

Analysis of Human Multidrug Resistance Protein 1 (ABCC1) by MALDI-TOF Mass Spectrometry: Towards Identification of Leukotriene C₄ Binding Sites

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ABBREVIATIONS: MRP1, multidrug resistance protein 1; ABC, ATP-binding cassette; MSD, membrane spanning domain; NBD, nucleotide binding domain; TM, transmembrane helix; mAb, monoclonal antibody; LTC₄, leukotriene C₄; CL, cytoplasmic loop; PMSF, phenylmethylsulfonyl fluoride; LPG, lysophosphatidyl glycerol; LPC, lysophosphatidylcholine; DDM, n-dodecyl β-D-maltoside; Co²⁺-IMAC, Co²⁺-immobilized metal affinity chromatography; 4-HCCA, α-cyano-4-hydroxycinnamic acid; MALDI-TOF, matrix-assisted laser desorption ionization/time of flight.

ABSTRACT

Multidrug resistance in tumor cells may be caused by reduced drug accumulation resulting from expression of one or more proteins belonging to the ATP-binding cassette (ABC) transporter superfamily. In addition to their drug efflux properties, certain ABC proteins such as MRP1 (ABCC1) mediate the ATP-dependent transport of a broad array of organic anions. The intrinsically photoreactive glutathione conjugated cysteinyl leukotriene C₄ (LTC₄) is a high affinity physiological substrate of MRP1 and is widely regarded as a model compound for evaluating the substrate binding and transport properties of wild-type and mutant forms of the transporter. In the present study, we have optimized high level expression of recombinant human MRP1 in *P. pastoris* and developed a two step purification scheme that results in purification of the transporter to >90% homogeneity. Peptide mapping by MALDI-TOF mass spectrometry of the peptides generated by in-gel protease digestions of purified underglycosylated MRP1 identified 96.7% of the MRP1 sequence with >98% coverage of its 17 transmembrane helices. Subsequent comparisons with mass spectra of MRP1 photolabeled with LTC₄ identified six candidate LTC₄-modified peptide fragments which are consistent with the conclusion that the intracellular juxtamembrane positions of transmembrane helices 6, 7, 10, 17, and a COOH-proximal portion of the cytoplasmic loop that links the first and second membrane spanning domains are part of the LTC₄ binding site of the transporter. Our studies confirm the usefulness of mass spectrometry for analysis of mammalian polytopic membrane proteins and for identification of substrate binding sites of human MRP1.

Resistance to anti-cancer agents remains a major cause of chemotherapeutic failure in patients with malignant diseases. One widely accepted mechanism of resistance is the active extrusion of drugs out of cells by membrane transport proteins, resulting in cellular drug levels below the threshold needed for cytotoxicity (Haimeur et al., 2004b). Numerous clinical and *in vitro* studies have established that multidrug resistance may be caused by enhanced expression of one or more proteins belonging to the ABC transporter superfamily that use the energy provided by ATP binding and hydrolysis at their NBDs to power the transport of substrates across biological membranes.

MRP1 (ABCC1) belongs to the ‘C’ branch of ABC transporters and was originally identified based on its elevated expression in a multidrug resistant lung cancer cell line (Cole et al., 1992). In tumor cells, MRP1 confers resistance to a broad range of antineoplastic drugs while in normal tissues, MRP1 serves a protective role against these and other cytotoxic agents (Haimeur et al., 2004b; Leslie et al., 2005). A typical mammalian ABC protein has a 4-domain structure with two MSDs and two NBDs. However, MRP1 contains a third MSD at its NH₂-terminus that is linked to the 4-domain core by a cytoplasmic loop, CL3 (also referred to as L0), of approximately 125 amino acids. Thus the 1531 amino acid MRP1 contains 17 TM helices distributed among three MSDs configured MSD-CL3-MSD-NBD1-MSD-NBD2 (Haimeur et al., 2004b).

In addition to anticancer drugs, many of the chemicals transported by MRP1 are organic anions that include GSH, glucuronate, and sulfate conjugates that are not transported by the well known but distantly related drug transporter P-glycoprotein (ABCB1) (Haimeur et al., 2004b; Leslie et al., 2005). Most studies to date suggest that the first contacts of the hydrophilic amphipathic substrates of MRP1 are amino acids located in the inner leaflet of the membrane or in close proximity to the cytosolic-membrane interface of the transporter’s two core MSDs. The best characterized organic anion substrate of MRP1 *in vitro* is the cysteinyl leukotriene

LTC₄ that is formed by conjugation of LTA₄ with GSH during inflammatory and immunological responses (Leier et al., 1994; Loe et al., 1996; Muller et al., 1994; Mao et al., 2000). Analyses of *Mrp1*^{-/-} knock-out mice have confirmed that LTC₄ is an endogenous substrate of MRP1 *in vivo* (Wijnholds et al., 1997). LTC₄ has a high affinity ($K_m \sim 100$ nM) for MRP1 and is also intrinsically photoreactive (Leier et al., 1994; Loe et al., 1996). Consequently, LTC₄ has been widely used as a model substrate to evaluate the substrate binding and transport properties of MRP1 (Qian et al., 2001; Lee and Altenberg, 2003b, b; Yang et al., 2003; Bakos et al., 1998; Cai et al., 2001; Haimeur et al., 2002).

In previous studies, we showed that both the second and third MSDs of MRP1 can be photolabeled by [³H]LTC₄ with significantly more of the radioactivity associated with the NH₂-proximal half of the transporter (Qian et al., 2001). We also determined that a significant portion of CL3 is a prerequisite for efficient LTC₄ binding to the NH₂-terminal half of the protein, although neither this region nor the first MSD are themselves radiolabeled by the tritiated cysteinyl leukotriene. In addition, site-directed mutagenesis studies have identified a number of mutation-sensitive amino acids with respect to transport and/or binding of LTC₄. Thus, non-conservative (and in some cases, conservative) substitutions of certain residues located in or proximal to the cytosolic interface of TM6 (Lys³³², Asp³³⁶), TM8 (Asp⁴³⁶), TM11 (Asn⁵⁹⁰, Arg⁵⁹³, Phe⁵⁹⁴, Pro⁵⁹⁵), TM16 (Arg¹¹⁹⁷), and TM17 (Arg¹²⁴⁹) eliminate or substantially decrease LTC₄ binding to the transporter (Haimeur et al., 2002, 2004a; Campbell et al., 2004; Koike et al., 2004; Situ et al., 2004; Zhang et al., 2004). However, it is not known whether these amino acids are in direct contact with LTC₄ or whether they have a critical role in maintaining the architecture of the LTC₄ binding site on the protein, or both.

Progress in elucidating the substrate binding sites and transport mechanism of MRP1 and other mammalian ABC proteins has been hampered by the lack of high-resolution crystal structures. Mass spectrometry is a complementary approach to identifying substrate or

inhibitor binding sites on proteins that has been used with increasing success in recent years. However, their hydrophobicity and propensity to aggregate has limited the analysis of integral membrane proteins by this method. On the other hand, the feasibility of detailed mass spectrometric analysis has been enhanced by recent improvements in large-scale production of mammalian membrane proteins, as well as advances in solubilization, purification, and proteolytic digestion methods (Eichacker et al., 2004; Washburn et al., 2001; Quach et al., 2003). Nevertheless, complete sequence coverage of large polytopic mammalian proteins like MRP1 by mass spectrometry remains rare. In the current study, we have explored the feasibility of using mass spectrometry to better define how MRP1 interacts with LTC₄.

