from plasma. We have recently demonstrated by confocal laser scanning microscopy that in human skeletal muscle, HRG is mainly localized in the myofibrils, preferentially at the I-band of the sarcomere, in the sarcoplasm, and in the nuclei. Using transmission electron microscopy and immunogold analysis, we carried out this study on human and rat normal skeletal muscles with the purpose to deepen the ultrastructural localization of HRG in skeletal muscle fibers. The immunogold analysis evidenced the presence of HRG in the sarcomeres, mainly in the I-band and to a less extent in the A-band, in the heterochromatin of nuclei, and in the sarcoplasmic reticulum. The colocalization of HRG and skeletal muscle AMPD1 was also analyzed. A colabeling of HRG and AMPD1 was evident at sarcomeric, sarcoplasmic reticulum, and nuclear levels. The significance of these interesting and new results is discussed in this article. (J Histochem Cytochem 68:139–148, 2020)

Keywords

AMP deaminase, immunohistochemistry, metallochaperone, muscle biopsies, nucleus, sarcomere

Introduction

Histidine-rich glycoprotein (HRG) is a single-chain, 75-kDa plasma protein synthesized by parenchymal liver cells.[1] Plasma is the major pool of HRG (100–150 µg/ml), although it is also found in colostrum, milk, and infant urine, as well as in megakaryocytes, platelet α-granules, and immune cells.[2–4] HRG has a multidomain structure consisting of three distinct parts: the N-terminal region, which contains two cystatin-like N-terminal domains (N1 and N2); the central part, which contains a unique histidine/proline-rich domain; and the C-terminal domain.[5] The most salient feature of the protein is its unusually high content of both histidine and proline residues. Moreover, it contains approximately 14% carbohydrate attached to six N-linked glycosylation sites.[1] The multidomain structure of HRG and its ability to bind to a wide range of ligands (e.g. divalent metal cations, heparin, heparan sulfate, plasminogen, fibrinogen, IgG, complement),[6–10]

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as well as different cell surface receptors such as FcγR, heparan sulfate, and tropomyosin,[11,12] suggest a multivalent function of the protein. Indeed, the data from the literature clearly demonstrate the involvement of HRG in the modulation of a number of important biological processes such as blood coagulation, complement activation, immunocomplex clearance, angiogenesis, cell adhesion and migration, and phagocytosis of apoptotic cells.[13]

We discovered an HRG protein in rabbit skeletal muscle[14] while we were carrying out studies on AMP deaminase (AMPD1), a zinc enzyme that catalyzes the hydrolytic deamination of AMP to IMP and ammonia.[15] Moreover, we found that muscle HRG was associated with AMPD1 and was critical in assuring both the molecular integrity and the activity of the enzyme. Like the plasma protein, muscle HRG could also bind to zinc.[16] The existence of a specific zinc-binding site in muscle HRG has been later confirmed by X-ray absorption spectroscopy analysis,[17] permitting to envisage the addition of this protein into the family of metallochaperones-soluble proteins that function as intracellular shuttles for metal ions: They acquire the metal ion and deliver it to specific partner proteins.[18] In this view, HRG could enhance the in vivo stability of metalloenzymes such as AMPD1.[17]

We also detected HRG in human skeletal muscle, where it was mainly localized in type IIB fibers that contain higher level of AMPD1 compared with type I and IIA fibers.[19] Moreover, a positive correlation between the muscle content of HRG and the level of AMPD1 activity has been shown by an immunohistochemical study on skeletal muscle of patients affected by AMPD1 deficiency.[20] Interestingly, we have demonstrated by an in vitro study on rhabdomyosarcoma cell line that muscle HRG is not synthesized by muscle cells, but they can internalize it.[21] Therefore, we have given evidence, for the first time, that plasma HRG can be carried to skeletal muscle, and probably also to other tissues, via circulation. Our finding has been later confirmed by Tugues et al.[22] through in vivo experiments performed with radiolabeled HRG. They showed that after intravenous injection, HRG was internalized quickly in healthy tissues, including muscle, and in tumors. The HRG cellular localization has been recently investigated by our group in normal human skeletal muscle by the use of optical and confocal microscopy.[23] We observed a diffuse, uniform immunoreactivity for HRG in the connective tissue among the muscle fibers and, in muscle fibers, a preferential distribution of the protein in the sarcomere, mainly in the I-band. An HRG positivity was also evidenced in the nuclei.

The aim of this study was to deepen the subcellular localization of HRG in skeletal muscle fiber. For this purpose, the ultrastructural distribution of HRG was studied by transmission electron microscopy (TEM) immunogold analysis using human and rat skeletal muscles. The TEM analysis allowed us to better understand the relationship between HRG and the cellular compartments such as nuclear chromatin, organelles, sarcoplasmic reticulum (SR), and sarcoplasm. In addition, the HRG distribution was also compared with that of AMPD1.

