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Allhorn, Maria; Lundqvist, Katarina; Schmidtchen, Artur; Åkerström, Bo

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Heme-Scavenging Role of α1-Microglobulin in Chronic Ulcers

Maria Allhorn, Katarina Lundqvist,* Artur Schmidtchen,* and Bo Åkerström
Departments of Cell and Molecular Biology and *Medical Microbiology, Dermatology and Infection, Lund University, Lund, Sweden

Chronic venous ulcers are characterized by chronic inflammation. Heme and iron, originating from blood cell hemolysis as well as extravascular necrosis, have been implicated as important pathogenic factors due to their promotion of oxidative stress. It was recently reported that the plasma and tissue protein α1-microglobulin is involved in heme metabolism. The protein binds heme, and a carboxy-terminally processed form, truncated α1-microglobulin, also degrades heme. Here, we show the presence of micromolar levels of heme and free iron in chronic leg ulcer fluids. Micromolar amounts of α1-microglobulin was also present in the ulcer fluids and bound to added radiolabeled heme. Truncated α1-microglobulin was found in the ulcer fluids and exogenously added α1-microglobulin was processed into the truncated α1-microglobulin form. Histochemical analysis of chronic wound tissue showed the presence of iron deposits, heme/porphyrins in infiltrating cells basement membranes and fibrin cuffs around vessels, and α1-microglobulin ubiquitously distributed but especially abundant in basement membranes around vessels and at fibrin cuffs. Our results suggest that α1-microglobulin constitutes a previously unknown defense mechanism against high heme and iron levels during skin wound healing. Excessive heme and iron, which are not buffered by α1-microglobulin, may underlie the chronic inflammation in chronic ulcers.

pathogenic role of heme, we have investigated concentration, distribution, and biochemical properties of α-m in wound fluids from chronic venous leg ulcers. It is shown that α-m is ubiquitously distributed in wound sections, that it is a heme-binding protein in ulcer fluids, and that t-α-m is formed. These results are consistent with a protective role of α-m in the ulcer fluids as a heme antagonist.

MATERIALS AND METHODS

Patients, wound fluid, and plasma Wound fluid and plasma were collected from patients with venous ulcers. Wound fluid was collected either by sampling on filters as described previously (Schmidtchen, 1999, 2000) or under a Tegaderm dressing (Schmidtchen, 2000). In the first procedure (used in experiments described in Fig 1; sampling from a group of 12 patients), sterilized filters (Whatman GF/D; diameter 2.5 cm) were applied to wounds for 4 h and wound fluid was extracted from the filter. Proteinase activity was blocked by the addition of the proteinase inhibitors disopropyl phosphorothioate, N-ethylmaleimide, and ethylenediamine tetraacetic acid (Schmidtchen, 2000). The filters did not induce degradation of α-m in human plasma (not shown). Wound fluid from 12 patients with venous ulcers (>3 mm2 area) was used for the experiments. In the second procedure (used for all other experiments), Tegaderm dressings were applied on the wound and wound fluid was collected by gentle aspiration underneath the film after 2 h, centrifuged at 10,000 r.p.m. (3500 g) in an Eppendorf centrifuge, aliquoted and stored at −20°C until further use. The venous insufficiency was routinely determined either by a handheld Doppler (5 MHz probe; examination of reflux in the political vein, great saphenous vein and small saphenous vein) or by color duplex examination. The patients had a systolic index of more than 0.8. Patients with diabetes or signs of general infection (malaise, fever) or local infection (cellulitis, erysipelas) were excluded. Plasma from healthy volunteers was collected by intravenous puncture. The research project was approved by the local Ethics Committee. Informed consent was obtained from the patients.

Proteins and reagents Human plasma α-m was prepared from plasma as described previously (Åkerström et al., 1995; Berggård et al., 1997, 1999). Protein LG was a generous gift from Dr Lars Björck, Department of Cell and Molecular Biology, Lund University, Sweden, and was coupled to CNBr-activated Sepharose-4B (Pharmacia-Biotech, Uppsala, Sweden), 7 mg per mL gel, as described by Pharmacia-Biotech. Orosomucoid, human albumin and other chemicals were from Sigma-Aldrich Stockholm, Sweden AB if not indicated otherwise. Mouse monoclonal anti-human α-m antibody was raised as described (Nilson et al., 1987). Rabbit anti-serum against human α-m was prepared in this laboratory by following the earlier description (Berggård and Bearm, 1968). Rabbit anti-LIPR was prepared by AgriSera AB (Vännäs, Sweden) by immunization with the synthetic peptide CKKLIPLIR conjugated to keyhole limpet hemocyanin (KLH). The preparation of goat anti-rabbit immunoglobulins has been described previously (Björck et al., 1977). Proteins were labeled with 125I-lodo (Bio-Nuclear AB, Stockholm, Sweden) using the chloramine T method (Greenwood et al., 1963). Labeled proteins were separated from free iodide by gel filtration on Sephadex G-25 column (Pharmacia). The specific activity was approximately 0.5 MBq per μg protein.