Materials and Methods

Chemicals and Reagents. The *P. pastoris* strain KM71 transformed with plasmid pHIL-MRP1-cHA-His₆ was a generous gift of Drs. Philippe Gros and Jie Cai (McGill University, Montreal, PQ) (Cai et al., 2001). Leupeptin and aprotinin were from Roche Applied Science (Indianapolis, IN). PMSF and pepstatin A were from ICN (Aurora, OH) and LPG was from Avanti Polar Lipids (Alabaster, AL). DDM, chymotrypsin (protein and peptide sequencing grade), protease V8 (protein and peptide sequencing grade), and 4-HCCA were from Sigma-Aldrich (St. Louis, MO). Trypsin Gold (mass spectrometry grade) was from Promega Corp (Madison, WI). BD Talon™ superflow Co²⁺-IMAC resins were from BD Biosciences Clontech (Palo Alto, CA). Pre-swollen microgranular anion exchange DE52 diethylaminoethyl cellulose was from Whatman International Ltd (Maidstone, UK). [14,15,19,20-³H]LTC₄ (115.3 Ci mmol⁻¹) was from Amersham Biosciences (Piscataway, NJ). LTC₄ was from CalBiochem (San Diego, CA). Other chemicals were HPLC or analytical grade unless specified otherwise.

Large-scale Expression of MRP1 in *P. pastoris*. Large-scale expression of MRP1 in *P. pastoris* was carried out in baffled flasks at 28-30 °C essentially as described by the manufacturer (Invitrogen, Carlsbad, CA). Briefly, a single colony was inoculated in 50 ml of MGY (1.34% yeast nitrogen base with ammonium sulfate, 1% glycerol, 4×10⁻⁵% biotin) in a 250 ml flask and incubated at 28-30 °C and 250-275 rpm overnight. Ten ml of cultured cells were transferred into 1.0 l of MGY and further incubated to an OD₆₀₀ 2.0-6.0. Cells were collected by centrifugation and resuspended in the same volume of MM (1.34% yeast nitrogen base with ammonium sulfate, 0.5% methanol, 4×10⁻⁵% biotin) to induce MRP1 expression. Cell growth was then continued for a further 3 days and methanol was added to a final concentration of 0.5% every 24 h to maintain induction. Finally, cells were collected by centrifugation and washed three times with ice-cold homogenization buffer (300 mM Tris-HCl, 250 mM sucrose, 100 mM

EACA, 1 mM EDTA, 1 mM EGTA, and 1 mM DTT, pH 7.4) at 1,500 ×g for 15 min at 4 °C.

Cell pellets were snap-frozen in liquid N₂ and stored at –80 °C.

Preparation of Crude Membranes. Yeast cells were diluted 50% (v/v) in homogenization buffer containing protease inhibitors (1 mM PMSF, 10 μg ml⁻¹ pepstatin A, 10 μg ml⁻¹ leupeptin, 2 μg ml⁻¹ aprotinin) and then disrupted three times using a French Pressure Cell Press (Thermo Spectronic, Rochester, NJ) set at 20,000 psi; fresh PMSF (1 mM) was added after each interval. After centrifugation, the pellet was washed twice, and supernatants were pooled and centrifuged at 100,000 ×g for 60 min. The resulting membrane pellet was homogenized vigorously with a motor-driven homogenizer in resuspension buffer (50 mM Tris-HCl, 20% glycerol, 10 mM imidazole, 1 mM 2-mercaptoethanol, pH 8.0). The crude microsomes were recentrifuged and rehomogenized twice as above. The resulting crude membrane proteins were stored at –80 °C in resuspension buffer containing protease inhibitors. Protein concentrations were determined using a Bradford assay using bovine serum albumin as a standard.

Purification of MRP1. Crude membrane proteins were thawed and diluted to 5.0 mg ml⁻¹ in resuspension buffer containing protease inhibitors. Typically, 100 mg membrane proteins were solubilized by addition of LPG (4-6 mg ml⁻¹) followed by inversion for 2-3 h at 4 °C. Insoluble proteins were removed by centrifugation at 100,000 ×g for 20 min at 4 °C. The supernatant were diluted 3-fold by addition of resuspension buffer containing protease inhibitors, 0.8 M NaCl, and 0.187 mg ml⁻¹ DDM in order to minimize the interaction of LPG with Co²⁺-IMAC resin. Co²⁺-IMAC resin (100 μl per mg membrane protein) that had been pre-equilibrated in resuspension buffer containing DDM was added to the diluted supernatant. The slurry was incubated at room temperature for 1-2 h with continuous inversion and then transferred into a Bio-Rad column (1×35 cm). The resin was washed extensively with 5-10 bed volumes of

resuspension buffer and followed by 20 bed volumes of washing buffer (50 mM Tris-HCl, 0.8 M NaCl, 20% glycerol, 20 mM imidazole, 1 mM 2-mercaptoethanol, 0.187 mg ml⁻¹ DDM, pH 8.0). The bound MRP1 was eluted with elution buffer (50 mM Tris-HCl, 450 mM NaCl, 20% glycerol, 200 mM imidazole, 1 mM 2-mercaptoethanol, 0.187 mg ml⁻¹ DDM, pH 7.4) containing protease inhibitors. Proteins in each fraction were analyzed by 7% SDS-PAGE followed by silver staining. Fractions containing MRP1 were pooled and dialyzed against storage buffer (50 mM Tris-HCl, 10% glycerol, 1 mM 2-mercaptoethanol, 0.187 mg ml⁻¹ DDM, pH 8.0). MRP1 was further purified by adding the dialyzed protein to DE52 anion exchange resin pre-equilibrated in storage buffer and incubated for 1 h at 4 °C. The supernatant was removed by centrifugation and purified MRP1 was eluted with 400 mM NaCl in storage buffer by centrifugation at 3,500 ×g for 5 min at 4 °C and then stored in aliquots at -80 °C.

Immunoblot Analysis of MRP1. Protein samples (15 µg crude membranes; 0.5 µg purified MRP1) were resolved by SDS-PAGE and transferred to an Immobilon-P membrane (Millipore, Bedford, MA). MRP1 was routinely detected using mAb QCRL1 (epitope residues 918–924) (Hipfner et al., 1996). Antibody binding was detected with a horseradish peroxidase-conjugated secondary antibody and the signal was enhanced using Renaissance chemiluminescence reagent (Perkin Elmer Life Sciences, Boston, MA) and exposed to film. Relative levels of MRP1 were determined by densitometry of the films using ImageJ 1.32j software (<http://rsb.info.nih.gov/ij/index.html>).