Materials and Methods

Antibodies and Reagents

Rabbit anti-human HRG polyclonal antibody (HRG-462) raised against the C-terminal region (residues 462–471) of plasma HRG and rabbit anti-human AMPD1 polyclonal antibody were produced in-house as previously described.[19,20] Rabbit anti-rat HRG polyclonal antibody was purchased from Cloud-Clone Corp (Katy, TX). Goat anti-rabbit 10 nm and 20 nm gold-conjugated antibodies were purchased from Ted Pella Inc. (Redding, CA) and British Biocell International (Cardiff, UK), respectively. All other reagents were of analytical grade and were purchased from Sigma-Aldrich and Fluka (Buchs, Switzerland).

Human Sample Collection

Three human muscle biopsies, one from gastrocnemius (male, patient age = 28 years) and two from quadriceps femoris (females, patient age = 69 and 78 years), were selected from the archives of Division of Pathology, Department of Surgical, Medical, Molecular Pathology and Critical Care, University of Pisa because they were healthy controls obtained from surgery for fracture resolution. Each was preserved both by freezing and by Epon/Durcupan embedding method. Serial sections of 8 μm were cut from frozen biopsies and processed for routine histological and histochemical stains, that is, hematoxylin and eosin, succinate dehydrogenase activity, NADH tetrazolium reductase, routine ATPase (pH 9.4), and ATPase preincubated at pH 4.3 and 4.6.[24] Semi- and ultrathin sections were cut from Epon/Durcupan-embedded biopsies for TEM analysis.[25]

Rat Sample Collection

Muscle biopsies from biceps femoris were taken from two male Wistar rats and embedded both in paraffin for routine hematoxylin and eosin staining and in Poly/Bed 812 for TEM analysis. In particular, after removal, rat samples were immediately trimmed into small

blocks (1 mm^3) and fixed in 1% (w/v) glutaraldehyde–4% (w/v) formaldehyde (freshly obtained from paraformaldehyde) in phosphate-buffered saline (PBS; 0.1 M, pH 7.2) for 4 hr at 4C, and after washing in the same buffer, the specimens were postfixed in 1% (w/v) OsO_4/PBS for 2 hr. Samples were also fixed in 4% paraformaldehyde/PBS for 4 hr at 4C omitting the postfixation step in 1% (w/v) OsO_4/PBS. All samples were then washed in distilled water and dehydrated with a graded series of ethanol before transferring the specimens to propylene oxide for 6 min. Finally, Poly/Bed 812 embedding in flat mold at 60C for 48 hr was carried out, and semi- and ultrathin sections were cut for TEM analysis.

A rat liver sample was submitted to the procedure described above and used as tissue positive control.

TEM and Immunogold Analysis

To assess the specimen quality and orientation, a number of semi-thin sections were stained with toluidine blue and observed by light microscopy. Ultrathin sections (60- to 80-nm thick) were obtained with a diamond knife, placed on 200-mesh formvar/carbon-coated nickel grids and allowed to dry. Some sections were counterstained with uranyl acetate and lead citrate and observed with a Jeol JEM-100SX transmission electron microscope (Jeol; Tokyo, Japan) at 80 kV to assess their quality.

For the immunogold analysis, all the steps were performed at room temperature using the basic buffer solution (BBS) containing 0.4 M NaCl in PBS (pH 7.2) to avoid nonspecific antibody binding. The grids with the sections face down were placed on a droplet of saturated aqueous $NaIO_4$ solution. After five washes in BBS, the sections were treated with 0.5 M NH_4Cl, transferred onto a droplet of 10% BSA–BBS, and then incubated overnight at 4C in a moistened chamber with anti-human (HRG-462 1:3000) or anti-rat HRG (1:50) polyclonal antibodies in 1% BSA–BBS. The sections were then washed with 1% BSA–BBS and incubated with the gold-conjugated secondary antibody (10 or 20 nm gold particles for rat and human HRG detection, respectively) diluted 1:30 in 5% FBS, 0.1% BSA, and 0.05% Tween 20 in BBS. Grids were jet-washed with BBS and fixed in 1% glutaraldehyde for 3 min. Sections were finally jet-washed in distilled water and counterstained with uranyl acetate and lead citrate.[25,26]

For the double immunogold staining performed in human samples, before fixing the samples in 1% glutaraldehyde, an additional incubation with anti-AMPD1 primary antibody (overnight at 4C), followed by an incubation with 10 nm gold-conjugated secondary antibody diluted 1:30, was performed. Negative controls for secondary antibodies were performed omitting primary antibodies and incubating the specimens with non-immune serum.