Sodium dodecyl sulfate–polyacrylamide gel electrophoresis (SDS–PAGE) and immunoblotting of α-m in wound fluids and plasma The molecular forms of α-m in wound fluids and plasma were investigated by SDS–PAGE and immunoblotting. SDS–PAGE was performed under denaturing conditions using 12% gels in the buffer system described by Laemmli (1970). Samples mixed with sample buffer 1:1 (v/v) containing 2% (v/v) β-mercaptoethanol and SDS were boiled 3 min before loading to the gel. High molecular mass standards (Rainbow markers, Amersham, International plc, Amersham, Buckinghamshire, England) were used. The gels were stained with Coomassie Brilliant Blue R-250 (BDH Chemicals, Ltd, Poole, UK) and dried. In some cases 3% to 12% polyacrylamide gradient gels with a 3% stacking gel were used. The separated proteins were transferred to polyvinylidene fluoride membranes (Immobilon, Millipore, Bedford, Massachusetts) as described (Matsudaira, 1987). Immunoblotting was performed as previously described (Schmidtchen, 1999) using polyclonal anti-α-sera against α-m diluted 1000 times. The membranes were developed using the ECL system (Boehringer, Mannheim GmbH, Mannheim, Germany).

Affinity chromatography of wound fluids To distinguish between full-length α-m and t-α-m, i.e., the form of the protein that lacks the C-terminal tetrapeptide LIPR, α-m was purified from wound fluids by anti-α-m affinity chromatography and subsequently immunoblotted both with antibodies against full-length α-m and antibodies against LIPR. Affinity chromatography was performed according to an earlier description (Allhorn et al., 2002), using mouse monoclonal anti-α-m, BN11.10, which had been immunomobilized to Affigel Hs (Bio-Rad Laboratory, Hercules, California) at 20 mg per mL following instructions from the merchant. The eluted proteins were separated by SDS–PAGE and identified by immunoblotting (see above) using anti-α-m diluted 1000 times or anti-LIPR diluted 300 times. The blots were developed by incubation with 125I-goat anti-rabbit immunoglobulin as described (Wester et al., 1997) and analysis with a Fuji Bas 2000 Bio-imaging analyzer (Fuji Films Co., Japan).

Cleavage of α-m by wound fluids The cleaving activity of wound fluids was tested by adding small amounts of radiolabeled α-m. One Bq of 125I-α-m or 125I-labeled α-m was added to 1 μL wound fluid (10 μg total proteins as measured by the Bradford method) diluted in phosphate-buffered saline (PBS: 10 mM phosphate buffer, pH 7.4, 120 mM NaCl, 3 mM KCl). The reaction proceeded for 1 h at room temperature. The samples were then applied to SDS–PAGE and the dried gel analyzed with a Fuji Bas 2000 Bio-imaging analyzer.