Photolabeling of Purified MRP1 with LTC₄ and [³H]LTC₄. Purified MRP1 in buffer (50 mM Tris-HCl, 250 mM sucrose, 0.187 mg ml⁻¹ DDM, pH 7.4) containing 50 or 100 mM MgCl₂ was incubated with unlabeled and/or ³H-labeled LTC₄ at room temperature for 30 min and then frozen in liquid N₂. LTC₄ was cross-linked to MRP1 by alternately irradiating the mixture at 302 nm for 1 min using a CL-1000 Ultraviolet Crosslinker (DiaMed, Mississauga, ON) and snap-freezing in liquid N₂ 10 times. LTC₄-labeled MRP1 was resolved by SDS-

PAGE and gels containing [³H]LTC₄-labeled MRP1 were processed for autoradiography at –80 °C (Loe et al., 1996). Relative levels of photolabeled MRP1 were determined by densitometry as above.

In-gel Proteolytic Digestions of Unlabeled and [³H]LTC₄-labeled MRP1. Trypsin, chymotrypsin, and protease V8 were used alone or in combination for in-gel digestions of MRP1, first as the unlabeled protein and subsequently after photolabeling with LTC₄. After a series of initial experiments, a protocol was developed as follows (Fig. 2). Unlabeled or LTC₄-labeled MRP1 was incubated with 20 mM DTT in 100 mM NH₄HCO₃ (pH 7.8) for 45 min at 37 °C and then carbamidomethylated by incubation with freshly prepared 45 mM iodoacetamide in 100 mM NH₄HCO₃ (pH 7.8) in the dark for 20 min. After SDS-PAGE, protein bands at ~165 kDa were cut into small slices and transferred to siliconized tubes. The gel pieces were washed three times with water and five times with 50% acetonitrile in 100 mM NH₄HCO₃, dehydrated in 100% acetonitrile, and then taken to dryness in a Speed Vac. The dried gel pieces were reswollen and incubated with 40 μl trypsin (20 ng μl⁻¹, pH 7.8), chymotrypsin (5 ng μl⁻¹, pH 7.8), or protease V8 (6 ng μl⁻¹, pH 6.5) overnight at 37 °C. When more than one proteolytic digestion was performed, the first digested peptide mixture was adjusted to the optimal incubation conditions for the second enzyme. Subsequently, 1 μl of the second enzyme [trypsin (100 ng μl⁻¹, pH 7.8), chymotrypsin (25 ng μl⁻¹, pH 7.8), or protease V8 (30 ng μl⁻¹, pH 6.5)] was added followed by incubation for 4 h at 37 °C. The peptide fragments were extracted three times by sonication at room temperature for 10 min with 50% acetonitrile and 0.2% trifluoroacetic acid. All extracts were pooled and concentrated by Speed Vac prior to analysis by mass spectrometry.

MALDI-TOF Mass Spectrometry. Samples for MALDI-TOF analyses were prepared using the two-layer deposition method (Dai et al., 1999). Briefly, 1 μl thin layer matrix solution (6 mg ml⁻¹ 4-HCCA in 70% acetone and 30% methanol) was deposited on a clean target, where

the solution spread and evaporated rapidly. The digested peptides were mixed with an equal volume of thick layer matrix solution (4-HCCA saturated in 60% methanol) and 0.5 μ l of this mixture was deposited on top of the first layer and allowed to air dry. Samples were rinsed by placing deionized water (0.5 μ l) on the sample matrix surface for 20 sec and then blown off with N₂. This washing procedure was repeated three times.

Mass spectra were recorded using a Voyager DE STR MALDI-TOF mass spectrometer (Applied Biosystems, Framingham, MA), equipped with a standard nitrogen laser (337 nm). All mass spectra were collected in positive mode with delayed extraction and reflectron mode. The sample spot was scanned with the laser beam under video observation and spectra were acquired by averaging 200-500 individual laser shots and processed with Data Explorer software (Applied Biosystems). The spectra were internally calibrated with matrix peaks and enzyme autolysis peptide peaks. Known contaminant peak signals were removed from the resulting data and remaining sample peak signals used for database searching. The artificial modifications of peptides (carbamidomethylation of cysteines and partial oxidation of methionines) were also considered for the database searching. Peptide identification and sequence coverage were interpreted against the SwissProt.10.30.2003 protein database with the aid of three scoring algorithm programs: Protein Prospector (<http://prospector.ucsf.edu/>), Mascot (http://www.matrixscience.com/search_form_select.html), and FindPept (<http://ca.expasy.org/tools/findpept.html>).

Results

Large-Scale Production and Characterization of MRP1 in *P. pastoris*. Large-scale expression of recombinant full-length MRP1-His₆ was carried out using *P. pastoris* strain KM71 (*arg4, his4 aox1::ARG4, Mut^s*) (Cai et al., 2001). A typical preparation yielded 85 mg crude membranes per liter of yeast medium. MRP1 levels were determined by immunoblotting of the membranes and a major immunoreactive band of ~165 kDa was observed (Fig. 1A). The intensity of this band was comparable to that observed for an equivalent amount of membrane proteins from the human H69AR lung cancer cell line, the differences in electrophoretic mobility being attributed to differences in glycosylation. Since MRP1 is known to comprise approximately 5-6% of total H69AR membrane proteins (Mao et al., 1999, 2000), this indicates that the recombinant MRP1 accounts for a comparable proportion of the yeast membrane proteins.

When *P. pastoris* crude membranes enriched for MRP1 were treated with PNGase F, the electrophoretic mobility of the immunoreactive band was not altered (Fig. 1A). In contrast, PNGase F treatment of H69AR cell membranes reduced the apparent molecular mass of native MRP1 from 190 kDa to a mass similar to that of the recombinant MRP1 expressed in *P. pastoris*, confirming that human MRP1 expressed in the latter system is underglycosylated (Cai et al., 2001). Uptake assays using membrane vesicles prepared from *P. pastoris* cells expressing MRP1 confirmed that the recombinant protein could transport LTC₄ as well as reported previously (Cai et al., 2001).

Purification of Unlabeled MRP1 Expressed in *P. pastoris*. Solubilization of MRP1 from crude membranes prepared from *P. pastoris* cells was evaluated initially using several detergents followed by immunoblotting with mAb QCRL-1. CHAPS and taurocholic acid were ineffective, while ~50% of MRP1 was solubilized by DDM or LPC using a detergent:protein ratio of >6. LPG was more effective than either DDM and LPC, and solubilized >90% of

MRP1 at a relatively low detergent:protein ratio and at 4 °C (data not shown). It is worth noting that it was necessary to exclude NaCl during solubilization by LPG in order to avoid precipitation of the detergent. LPG did not interfere with binding of the recombinant MRP1 to Co²⁺-chelated SepharoseTM resin but did appear to reduce its affinity for the Co²⁺-IMAC resin. Consequently, LPG-solubilized MRP1 was diluted with DDM-containing buffer before mixing with the Co²⁺-IMAC resin. Use of DDM afforded the additional advantage of being a non-ionic detergent, and thus far less likely than LPG to interfere with ionization of peptides from the MALDI matrix (Reid, 2004).

Purification of MRP1 by Co²⁺-IMAC was followed by SDS-PAGE and the protein visualized by silver staining. In this way, MRP1 was purified to ~50% homogeneity with a single contaminating band at ~55 kDa (Fig. 1B). This latter band was not detected with three MRP1-specific mAbs directed against epitopes in three different regions of the transporter (data not shown), indicating that the impurity was not a MRP1 degradation product and was probably a co-purifying protein from the yeast host.