To better understand the HRG distribution at the sarcomeric level, a semiquantitative analysis was performed in human samples. Specifically, counting of immunogold particles (20 nm) placed inside the sarcomeres was carried out by transmission electron microscopy at 15,000× magnification. This magnification corresponds to the minimal magnification at which gold particles and sarcomeres can be detected concomitantly. Grid squares containing labeled sarcomeres were chosen randomly for the count as random selection makes the quality of the scanning independent from the intensity of gold labeling. In these squares, only longitudinal sections of sarcomeres were used to display their real sizes. In particular, starting at a grid square corner, the entire sarcomere within that grid square was scanned. In each sarcomere, the number of gold particles was counted, and we expressed the mean value of immunogold particles for I-band (MV_I) or A-band (MV_A) out of the 20 sarcomeres counted. The related density values (δMV_I and δMV_A), corresponding to the mean number of gold particles/μm^2, were worked out.

Statistics. The density values were obtained in 20 sarcomeres/grid; the total number of grids was 30 (10 grids per each human biopsy), which were collected from three separate experiments. Data are reported as $\delta MV \pm SD$. Inferential statistics to compare groups were carried out using Student's *t*-test (null hypothesis was rejected for $p \leq 0.05$).

Results

The human skeletal muscle biopsies used for the experiments showed no histological or histochemical abnormalities. Indeed, on the examination by optical microscopy, the histochemical stains, commonly used for the assessment of pathological samples, evidenced profiles of normal muscle in all the three biopsies. Moreover, the muscle fibers appeared highly contracted in all samples.

The rat specimens also showed no histological abnormalities on examination by optical microscopy. Although the anti-human HRG antibody specificity was already demonstrated,[19] the specificity of the anti-rat HRG antibody was ascertained in this work by immunofluorescence microscopy. In particular, the immunoreactivity of rat skeletal muscle fibers was comparable to the pattern obtained on human skeletal muscle by the anti-human HRG antibody (data not shown).