Binding of [14C]heme to α-m in wound fluids [14C]heme was produced using the Escherichia coli strain AN344 containing the plasmid pTYR13 as described by Schiött et al., 1997). AN344 is blocked in delta-aminolevulinic acid (ALA) synthesis and requires ALA for growth. Thus, the addition of 31 μM (508 Ci per mol) [4-14C]ALA (New England Nuclear Inc., Boston, MA) to strain AN344/pTYR13 in Luria broth (LB) medium resulted in production of [14C]heme with the yield 20 nmol per 60 μL culture and with a specific activity of 2.5 Ci per mmol. [14C]heme (15 pmol) was incubated with 1.5 μL wound fluid (3 μg total proteins as measured by the Bradford method) with or without added α-m (45 pmol) or albumin (45 pmol), or incubated with these amounts of α-m or albumin alone, diluted in PBS + 0.05% Tween-20 to 10 μL. After 30 min at 20°C, SDS–PAGE sample buffer was added and the samples analyzed by SDS–PAGE as described above, the gels dried and the radioactivity analyzed with a Fuji Bas 2000 Bio-imaging analyzer.
Binding of $^{14}$C-heme in HepG2 cell cultures To measure the binding of heme to newly synthesized $\alpha_m$, $^{14}$C-heme was added to cultures of the liver cell line HepG2, which synthesize and secrete $\alpha_m$. HepG2 cells were grown at 37°C in RPMI 1640 medium (Gibco, Life Technologies, Gaithersburg, MD) in an atmosphere of 5%. The medium contained 10% fetal bovine serum (FBS), 4.9 mM glutamine, 0.025% ascorbic acid, and 100 µg of erythrocyte membranes. At 5 h, the medium was replaced by fresh medium containing $^{14}$C-heme and the incubation proceeded for 2 h. The cells were centrifuged, washed, and saved for immunoprecipitation or SDS-PAGE. The proteins were then solubilized in $\alpha_m$ and SDS-PAGE and the autoradiographs were exposed to X-ray film. The bands corresponding to $\alpha_m$ were quantified by densitometry.

Biopsies Four millimeter biopsies were taken from the wound edge of a chronic venous leg ulcer. Control biopsies were taken from the edges of acute wounds or from healthy skin of the thigh. The tissue samples were fixed in 4% paraformaldehyde, dehydrated sequentially in ethanol, and embedded in paraffin. Tissue sections (5 µm) were cut and stained with hematoxylin and eosin. The sections were photographed with an Olympus BX51 microscope equipped with a cooled charge-coupled device camera.

Iron and porphyrin staining For iron staining, parafin-embedded sections were examined using Perl’s Prussian blue staining. The sections were incubated in a solution containing 1% potassium ferrocyanide in 1% HCl for 1 h. After several washes in H2O, the sections were incubated with a 1% neutral red solution for 5 min and washed again in H2O. Dehydrated and differentiated sections were mounted in DPX-type mountant. Porphyrins were stained using Fouchet technique, the method of choice for demonstration of bile pigments. After 5 min incubation in a reagent containing 12.5% trichloroacetic acid and 5% aqueous ferric chloride, the sections were washed in distilled water and counterstained with van Gieson’s solution: saturated picric acid, 0.1% acid fuchsin, and 0.1% glacial acetic acid, for 3 min. The sections were washed in alcohol before dehydration.

Determination of $\alpha_m$, porphyrin, and iron concentrations in wound fluids and plasma Specific concentrations of $\alpha_m$ were measured by a competitive radioimmunoassay (Åkerström, 1985). Porphophyrin IX was extracted using the pH-solubilization method as described by Falk (1964). Iron concentrations were determined by a spectrophotometric method with hydroxyamine and thioglycolate as the reducing agents and ferrozine as the ferrous ion complexing agent, at the Department of Clinical Chemistry, Malmö General Hospital, Malmö.

RESULTS $\alpha_m$ in wound fluids The wound fluids from 12 patients with chronic venous ulcers contained three variants of $\alpha_m$: free monomeric $\alpha_m$, t-$\alpha_m$, and $\alpha_m$ complex-bound to IgA (IgA-$\alpha_m$) when analyzing by SDS-PAGE (Fig 1). The IgA-$\alpha_m$ complex appears on SDS-PAGE as a nonreducible 90 kDa protein band containing $\alpha_m$ covalently linked to the $\alpha_m$-chain. A large variation in the relative concentrations of the three forms was noted. In contrast, plasma from the same patients contained no t-$\alpha_m$ and displayed less variation between individuals. Furthermore, the various high-molecular-weight $\alpha_m$ complexes described previously (Berggård et al, 1997) could be seen in plasma samples but were absent in wound fluids. T-$\alpha_m$ in wound fluids was identified by purification of $\alpha_m$ on anti-human $\alpha_m$ affinity chromatography, followed by immunoblotting with anti-LIPR (Fig 2). The results obtained confirmed that the protein band corresponding to t-$\alpha_m$ on SDS–PAGE lacked the C-terminal tetrapeptide.

Cleavage of $\alpha_m$ The appearance of t-$\alpha_m$ on SDS–PAGE prompted a further investigation of the cleaving activity of wound fluids. Thus, $^{125}$I-$\alpha_m$ or $^{125}$I-IgA-$\alpha_m$ was added to wound fluid samples and the mixtures were then analyzed on SDS–PAGE. The results obtained revealed the presence of a radioactive protein band corresponding to t-$\alpha_m$, approximately 3 to 4 kDa smaller compared with native $\alpha_m$ (Fig 3). $^{125}$I-IgA-$\alpha_m$ was also processed, which caused disappearance of the 90 kDa band and appearance of free $\alpha_m$.