After Co²⁺-IMAC, MRP1 was further purified to >90% homogeneity using DE52 anion chromatography (Fig. 1C). The overall yield of purified MRP1 obtained from 1.0 l of yeast medium was ~400 µg. This represents a two-fold higher yield than that previously reported using a *S. cerevisiae* expression system (Lee and Altenberg, 2003b). The purified recombinant MRP1 could be photolabeled with [³H]LTC₄ (see below) and 8-azido-[α-³²P]ATP, and had a substantial amount of intrinsic ATPase activity, indicating the protein had retained its activity through the purification process (data not shown).

In-Gel Proteolytic Digestion and MALDI-TOF Analysis of Unlabeled MRP1. To assess the feasibility of identifying MRP1 LTC₄ binding sites by MALDI TOF, intact unlabelled purified MRP1 was first digested with a variety of conventional proteases and chemicals, and the resulting fragments analyzed by MALDI-TOF mass spectrometry. DDM was routinely

required during sample concentration and MALDI matrix crystal formation to maintain solubility. In contrast to analysis of the bacterial lactose transporter LacS (Van Montfort et al., 2002), treatment of MRP1 with trypsin and cyanogen bromide yielded relatively few identifiable peptides, and of these, even fewer corresponded to predicted TM helices (data not shown). To increase sequence coverage, a protocol was developed that ultimately led to identification of 96.7% of the MRP1 sequence (Fig. 2); of this, 98.8% of the TM sequences in the two core MSDs were identified (Table 1). Important modifications included subjecting the protein to reducing and carbamidomethylating conditions prior to separation by SDS-PAGE, and sequential use of two proteases. Thus, MRP1 was first digested with trypsin, chymotrypsin, or protease V8, and then the resulting peptide mixtures were subjected to a second digestion with a different enzyme, as outlined in Fig. 2.

The presence of unassignable mass peaks in MALDI TOF mass spectrometry is not uncommon and such peaks were also found in our analyses (Ding et al., 2003). Typically, contaminating peaks originate from matrix clusters, proteolytic autolysis, or human keratin. The peaks from matrix cluster (m/z 568.1), gel (m/z 882.5), proteolytic autolysis (m/z 2211.1 for trypsin), and some known peptides were used for internal mass calibration (Fig. 3). To avoid potential contamination from matrix, only mass peaks greater than m/z 700 were searched against the SwissProt.10.30.2003 protein database (Table 1). All searches were limited to the first monoisotopic peaks, and all cysteine residues were presumed to be reduced and carbamidomethylated, and partial oxidation of methionine residues was considered. Up to four missing enzyme cleavage sites were considered for single digests and for double digests, up to seven missing cleavage sites were considered.

As indicated in Table 1, more sequence coverage was obtained from single digestions with trypsin than from chymotrypsin or protease V8 digestions. Chymotrypsin digestion produced very short peptides and as a result, many potential MRP1 peptides were artificially

excluded during database searching. MRP1 digestion with protease V8 in NH_4HCO_3 yielded poorer correlations of mass spectra with MRP1 sequences (data not shown). This shortcoming was overcome by carrying out protease V8 digestions at pH 6.5. When protease V8 and chymotrypsin were used in combination, the resulting coverage of the MRP1 sequence was significantly greater than that obtained by digestion with each enzyme alone. Additionally, the number of peptides obtained from a dual digestion depended on the order in which the proteases were added (Table 1). The reason for this is not known but it may reflect differences in the accessibility of the cleavage sites in gel-trapped MRP1 to the proteases. After compiling sequences from multiple proteolytic digestions, it was clear that coverage of the MRP1 sequence was nearly complete, and included almost all of the TM helices. These experiments established the feasibility of identifying MRP1 substrate binding sites by MALDI TOF mass spectrometry.

Photolabeling of Purified MRP1 with LTC_4 . As mentioned previously, LTC_4 is intrinsically photoreactive, a property attributable to its conjugated triene structure (Fig. 4A) (Falk et al., 1989). In general, the efficiency of photochemical reactions is low and consequently, prior to mass spectrometry, conditions for optimal photolabeling with LTC_4 were determined by photolabeling a constant amount of purified MRP1 in increasing concentrations of [^3H] LTC_4 . As shown in Fig. 4B, the extent of MRP1 photolabeling increased with increasing concentrations of LTC_4 until a maximum was reached at $\sim 4 \mu\text{M}$ at which point the cysteinyl leukotriene was estimated to be in ~ 50 -fold molar excess of MRP1.

Mass Spectrometry Analysis of LTC_4 -labeled MRP1. Purified MRP1 (typically $1 \mu\text{g}$) was irradiated at 302 nm in the presence of LTC_4 ($4 \mu\text{M}$) as outlined in the protocol shown in Fig. 2. Controls included non-irradiated MRP1 and UV irradiated MRP1 in the absence of LTC_4 . MALDI TOF analyses of all three samples showed several differences in terms of signal appearances (Fig. 5A). This is to be expected since MALDI TOF is very sensitive to small differences in sample preparation or crystal formation, which in some cases can limit the

usefulness of controls. Also, UV irradiation of MRP1 can be expected to result in some degree of intra- or inter-molecular cross-linking and/or other chemical reactions. However, since our goal was to identify LTC₄-modified peptides, and because the formation of covalent bonds between LTC₄ and amino acid residues in MRP1 involves the opening of one or more of the triene double bonds during irradiation (Falk et al., 1989), those differences in the obtained spectra that did not match an exact mass shift of 625.5 Da from an unlabeled peptide to a LTC₄-labeled peptide were excluded from further consideration. Also, the mass shifts were required to occur only for MRP1 irradiated in the presence of LTC₄ and not for the two controls.

Fig. 5 shows an example of a positive match that meets the above stated selection criteria and the properties of this and five other candidate LTC₄-modified peptide fragments are summarized in Table 2. These data suggest that the regions of MRP1 covalently bound to LTC₄ are preferentially located at the intracellular juxtamembrane positions of TM6, TM7, TM10, TM17, and in CL3 linking the first and second MSDs. The appearance of unlabeled peptide in the two controls as well as in the photolabeled sample is expected, since only a portion of the protein present is labeled in the photolabeling reaction.

Discussion

Despite many recent advances, analysis of polytopic mammalian membrane proteins by mass spectrometry and other biophysical methods still remains technically quite challenging (Eichacker et al., 2004; Reid, 2004; Glish and Vachet, 2003). Studies of human MRP1 and other mammalian ABC transporters have been further hampered by the difficulty of obtaining sufficiently large amounts of purified protein. Although MRP1 has been successfully purified to a high degree of homogeneity by several groups (Mao et al., 1999, 2000; Chang et al., 1997), the expression systems used to date are relatively inefficient, making it difficult and costly to generate the large amounts of protein needed for most biophysical studies. In contrast, the *P. pastoris* expression system can be readily scaled up and indeed, this system has been successfully applied to the large scale production of a number of human polytopic membrane proteins including P-glycoprotein (ABCB1) and the breast cancer resistance protein (ABCG2) (Cai and Gros, 2003; Mao et al., 2004).