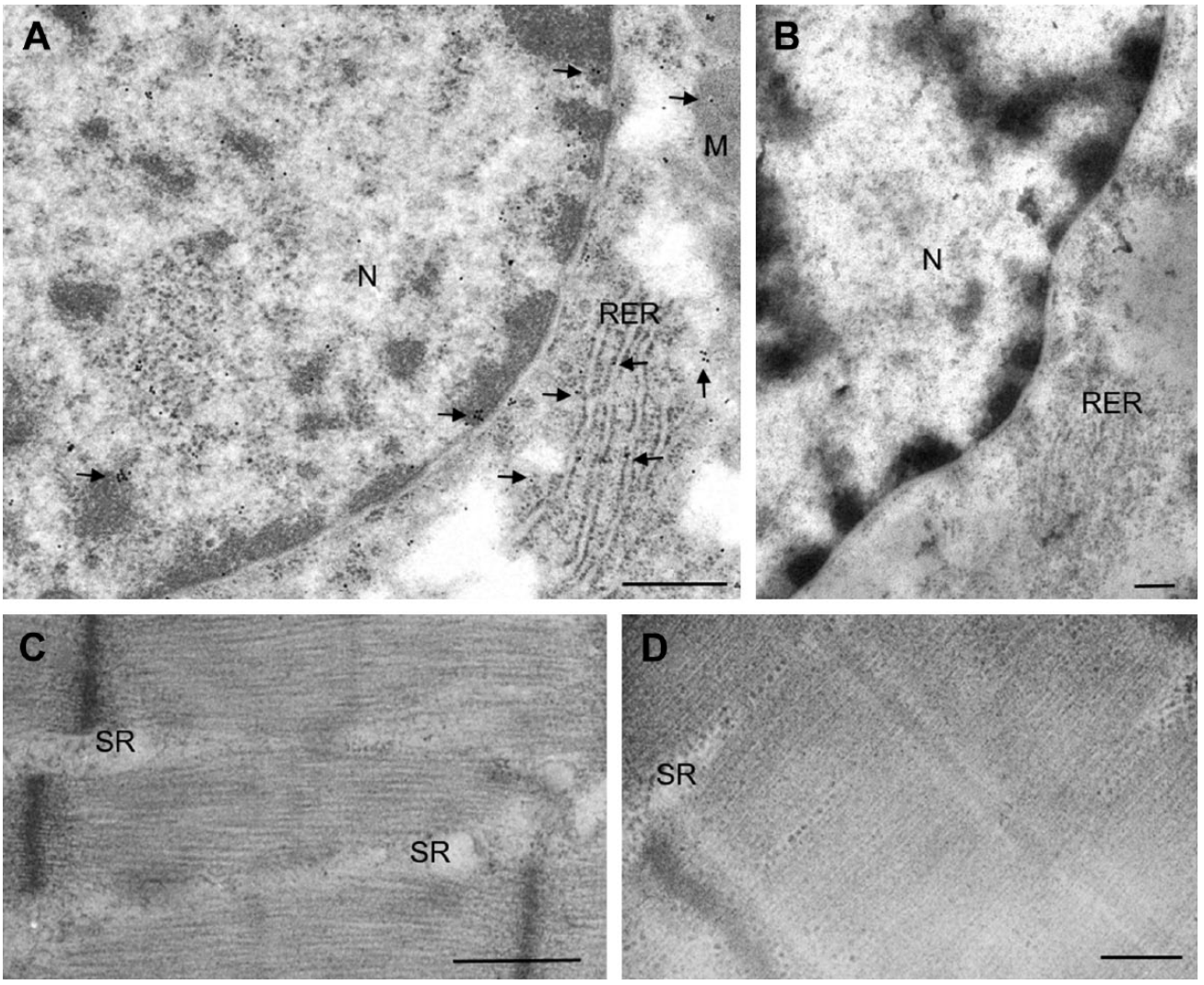

Figure 1. Controls for TEM immunogold analysis. (A) Tissue positive control: representative image of rat hepatocyte showing HRG immunopositivity at the level of rough endoplasmic reticulum, mitochondrion, and nucleus. (B–D) Negative controls: rat liver (B), rat skeletal muscle (C), and human skeletal muscle (D) did not show any immunoreaction. Scale bars: panels A and C = 500 nm, panel B = 200 nm, panel D = 520 nm. Abbreviations: TEM, transmission electron microscopy; HRG, Histidine-rich glycoprotein; M, mitochondrion; N, nucleus; RER, rough endoplasmic reticulum; SR, sarcoplasmic reticulum.

For TEM immunogold analysis, positive and negative controls were run on rat and human samples. Rat liver, used as tissue positive control, showed a strong positive reaction at the level of both rough endoplasmic reticulum and nucleus, mainly at the heterochromatin level (Fig. 1A). Rare immunogold particles could be detected in the mitochondria. Negative controls, obtained omitting primary antibodies, showed no immunoreaction (Fig. 1B–D).

HRG Immunogold Analysis

TEM analysis of the three human skeletal muscle biopsies confirmed that muscle fibers were highly contracted as demonstrated by the narrow I-bands (Fig. 2A).

The results of the immunogold analysis were comparable in the three biopsies. In particular, they evidenced the presence of HRG in the nuclei, in the SR, and in the myofibrils (Fig. 2B–D). Only rare, occasional immunogold particles could be detected in the mitochondria, whereas no immunoreaction could be localizable in the rough endoplasmic reticulum and in the Golgi apparatus. However, the majority of the protein was found within the myofibrils and in the nuclei. In particular, at the sarcomeric level, HRG was mainly concentrated in the I-band, although gold particles were also detectable in the actin-containing portions of