Binding of $^{14}$C-heme to $\alpha_m$ $^{14}$C-heme was added to wound fluid and the binding to exogenously added $^{14}$C-heme was tested (Fig 4). A clear binding of radiolabeled heme to $\alpha_m$ in the wound fluids could be seen (lane 1) and to $\alpha_m$ alone without wound fluid present (lane 2). Albumin, a known physiologic heme-binding protein, also bound the added heme when added to wound fluid (lane 3). The binding of $^{14}$C-heme to wound fluid without previous addition of $\alpha_m$ or albumin was not detected (not shown), possibly due to low concentrations of the proteins and/or because endogenous $\alpha_m$ is saturated with pre-existing heme in the wound fluids.

Binding of $^{14}$C-heme in HepG2 cells To examine the heme-binding properties of newly synthesized $\alpha_m$ not
previously exposed to heme, human hepatoblastoma (HepG2) cells were used. These cells synthesize $\gamma_m$ as a precursor protein, $\gamma_m$/bikunin, which is cleaved intracellularly and the proteins are secreted separately. Thus, $^{14}$C]heme was added to the culture medium containing newly synthesized and secreted $\gamma_m$. This medium was then immunoprecipitated with polyclonal anti-sera. The results displayed in Fig 5(A) show that the $^{14}$C]heme added to HepG2 cells bound to $\gamma_m$, but not to orosomucoid also synthesized by the HepG2 cells. Medium was also applied to a monoclonal affinity chromatography column and $\gamma_m$ isolated by affinity chromatography could be seen as a radioactive band on SDS–PAGE (Fig 5B). The lyzed cells from the same cultivation did not show any radioactivity on SDS–PAGE, suggesting that there were too small amounts of $^{14}$C]heme bound intracellularly to be detected (not shown). To exclude the possibility that $^{14}$C]heme bound to proteins from the FBS in the medium, FBS was replaced by Na$_2$SeO$_3$. In this case the binding of $^{14}$C]heme to $\gamma_m$ was even more pronounced, as indicated in Fig 5(B), possibly as a result of the absence of competing heme-binding factors in FBS. The synthesis rate of $\gamma_m$ was similar with or without FBS (not shown).

Iron, heme, and $\gamma_m$ in wound fluids and sections The skin sections from patients with chronic ulcers and from healthy individuals were investigated histologically using polyclonal anti-sera directed against $\gamma_m$. The results revealed a global distribution of $\gamma_m$ in the dermis layer, with more intense staining in basement membranes and fibrin cuffs surrounding the blood vessels (Fig 6B). The normal skin section prepared from a healthy individual also displayed a ubiquitous distribution of $\gamma_m$ with increased amounts around vessels (Fig 6A). Porphyrin-specific staining showed the presence of porphyrins in basement membranes and fibrin cuffs surrounding vessels, i.e., a colocalization with $\gamma_m$, as well as in infiltrating blood cells (Fig 6C). In contrast, much less porphyrins were found in sections from patients with acute wounds (Fig 6E) or normal skin sections. Furthermore, pronounced iron deposits were seen in chronic ulcers (Fig 6D), as opposed to acute wounds or skin sections from healthy individuals, which were negative with respect to iron (not shown). These results suggest that tissue deposition of heme and iron is accentuated in chronic ulcers as compared with acute wounds and normal skin, whereas $\gamma_m$ is ubiquitously present both in normal skin and chronic ulcers.

Heme (protoporphyrin IX), free iron, and $\gamma_m$ concentrations were determined in wound fluids and plasma from patients with chronic ulcers (Table I). The heme content was estimated to
19.8 μM (SEM 6.7) in wound fluids and 13.4 μM (SEM 3.6) in plasma. The iron concentration was 6.5 μM (SEM 2.7) in wound fluids and 7.3 μM (1.5) in plasma. The a1m concentration was 1.7 μM (SEM 0.8) in wound fluids and 1.9 μM (SEM 1.5) in plasma. As a control, the heme, iron, and a1m concentrations were determined in plasma from normal donors. The heme and a1m concentrations were 12.1 μM (SEM 3.6) and 1.8 μM (SEM 0.3), respectively (Table I), i.e., similar values as in plasma from patients with chronic ulcers. The iron concentration in normal plasma was 13.9 (SEM 0.7), which is higher than in plasma and ulcer fluids from patients with chronic wounds.