When expressed in mammalian cells, MRP1 is *N*-glycosylated with complex carbohydrates at Asn residues at positions 19, 23, and 1006 (Hipfner et al., 1997), which has the potential to impede physical characterizations of the transporter. Indeed, the glycan chains of MRP1 have been reported by Muller et al. (2002) to impair the accessibility of its extracellular domains. Thus another advantage of using *P. pastoris* is the fact that MRP1 expressed in this system is underglycosylated (Fig. 1) (Cai et al., 2001). Previous studies have shown that the absence of glycosylation does not cause any substantial alterations in the ability of MRP1 to transport LTC₄ (Gao et al., 1998), although in mammalian cells, the glycan chains may enhance the stability of the transporter (Weigl, Deeley and Cole, unpublished observations).

By using a combination of DDM solubilization and Co²⁺-IMAC and DE52 anion exchange chromatography, we were able to purify the recombinant MRP1 from *P. pastoris* membranes to >90% homogeneity. A typical yield from a 1 l culture was ~400 µg, which is two-fold

higher than the yield reported previously for recombinant MRP1 using a heterologous *S. cerevisiae* expression system (Lee and Altenberg, 2003b). The DDM-solubilized purified MRP1 could be photolabeled with [³H]LTC₄ and 8-azido-[α-³²P]ATP, and also exhibited significant ATPase activity (data not shown). Thus, we can conclude that expression in *P. pastoris* together with our two-step purification protocol is a good system for obtaining substantial amounts of purified functional MRP1 that can be used with confidence for high resolution structural analyses.

Previous studies indicate that many of the sites in MRP1 and other ABC proteins likely to interact directly with its xenobiotic and endogenous substrates are located in or at the cytosolic interface of its TM helices (Haimeur et al., 2004b). Thus, complete sequence coverage of the TMs is a critical prerequisite for identifying substrate contact sites on the transporter by mass spectrometry. Because of their hydrophobicity, this is often difficult to achieve with membrane proteins (Reid, 2004). Despite the fact that P-glycoprotein contains 5 fewer TMs than MRP1, Chiba and colleagues reported just 80% coverage of the human P-glycoprotein sequence by MALDI TOF analysis in one study and in a more recent study, 95% coverage of the two MSDs and 80% of the NBDs (Ecker et al., 2002; Pleban et al., 2005). Using our sequential protease digestion protocol, all residues in the TMs of the three MSDs of MRP1 were identified except for 3 amino acids in TM11, and the NBDs were 96.5% covered (Table 1). Thus our MALDI TOF analysis of human MRP1 with >96% overall sequence coverage represents a significant improvement and our protocol may facilitate the study of other large mammalian ABC transporters.

Mass spectrometric analysis of ligand binding sites of photolabeled proteins is often not possible because of low photolabeling efficiency by the ligand. However, current techniques can often overcome this limitation and our study shows that this is the case, at least to a significant degree, for analysis of LTC₄-labeled MRP1. The six candidate LTC₄-modified MRP1

peptide fragments identified here are found in several different regions of the transporter with respect to its primary structure and include the COOH-proximal region of CL3 (peptide 260-274), TM6 (peptide 320-331), TM7 (peptide 372-385), TM10 and its cytosolic juxtamembrane region (peptide 546-553), and TM17 and its cytosolic juxtamembrane region (peptides 1233-1255 and 1248-1264). Thus, at least a portion of all candidate LTC₄ modified MRP1 peptides is predicted to be intracellular or in relatively close proximity to the membrane-cytosol interface of the protein, in agreement with this region being an initial contact site of LTC₄.

To a significant extent, the sequence assignments of the LTC₄-modified peptides identified here are consistent with previous studies of wild-type and mutant MRP1 proteins. For example, more of the LTC₄ modified candidate peptides are found in the NH₂-proximal half of MRP1 than the COOH-proximal half, in agreement with our earlier finding that the two halves of MRP1 are differentially photolabeled by [³H]LTC₄ (Qian et al., 2001). Furthermore, residues 1-204 were not found in any of the candidate peptides consistent with studies from several groups demonstrating that the first MSD of MRP1 is not necessary for binding or transport of LTC₄ (Bakos et al., 1998; Lee and Altenberg, 2003a). On the other hand, although peptide 260-274 is located in the COOH-proximal half of CL3, a region previously suggested to be necessary for LTC₄ binding (and transport) and to contain a GSH binding site (Ren et al., 2001), we have found no evidence that residues NH₂-proximal to 281 could be directly photolabeled by this cysteinyl leukotriene (Westlake et al., 2003). Furthermore, deletion of residues 261-279 caused only a 30% decrease in LTC₄ transport activity and mutation of Pro²⁷² in this region had no effect at all (Ito et al., 2003). Clearly, further study is needed to resolve this apparent discrepancy.

Identification of amino acids 320-331 as an LTC₄-modified peptide is consistent with earlier reports demonstrating the critical importance of TM6 for LTC₄ binding and transport. Thus, Bao et al. (2005) showed that replacement of TM6 (amino acids 320-337) with a

poly-Ala chain abolishes LTC₄ transport by MRP1. Furthermore, we have shown that mutation of Lys³³² immediately adjacent to the candidate TM6 peptide selectively eliminates LTC₄ binding and transport (Haimeur et al., 2002, 2004a). Taken together, the data support the idea that residues in TM6 can form direct contacts with LTC₄. However, further studies using more sophisticated methods such as MALDI-MS/MS technology for fragmentation studies of the LTC₄-labeled peptides are needed to determine definitively if this is the case.

The identification of peptide 372-385 as a candidate LTC₄ modified peptide represents the first time that TM7 has been implicated in LTC₄ binding by MRP1. However, our atomic homology models of MRP1 place TM7 in close proximity to TM12, TM16 and TM17 (Campbell et al., 2004), and the latter two TMs are known to contain a significant number of mutation-sensitive residues with respect to LTC₄ binding and transport (see below). Thus, it is possible that TM7 may be photolabeled by LTC₄ by virtue of its close proximity to the photoreactive region of the LTC₄ molecule rather than by any of its component amino acids directly contributing to the high affinity binding of this substrate. On the other hand, candidate LTC₄ modified MRP1 peptide 546-553 is predicted to be proximal to the cytoplasmic interface of TM10, and this region has been identified in several studies as being important for binding and transport of LTC₄, as well as for binding of several photoaffinity analogs of a number of different compounds (Koike et al., 2002; Daoud et al., 2001).