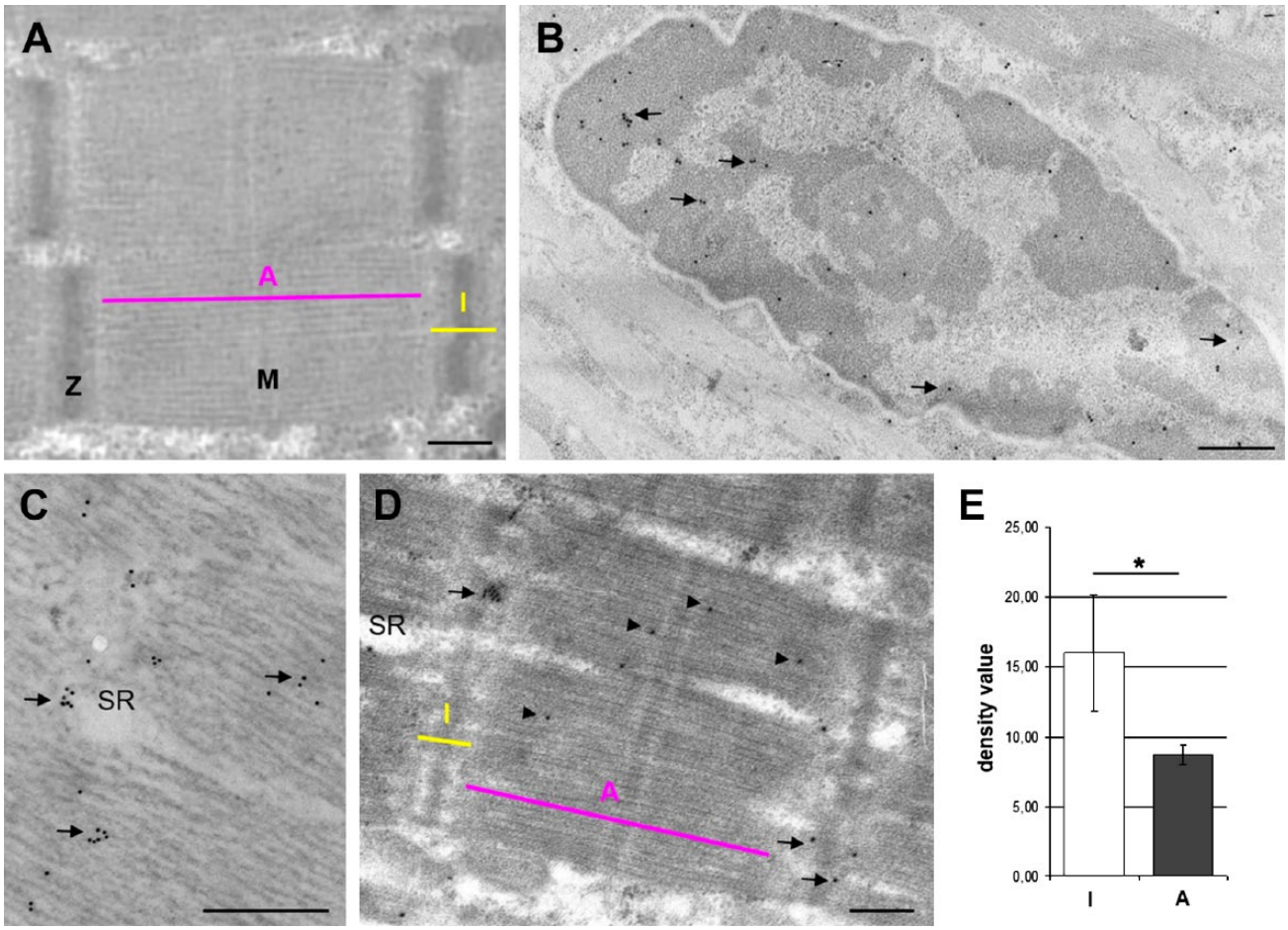

Figure 2. TEM immunogold analysis of human skeletal muscle. Pink A and yellow I capital letters indicate the A-band and I-band, respectively. (A) Representative image of a section counterstained with uranyl acetate and lead citrate. The sarcomeres are highly contracted (see the narrow I-bands). (B) Representative image of a nucleus of a muscle fiber showing a clear immunopositivity for HRG (arrows). Gold particles localize almost exclusively in the heterochromatin. (C) Representative image of HRG immunopositivity (arrows) in SR and sarcomeres. (D) Representative image of HRG immunopositivity in sarcomeres. Gold particles (20 nm) are mainly localized at the I-band (arrows) and, to a less extent, in the A-band (arrowheads). (E) Density values of gold particles (mean number of gold particles/μm^2) in the sarcomeric I-band (δMV_I) and A-band (δMV_A). Error bars represent the standard deviation. The difference is statistically significant (*$p<0.05$). Scale bars: panels A, C, and D = 500 nm, panel B = 600 nm. Abbreviations: TEM, transmission electron microscopy; HRG, Histidine-rich glycoprotein; M, M-line; Z, Z-line; SR, sarcoplasmic reticulum.

the A-band (Fig. 2D). The semiquantitative analysis confirmed this result as the density of the gold particles was significantly higher in the I-band than in the A-band (16.03 ± 4.16 and 6.7 ± 0.7, respectively; p=0.0198) (Fig. 2E).

A clear positive staining for HRG could also be evidenced in the nuclei where it localized almost exclusively in the heterochromatin (Fig. 2B). The HRG nuclear localization in the heterochromatin could suggest a nonspecific immunoreaction. In fact, as reported in the literature,[27] the fixation with glutaraldehyde and OsO_4 could ruin the antigens; therefore, a nuclear background by immunogold particles over heterochromatin in osmicated muscle tissue could be observed. To rule out this event, further immunogold experiments were carried out using either 1% glutaraldehyde and postfixing in 1% OsO_4 solution or 4% paraformaldehyde omitting the postfixation step in 1% OsO_4 solution. Due to the difficulty in the availability of human samples, rat skeletal muscle was used for this purpose. Interestingly, we found the signal in the osmicated sections to be similar to that in the non-osmicated sections (Fig. 3A and B). In particular, in all the rat specimens tested, the immunogold analysis evidenced the presence of HRG gold particles at the nuclear level, confirming the pattern obtained in human samples, where the signal was localized mainly in the heterochromatin. Furthermore, in rat muscle fibers, the immunogold