**Table I.** Concentrations of heme (protoporphyrin IX), free iron, and a1m in chronic wound fluids and in plasma from patients with chronic ulcers and normal donors. Mean values of determinations on five samples (n = 5) and SEM values in each category are shown

<table>
<thead>
<tr>
<th></th>
<th>Heme (μM)</th>
<th>Iron (μM)</th>
<th>a1m (μM)</th>
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<tbody>
<tr>
<td>Chronic ulcers</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Wound fluid</td>
<td>19.8 (6.7)</td>
<td>6.5 (2.7)</td>
<td>1.7 (0.8)</td>
</tr>
<tr>
<td>Plasma</td>
<td>13.4 (3.6)</td>
<td>7.3 (1.5)</td>
<td>1.9 (1.5)</td>
</tr>
<tr>
<td>Normal plasma</td>
<td>12.1 (3.6)</td>
<td>139 (0.7)</td>
<td>1.8 (0.3)</td>
</tr>
</tbody>
</table>

**DISCUSSION**

Recent results indicate that the lipocalin a1m is a heme scavenger, and that it participates in protection against toxic effects of extracellularly exposed heme. Heme has been proposed as an inducer of inflammation and constitutes one of several pathogenic factors in chronic leg ulcers. Chronic venous ulcers, characterized by accumulated heme, may therefore serve as a relevant model for investigation of physiologic interactions between a1m and heme. The results in this study show the simultaneous presence of heme, iron, and a1m in chronic wound fluids and a colocalization of a1m and heme in tissue sections to basement membranes and fibrin cuffs around vessels. Moreover, a1m binds heme in the wound fluids and is processed into the truncated form t-a1m, which has heme-degrading properties. The results obtained here
thus support a view of ζ1m as a heme scavenger during inflammation.

It was previously noted that the C-terminal processing of ζ1m is induced by purified hemoglobin or by membranes from ruptured erythrocytes (Allhorn et al., 2002). It was speculated that an oxidized form of hemoglobin, which can be found deposited in erythrocyte membranes, may be responsible for the cleavage. The identity of the cleaving factor(s) in the leg ulcer fluids was not determined in this investigation; however, hemoglobin is usually found in this type of chronic leg ulcers (Blomgren et al., 2001) and this paper as well as others (Wenk et al., 2000) has shown the presence of heme and iron. It is therefore possible that the processing of ζ1m in chronic leg ulcers is induced by hemoglobin, hemoglobin variants, or free heme. We have previously shown that ζ-ζ1m is excreted in normal urine and that urinary ζ-ζ1m may be elevated in urine from hemolytic patients (Allhorn et al., 2002). In analogy, an increased ζ-ζ1m formation in patients with chronic ulcers may be reflected as an elevated urinary ζ-ζ1m concentration in these patients, and therefore, it is interesting to speculate that the urinary ζ1m/ζ1m ratio could be a useful parameter for evaluation of the clinical status of the ulcer patients.

About 50% of ζ1m in blood is in complex bound to monomeric IgA (Grubb et al., 1986; Berggård et al., 1997). The IgA-ζ1m complex is also found in extravascular compartments (Berggård et al., 1999; Bouic et al., 1985; Vincent and Revillard, 1987). It was shown that IgA-ζ1m is processed by erythrocyte membranes and hemoglobin, forming intact IgA and ζ1m (Allhorn et al., 2002). IgA-ζ1m may therefore be regarded as a depot from which the activated ζ-ζ1m is released. Leg ulcer fluids cleaved exogenously added IgA-ζ1m, suggesting that a mobilization of activated, heme-binding and heme-degrading ζ1m from the IgA-ζ1m depot takes place in leg ulcers in vivo. IgA is a normal component of skin, and granular deposits containing various forms of IgA were found in skin patients with dermatitis herpetiformis (Eggleston and Bank, 1987), suggesting a role of this molecule in homeostasis and pathology of the skin. It should therefore be of interest to investigate the normal distribution of IgA-ζ1m as well as the presence of the complex in the pathologic granular deposits.