The identification of LTC₄-modified peptides 1233-1255 and 1248-1264 that correspond to TM17 and its cytosolic juxtamembrane region was not surprising given that, like peptide 546-553, these overlapping peptides are part of a larger region that has been consistently reported by several groups to be critical for MRP1 transport activity as well as for the binding of several photoaffinity drug analogs (Daoud et al., 2001; Ito et al., 2001; Zhang et al., 2002; Mao et al., 2002; Ren et al., 2003). However, although we have shown that several polar residues within TM17 are important for MRP1 transport activity, mutations of these residues typically

alter the substrate specificity of the transporter rather than abrogate its activity altogether. More notably, mutations of these residues do not affect LTC₄ binding or transport in any substantial way (Ito et al., 2001; Zhang et al., 2002). For example, mutations of Trp¹²⁴⁶ eliminate transport of E₂17βG and other glucuronide conjugates but leave LTC₄ transport essentially unchanged (Ito et al., 2001). Similarly, substitution of Tyr¹²⁴³ with Phe causes a 70% reduction in E₂17βG transport but has little effect on LTC₄ transport (Zhang et al., 2002). Supporting these findings are the observations of Bao et al. (2005), who recently reported that when amino acids 1228-1248 (TM17) are replaced with a poly-Ala chain, the mutant MRP1 retains the ability to transport LTC₄ as well as the wild-type protein. However, when residues in the COOH-proximal portion of the TM17 α-helix that extends beyond position 1248 into the cytoplasm are mutated, loss of transport activity becomes complete. Thus, in contrast to the minimal effect on LTC₄ transport caused by mutations of Trp¹²⁴⁶ and Tyr¹²⁴³, even a conservative substitution of Arg¹²⁴⁹ (Situ et al., 2004) (or Met¹²⁵⁰ (unpublished observations)) eliminates both binding and transport of LTC₄ as well as all other organic anions tested. Taken together, these observations suggest that the amino acid(s) in peptides 1248-1264 and 1233-1255 indicated in the present study to be cross-linked to LTC₄ are likely to reside in the cytoplasmic juxtamembrane position of TM17 between residues 1249 and 1264, rather than in the lipid bilayer itself. However, as mentioned above, further fragmentation analysis of the LTC₄-labeled peptides by MALDI MS/MS are needed to confirm this.

Recently, Karwatsky et al. (2005) photolabeled recombinant MRP1 containing multiple inserted epitope tags with [¹²⁵I]AALTC₄, an ¹²⁵I-iodoarylazido derivatized analog of LTC₄, and after analysis of photolabeled tryptic fragments of the transporter, they concluded that the binding regions for LTC₄ included TM10-11 (amino acids 542-593) in the second MSD, and TM12 (amino acids 969-1013) and TM16-17 (amino acids 1203-1249) in the third MSD, as well as the first MSD and NH₂-proximal portion of CL3 (amino acids 1-271). Our results

obtained using the parental leukotriene appear to differ in several respects. For example, our study did not identify any candidate LTC₄-modified MRP1 peptides corresponding to residues in the first MSD (TM1-5) or in CL3 NH₂-proximal to position 260, or in TM12. On the other hand, Karwatsky et al. (2005) did not observe labeling of either the COOH-proximal portion of CL3 or TM6 or TM7 by [¹²⁵I]AALTC₄ as our present data suggest is the case with LTC₄.

There are a number of possible technical explanations for these differences that are related to the inherently different sensitivities and limitations of the different analytical methods used. However, the differences are also likely related to the fact that in the study of Karwatsky et al. (2005), as in many other photoaffinity labeling studies, an iodoarylazido derivative of LTC₄ was used (Sun et al., 1986). Thus these investigators enhanced the photoreactivity of LTC₄ by introducing a bulky azido-benzoate group onto the γ -glutamyl residue of the GSH moiety of LTC₄. Since the γ -glutamyl residue is critical for the high affinity of LTC₄ for MRP1 (Leier et al., 1994), it is not surprising that this modification lowered the apparent affinity (K_m) of the organic anion substantially (Karwatsky et al., 2005), indicating that the chemical modification altered the binding characteristics of LTC₄. This difference in binding properties may also explain why LTC₄ preferentially photolabels the NH₂-terminal half of MRP1 (Qian et al., 2001), while IAALTC₄ preferentially photolabels the COOH-terminal half (Karwatsky et al., 2005). Thus it is likely that the amino acid contacts for LTC₄ and IAALTC₄ in MRP1 are not precisely the same.

The mechanism of substrate transport by MRP1 is complex and not yet fully understood. However, it is generally accepted that the transport cycle is initiated by substrate binding that gives rise to a conformational change in MRP1 followed by sequential ATP binding to the NBDs and conformational change of the binding pocket, so that the substrate shifts from a high affinity binding site to a low affinity binding site facilitating its release on the other side of the membrane. The transport cycle is completed by hydrolysis of ATP (primarily at NBD2)

and subsequent energy transfer from the NBDs to the TMs, and release of ADP and restoration of the ‘resting’ high affinity state of the transporter (Higgins and Linton, 2004). Therefore, studies such as those described here provide only a static snapshot of LTC₄ binding by the transporter in its basal conformation. Recently, Ecker et al. (2004) showed by MALDI TOF mass spectrometry that ATP binding increased the accessibility of the fifth TM helix of the bacterial ABC transporter LmrA to labeling by a photoactive ligand while ATP hydrolysis had an opposite effect. Accordingly, our future studies are directed towards determining whether the LTC₄-modified MRP1 peptide fragments (and individual amino acids) that can be identified by mass spectrometry differ at the different stages of the transport cycle of this ABC protein.

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Footnotes

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FIGURE LEGENDS

Fig. 1. Expression and purification of recombinant human MRP1 in *P. pastoris*. *A*, immunoblot of MRP1-enriched membranes prepared from *P. pastoris* cells and human H69AR lung cancer cells with mAb QCRL-1 after treatment with PNGase F. Crude membrane proteins (20 µg) were incubated at 37 °C for 1-2 h in the absence (–) or presence (+) of PNGase F, and MRP1 proteins detected by immunoblotting with mAb QCRL-1. *B*, purification of MRP1 by Co²⁺-IMAC was monitored by SDS-PAGE and proteins visualized by silver staining. *Lane 1*, unstained protein standards; *lane 2*, LPG-solubilized crude membrane proteins (2 µl); *lane 3*, supernatant of LPG-solubilized protein (2 µl); *lane 4*, flow-through from Co²⁺-IMAC column (2 µl); *lane 5*, eluate from first wash of Co²⁺-IMAC column with resuspension buffer (20 µl); *lane 6*, eluate from second wash of column with washing buffer (20 µl); *lane 7-18*, sequential fractions of column eluates with 200 mM imidazole (20 µl). *C*, silver-stained gel after typical two-step purification of MRP1 by Co²⁺-IMAC and DE52 anion chromatography. *Lane 1*, DDM-solubilized and dialyzed MRP1 after Co²⁺-IMAC (20 µl); *lane 2*, eluate after DE52 chromatography with 400 mM NaCl (20 µl). Molecular weight markers are shown on the left.

Fig. 2. Scheme showing experimental strategy for analysis of recombinant human MRP1 expressed in *P. pastoris* by MALDI TOF. A six step protocol for analysis of MRP1 with full sequence coverage was developed as follows: *1*, solubilization of purified recombinant MRP1 from *P. pastoris* in DDM. *2*, photolabeling of purified MRP1 with LTC₄ by irradiation at 302 nm. Controls include unlabeled MRP1 and irradiated unlabeled MRP1. *3*, treatment of MRP1 with DTT and iodoacetamide. *4*, separation of unlabeled or LTC₄-labeled MRP1 by SDS-PAGE, and excision of protein bands of ~165 kDa. *5*, in-gel digestion of dried gel pieces with various combinations of proteases. *6*, analysis of peptide fragments by MALDI TOF mass spectrometry

assisted by software programs MS-Fit, Mascot, and FindPept.