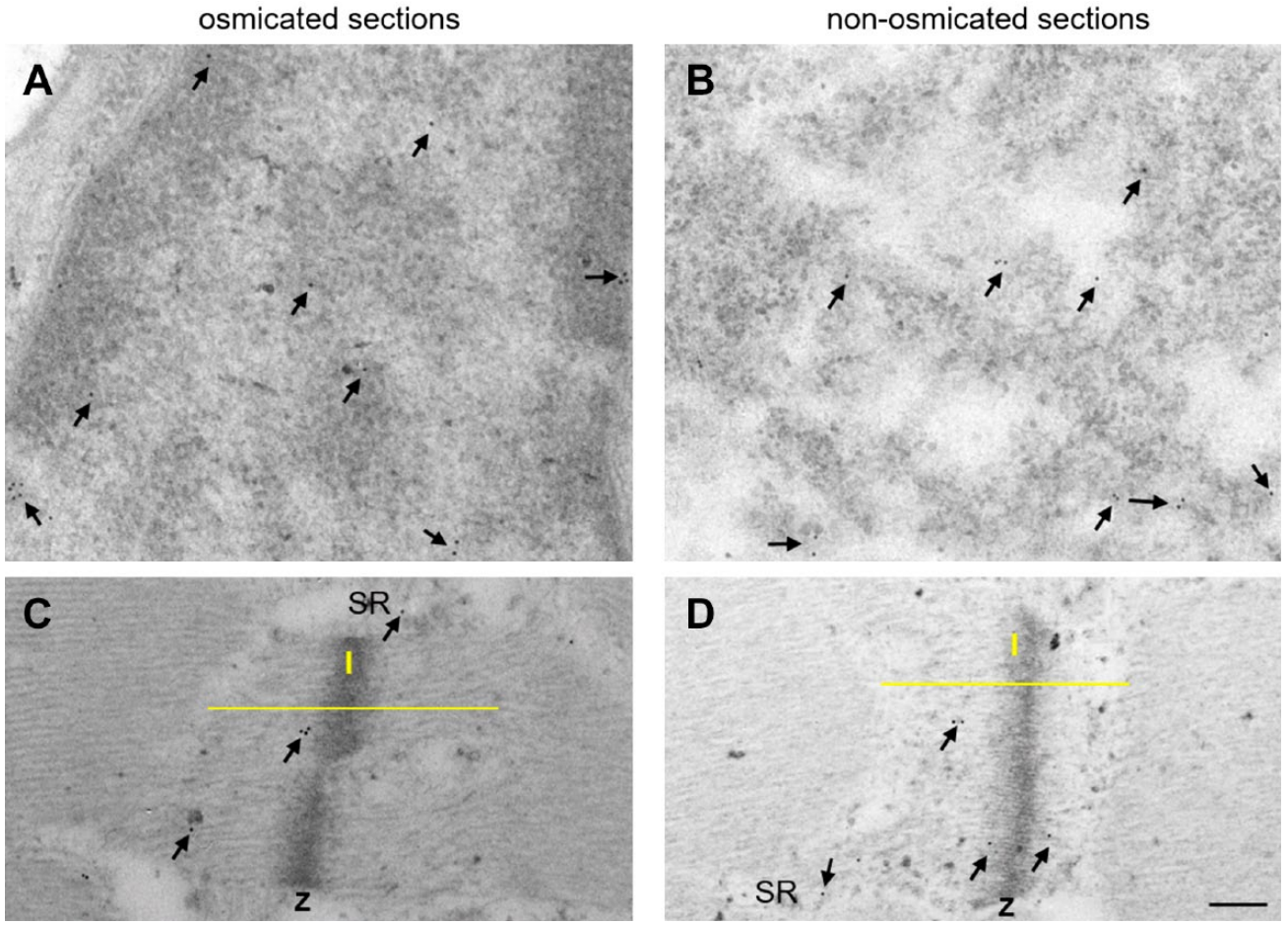

Figure 3. TEM immunogold analysis of rat skeletal muscle. Comparison of sections processed with and without the postfixation step in 1% OsO_4 solution and incubated with anti-rat HRG antibody: the signal in the osmicated samples was similar to that observed in the non-osmicated sections. (A and B) Representative images of the nuclear positivity (arrows) obtained in osmicated (A) and in non-osmicated sections (B): in both samples, the immunogold particles (10 nm, arrows) were localized almost exclusively in the heterochromatin. (C and D) Representative images of the sarcomeric positivity (arrows) obtained in osmicated (C) and in non-osmicated sections (D): in both samples, HRG was concentrated above all in the I-band. Gold particles were also detectable in SR. Scale bars: panels A–D = 200 nm. Abbreviations: TEM, transmission electron microscopy; HRG, Histidine-rich glycoprotein; I, I-band; SR, sarcoplasmic reticulum; Z, Z-line.

particles were dispersed both in the intermyofibrillar spaces and within the myofibrils. In particular, HRG was concentrated mostly at the sarcomeric level and above all in the I-band (Fig. 3C and D), corroborating the observations made on human samples.

HRG and AMPD1 Double Immunogold Analysis

The colocalization of HRG and AMPD1 was analyzed on human skeletal muscle. A colabeling of HRG and AMPD1 was evidenced in the SR, in the myofibrils (Fig. 4A), and in the nuclei (Fig. 4B). The percentage of HRG/AMPD1 colocalization was calculated with respect to the total number of HRG gold particles. Three grids per each skeletal muscle biopsy were analyzed, and 20 sarcomers/grid were observed. The average colocalization in the SR and in the sarcomere was 43% ± 24 and 44% ± 25, respectively. At the nuclear level, the colabeling of HRG and AMPD1 was found almost exclusively in the heterochromatin (7 ± 1%).

To exclude an AMPD1 nonspecific signal, possibly due to the use of two primary antibodies obtained from rabbit, additional immunogold experiments were performed using only the AMPD1 antibody. These experiments confirmed the pattern of positivity obtained with the double immunogold analysis (Fig. 4C and D).