Other high-molecular-weight plasma forms with masses around 200 kDa, representing complexes with albumin, prothrombin, and other as yet unknown molecules, have also been found to be associated with ζ1m (Berggård et al., 1997). Interestingly, these high-molecular-weight complexes are still present in plasma from patients with chronic leg ulcers but absent in wound fluids, as judged by SDS–PAGE. The reason for this is unclear but demonstrates that the distribution and metabolism of the ζ1m complexes are different.

The liver is the main site of synthesis of ζ1m and only traces of ζ1m-encoding mRNA are found in other organs (Kaumeyer et al., 1986; Itoh et al., 1996; Daveau et al., 1998). No production of ζ1m in keratinocytes or fibroblasts could be detected (not shown). The ζ1m and ζ1m complexes found in ulcer fluids therefore most likely originate from the liver and are transported there via the blood, rather than being synthesized locally. Plasma ζ1m and hepatocyte-derived ζ1m could indeed bind to radiolabeled heme in wound fluids, supporting this view (Figs 4 and 5). Such a transport of ζ1m from blood to tissues was demonstrated experimentally after injection of 125I-labeled ζ1m and ζ1m complexes intravenously into rats (Larsson et al., 2000). The protein composition in chronic wound fluids closely resembles that of plasma (Schmidtchen, 2000), suggesting a leakage of plasma proteins into wounds and further supporting the notion that ζ1m in wound fluids is indeed plasma derived.

Heme was found both in ulcer fluids and in plasma of ulcer patients (Table I). Heme was also found widely distributed in tissue sections from the chronic ulcers as opposed to acute wound sections or normal skin sections (Fig 6). Owing to venous hypertension in chronic ulcers (Ågren et al., 2000; Falanga, 2001), a flow of heme from plasma to the extravascular compartments across the endothelium and basement membranes is expected. Heme may therefore be trapped and accumulated in the membranous compartments of the endothelium and basement membranes and accumulated in pericapillary fibrin cuffs, which probably develop as a result of venous hypertension and extravasation of fibrinogen (Van de Scheur and Falanga, 1997). Such a distribution of heme to basement membranes and fibrin cuffs was indeed found in this investigation. Interestingly, especially high amounts of ζ1m were also found in these compartments (Fig 6), supporting the view of ζ1m as a heme scavenger. This localization of ζ1m also agrees with previous immunohistochemical studies of skin and placenta (Bouic et al., 1985; Berggård et al., 1999).

Free heme, released from hemoglobin and other heme proteins as a result of oxidation, generates reactive oxygen species leading to subsequent cell and tissue damage. Excess accumulation of heme causes an increased vasopermeability, increased expression of endothelial adhesion molecules and infiltration of leukocytes, signs of inflammation (Wagener et al., 2001). These events appear to be linked to the chronic inflammation in venous leg ulcers. The pro-inflammatory effects of heme induce expression of heme oxygenase, an intracellular, heme-degrading enzyme (Panchenko et al., 2000; Wagener et al., 2001). The products of the heme degradation by heme oxygenase, CO, and bilirubin, have cyto-protecting properties against oxidative stress (Otterbein and Choi, 2000). It may be speculated that ζ1m, which seems to have its heme-degrading property in common with heme oxygenase (Allhorn et al., 2002), affects heme in a similar way giving rise to these anti-oxidative mediators.

Another product of heme degradation is, of course, free iron. The results in this paper, in agreement with previous reports, demonstrate the presence of iron in the ulcer fluids, as well as iron deposits in chronic wound sections. Interestingly, the levels of iron (free + protein bound) were lower in wound fluids and plasma from chronic ulcer patients than in normal plasma, whereas iron deposits were seen in chronic wound tissue but not in acute wound or normal tissue. This suggests that the iron-chelating mechanisms are insufficient in the inflammatory tissue. Iron represents an oxidative threat to the tissue components, but heme oxygenase has been suggested to promote sequestering of the iron into the storage protein ferritin, which serves a dual role by hiding the iron and itself possesses a cyto-protective and anti-oxidant activity (Balla et al., 1992; Otterbein and Choi, 2000; Ryter and Tyrell, 2000). It may be speculated that ζ1m has a similar effect as heme oxygenase also in this case, promoting iron storage; however, additional observations are necessary before any conclusions can be drawn about the role of ζ1m in iron metabolism.

Unlike heme oxygenase, ζ1m operates extracellularly, possibly providing the main source of protection against unsequestered heme in the extracellular space. In conclusion, our results support the concept of ζ1m as part of a novel endogenous defense mechanism against heme-induced oxidative stress.

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