Fig. 3. Representative MALDI TOF mass spectrum of in-gel trypsin digested unlabeled MRP1. Unlabeled recombinant MRP1 was resolved by SDS-PAGE, excised from the gel and then the dried gel pieces incubated with trypsin overnight at 37 °C. Shown is a MALDI TOF mass spectrum of the resulting tryptic peptides with expansion of the three main peaks used for internal calibration at m/z 568.1 (from matrix cluster), m/z 882.5 (from the gel), and m/z 2211.1 (from trypsin autolysis). Peaks at m/z 568.1 and m/z 882.5 were also observed in mass spectra of MRP1 digested with other proteases alone or in combination.

Fig. 4. Chemical structure of [^3H]LTC₄ and photolabeling of purified MRP1 with [^3H]LTC₄. *A*, chemical structure of [$^{14,15,19,20-3}\text{H}$]LTC₄. The asterisks indicate the location of the tritium atoms in the radiolabeled molecule. *B*, concentration dependence of LTC₄ photolabeling of MRP1. DDM-solubilized purified MRP1 (1.6 μg) was incubated with the indicated concentrations of [^3H]LTC₄ /LTC₄ for 30 min at room temperature. After irradiating at 302 nm, the radiolabeled proteins were resolved by SDS-PAGE, processed for autoradiography and the intensity of the bands quantified by densitometry. The figure is a composite of results obtained in two independent experiments, each with five different [^3H]LTC₄ concentrations (0.1, 0.2, 0.4, 0.8, 1.6; and 0.8, 1.6, 2.4, 3.2, 4.0). In the graph shown, the relative pixel densities for the second set of data were plotted after ‘correction’ so that the signal intensities of the two overlapping concentrations (0.8 and 1.6) were the same. Consequently, the signals for these two [^3H]LTC₄ concentrations in the second experiment are not shown. The dotted line in the graph connects the data points from the two experiments.

Fig. 5. Representative mass spectra identifying candidate LTC₄-modified peptides

of MRP1. A-C, MALDI TOF mass spectra of MRP1 digested with protease V8 and chymotrypsin. In all panels, (i) unlabeled non-irradiated MRP1 (*MRP1*); (ii) unlabeled irradiated MRP1 (*MRP1-UV*); and (iii) LTC₄-photolabeled MRP1 (*MRP1-LTC₄-UV*). A, mass spectra of MRP1 peptides at m/z 1000-3500 obtained by in-gel digestion with protease V8 and chymotrypsin. Peaks marked with asterisks in (ii) are not detected in (i) and are attributed to differences in sample preparation or UV-irradiation alone. The peak marked with a diamond in (iii) is candidate LTC₄-modified MRP1 peptide fragment. B and C, expanded sections of the mass spectra shown in A. B, the best match for the unmodified peptide at m/z 2739.7 is peptide 1233-1255 (Table 2). C, The peptide at m/z 3365.1 is detected only in digests of LTC₄ cross-linked MRP1 (iii), and matches the unmodified peptide at m/z 2739.7 shown in B after subtraction of the mass of LTC₄. The m/z 2739.7 fragment (B) is also found in the spectrum obtained after digestion of the LTC₄-labeled protein (C) because of the relatively low cross-linking efficiency of MRP1 by LTC₄.

Fig. 6. Topological illustration showing location of candidate LTC₄ –modified regions of MRP1 identified by MALDI TOF mass spectrometry. The topological structure of MRP1 shown is based on a model derived by molecular dynamics simulations using the crystal structure of the bacterial lipid transporter MsbA as template (Campbell et al., 2004) as well as the HMMTOP 2.0 algorithm for predicting locations of TM helices of the first MSD (www.enzim.hu/hmmtop). The approximate locations of the candidate LTC₄-modified peptide sequences of MRP1 suggested by MALDI TOF mass spectrometry of photolabeled protein are indicated by broken lines.

Table 1. Relative sequence coverage of human MRP1 (ABCC1) identified by MALDI TOF mass spectrometry

| Protease | % Sequence coverage | MSD1 ^a | | CL3 ^{a,b} | MSD2 ^{a,c} | | NBD1 ^{a,d} | MSD3 ^{a,c} | | NBD2 ^{a,d} |
|----------------------------|---------------------|-------------------|------------|--------------------|---------------------|------------|---------------------|---------------------|------------|---------------------|
| | | (1-193) | | (194-322) | (323-600) | | (601-978) | (979-1251) | | (1252-1531) |
| | | <i>loops</i> | <i>TMs</i> | | <i>loops</i> | <i>TMs</i> | | <i>loops</i> | <i>TMs</i> | |
| Trypsin | 39.3 | 14.8 | 20.0 | 54.3 | 47.1 | 24.3 | 44.6 | 28.2 | 18.9 | 59.3 |
| Chymotrypsin | 19.4 | 15.9 | 41.9 | 10.0 | 25.4 | 47.9 | 12.5 | 4.2 | 35.6 | 8.6 |
| Protease V8 | 10.5 | 0.0 | 0.0 | 4.7 | 0.0 | 0.0 | 24.9 | 3.5 | 0.0 | 19.6 |
| Trypsin + chymotrypsin | 56.7 | 89.8 | 75.2 | 40.3 | 86.2 | 58.6 | 41.4 | 60.6 | 48.5 | 53.9 |
| Trypsin + protease V8 | 48.7 | 47.7 | 20.0 | 38.8 | 63.8 | 12.1 | 69.8 | 26.1 | 24.2 | 70.4 |
| Chymotrypsin + trypsin | 59.6 | 64.8 | 89.5 | 86.8 | 79.0 | 54.3 | 40.1 | 62.0 | 64.4 | 50.4 |
| Chymotrypsin + protease V8 | 42.5 | 56.8 | 55.2 | 50.4 | 42.0 | 52.9 | 36.9 | 41.5 | 46.2 | 26.4 |
| Protease V8 + trypsin | 43.5 | 23.9 | 20.0 | 66.7 | 64.5 | 0.0 | 52.8 | 43.0 | 43.2 | 47.1 |
| Protease V8 + chymotrypsin | 53.2 | 87.5 | 68.6 | 14.7 | 56.5 | 74.3 | 37.4 | 70.4 | 83.3 | 40.4 |

^aThe amino acids included in the MSDs (membrane spanning domains), loops (cytoplasmic and extracellular), TMs (transmembrane helices) and NBDs (nucleotide binding domains) are approximate and are based on predictions from atomic homology models of MSD2 and MSD3 (Campbell et al., 2004) as well as the HMMTOP 2.0 algorithm.

^bOverall coverage of CL3 was 100%.

^cOverall coverage of two core MSDs (TM6 to TM17) was 98.9% (only ⁵⁹⁰NIL⁵⁹² from TM11 was not identified).

^dOverall coverage of Walker A, Walker B, and active transport ‘C’ signature motifs was 100%.