Discussion

HRG is known to be a plasma protein that is synthesized by the liver.[1] We have previously demonstrated its presence in skeletal muscle, bound to the AMPD1

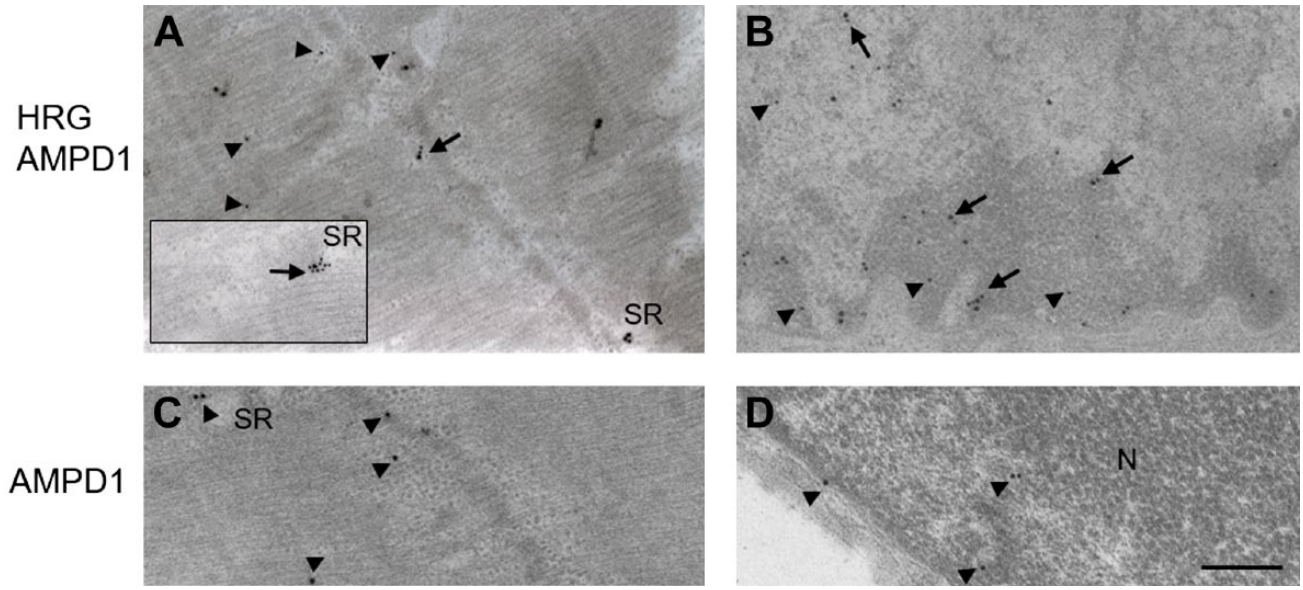

Figure 4. TEM immunogold analysis of HRG and AMPD1 in human skeletal muscle. (A and B) HRG–AMPD1 double immunogold: As pointed out by the arrows, HRG (20 nm gold particles) and AMPD1 (10 nm gold particles) colocalize in the sarcomere (A), in the SR (square in A), and in the heterochromatin of the muscle fiber nuclei (B). Arrowheads point to AMPD1 immunopositivity. (C and D) Representative image of AMPD1 immunopositivity (arrowheads): gold particles (10 nm) are localized in the sarcomere, in the SR, and in the heterochromatin of the muscle fiber nucleus (N). Scale bars: panel A = 600 nm, panels B and D = 150 nm, panels C = 300 nm. Abbreviations: TEM, transmission electron microscopy; AMPD1, AMP deaminase; HRG, histidine-rich glycoprotein; SR, sarcoplasmic reticulum; N, nucleus.

enzyme, giving the first evidence of a tissue localization of the protein.[14] Moreover, we have shown that muscle cells do not synthesize HRG, but they can internalize it from plasma.[21] We have recently analyzed the localization of HRG in muscle fibers by confocal microscopy, evidencing the protein in sarcoplasm, nuclei, and mainly in myofibrils.[23] This microscopic technique allowed us to demonstrate that HRG is mainly concentrated in the I-band of the sarcomere; however, it was not sufficient to understand a more specific ultrastructural localization of the protein. The main purpose of the present immunohistochemical study was to deepen the ultrastructural localization of HRG in skeletal muscle fibers. The results obtained on human samples by TEM immunogold analysis evidenced the presence of HRG mainly in the heterochromatin of nuclei, in the SR, and in the sarcomere. In particular, at the sarcomeric level, HRG was mainly concentrated in the I-band, although the gold particles were also detectable in the A-band. These results confirm those previously obtained with confocal laser microscopy by Mattii et al.[23] regarding the HRG localization in the I-band and also reveal that HRG has a wider distribution in the sarcomere. In fact, at the ultrastructural level, HRG was detectable not only in the I-band but also in the actin-containing portions of the A-band. Concerning the possible role of HRG in the sarcomere, we have already demonstrated its involvement, as zinc metallochaperone, in the regulation of AMPD1. HRG could enhance the stability of AMPD1 in vivo through insertion of zinc or by modulating the intracellular zinc availability.[16,17] As a matter of fact, an immunohistochemical study performed on human skeletal muscle biopsies from patients with primary and acquired AMPD deficiency has evidenced a positive correlation between the determined residual AMPD activity and the HRG abundance in the muscle specimens. The lower HRG polypeptide abundance observed in primary AMPD deficiency, which cannot be due to any pathological change except the AMPD1-deficient background, suggests that there is a mutual dependence between skeletal muscle HRG and AMPD1 regarding their stability.[20] A similar role for HRG could also be speculated for other sarcomeric proteins that have zinc-binding sites such as troponin T.[28]

Concerning the HRG presence at the level of SR vesicles, the data from the literature highlighting the zinc involvement in intracellular signaling[29] support a role for the HRG protein in providing and regulating free Zn^{2+} by virtue of its function as zinc metallochaperone. Previous evidence suggests that the endoplasmic reticulum/SR seems to have a role also in Zn^{2+} storage,[30] and a tight interplay may exist between Ca^{2+} and Zn^{2+} release events from this organelle. Moreover,

in cardiac muscle, $Zn^{2}+$ may be able to bind to ryanodine receptor (RyR2) and modulate its function.[31]

Zinc is a trace element essential for life.[32] In normal cellular physiology, more than 99% of intracellular zinc is bound to proteins. The levels of free $Zn^{2}+$ are very low and stringently regulated through the coordinated actions of zinc transporters, permeable channels, and metallothioneins (MT)[33] because too little concentrations of zinc inhibit metabolism, whereas high concentrations are toxic to cells. MT serve as a storage site for $Zn^{2}+$ and have chemical properties that support a dynamic role in zinc trafficking. Nevertheless, zinc trafficking occurs in MT-null animals and cells indicating that other general routes of trafficking exist.[34] HRG could be involved in one of these routes.

The HRG immunopositivity detected in the nuclei of human skeletal muscle was found almost exclusively in the heterochromatin. This new discovery, confirmed by control experiments on rat muscle fibers, is very intriguing as suggests a possible involvement of HRG in gene regulation. In fact, despite numerous data from the literature reporting the involvement of HRG in a number of important biological processes such as cell proliferation, phagocytosis of apoptotic cells, angiogenesis, and tumor progression and showing that all these activities are triggered in an indirect way, through HRG binding to cell surface molecules,[7,11,12,35] other studies have already described HRG cell internalization[21,22,36] and demonstrated a cytoplasmic HRG localization[19,23] and function[14,16] in skeletal muscle. Although the analysis of HRG amminoacidic sequence showed that HRG lacks the classical nuclear localization sequences that "tag" proteins for nuclear import, alternative nuclear localization mechanisms, which are likely to account for a large amount of nuclear traffic, could be involved in HRG nuclear localization.[37] Studies are in progress to investigate the role of HRG in the nucleus.

None of the HRG localization was detected at the level of rough endoplasmic reticulum and Golgi apparatus. We were not surprised to find it considering that HRG is not produced by skeletal muscle fiber but is taken up from the circulation.

In this article, we have also investigated the colocalization of HRG and AMPD1 in human skeletal muscle fibers, because a relationship between the two proteins at this level has been previously demonstrated as mentioned above.[14] Our ultrastructural analysis showed a colabeling of HRG and AMPD1 in the SR, in the sarcomere, and in the nucleus. Evidence of a colocalization of HRG and AMPD1 is not surprising considering the relationship between the two proteins.[16,23]

Interestingly, the present experimental work demonstrates for the first time the nuclear immunohistochemical localization of AMPD1 in human skeletal muscle. This finding corroborates a previous research that describes an AMPD activity in the nuclear fraction of rat brain.[38]

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Competing Interests

The author(s) declared no potential conflicts of interest with respect to the research, authorship, and/or publication of this article.

Author Contributions

All authors contributed to this article as follows: LM designed and conducted experiments, analyzed the data, created the figures, and edited the manuscript; FB and AF conducted experiments and analyzed the data; SF, GA, and GC conducted experiments; ARMS conceived, designed, and coordinated research studies, conducted experiments, analyzed the data, and drafted the manuscript. All authors read and approved the final manuscript.

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Human and Animal Study Compliance

All the procedures performed in the present study involving human participants were in accordance with the 1964 Helsinki Declaration and its later amendments. For this type of study, conducted retrospectively, formal consent was not required. The work on animals followed institutional, local, and national guidelines for animal experimentation. The investigation conforms with the Guide for the Care and Use of Laboratory Animals published by the U.S. National Institutes of Health (NIH publication no. 85-23, revised 1996).

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