Table 2. Candidate LTC₄-modified peptide fragments of MRP1 identified by MALDI TOF mass spectrometry

| Protease ^a | LTC ₄ -modified peptide [M+H ⁺] (m/z) | Corresponding unmodified peptide [M+H ⁺] (m/z) | Matched theoretical unmodified peptide [M+H ⁺] (m/z) | Mass accuracy (%) | Modified peptide ^b | Candidate peptide sequence | Predicted MRP1 domain ^c |
|-----------------------|---|---|---|-------------------|-------------------------------|---|------------------------------------|
| V8/tryp | 2528.41 | 1902.01 | 1901.05 | 0.048 | | ²⁶⁰ NWKKECAKTRKQPVK ²⁷⁴ | CL3 |
| Chymo/tryp | 2129.02 | 1503.40 | 1503.70 | -0.019 | | ³²⁰ TFGPYFLMSFFF ³³¹ | TM6 |
| Tryp/chymo | 2316.73 | 1691.98 | 1692.80 | -0.048 | | ³⁷² VTACLQTLVLHQYF ³⁸⁵ | TM7 |
| Chymo | 1494.35 | 868.63 | 868.42 | 0.024 | | ⁵⁴⁶ SAVGTFTW ⁵⁵³ | CL5/TM10 |
| V8/chymo | 3365.11 | 2739.74 | 2739.30 | 0.016 | Met-Ox | ¹²³³ SVSYSLQVTTYLNWLVRMSSEME ¹²⁵⁵ | TM17 |
| Chymo | 2590.42 | 1964.07 | 1963.99 | 0.004 | | ¹²⁴⁸ VRMSSEMETNIVAVERL ¹²⁶⁴ | TM17 cytoplasmic interface |

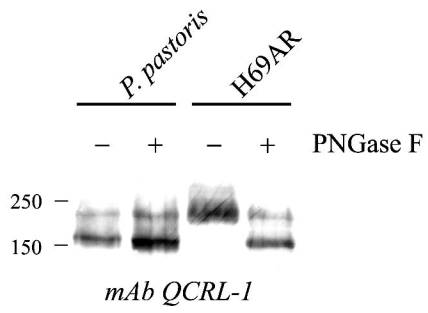
^aChymo, chymotrypsin; tryp, trypsin; V8, protease V8.

^bMet-ox, partial oxidation of methionine residues.

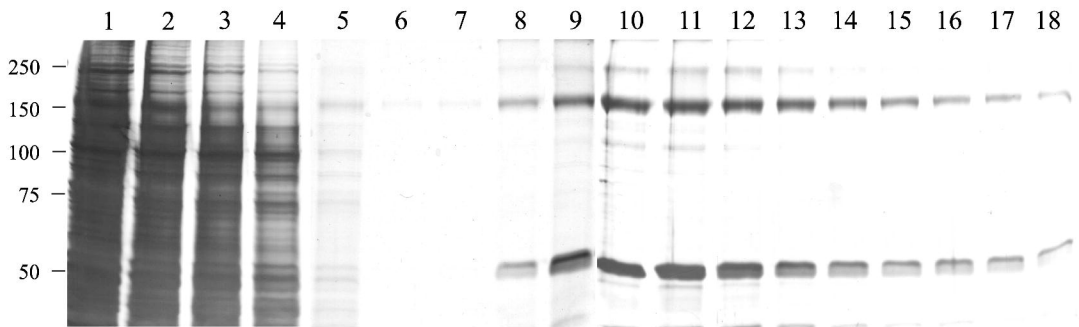
^cCL, cytoplasmic loop; TM, transmembrane helix.

Figure 1

A



B



C

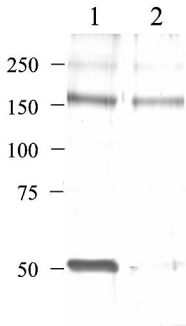


Figure 2

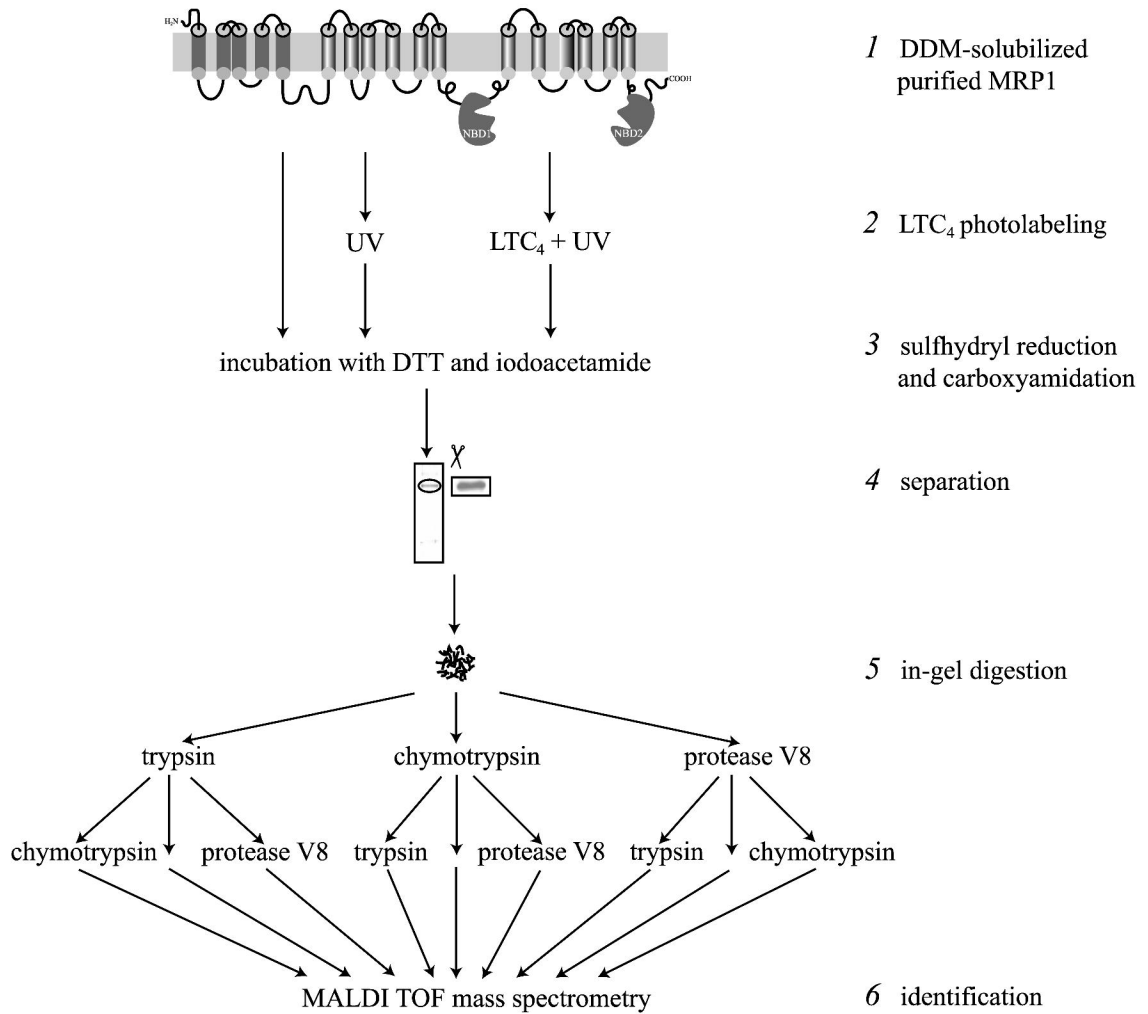


Figure 3

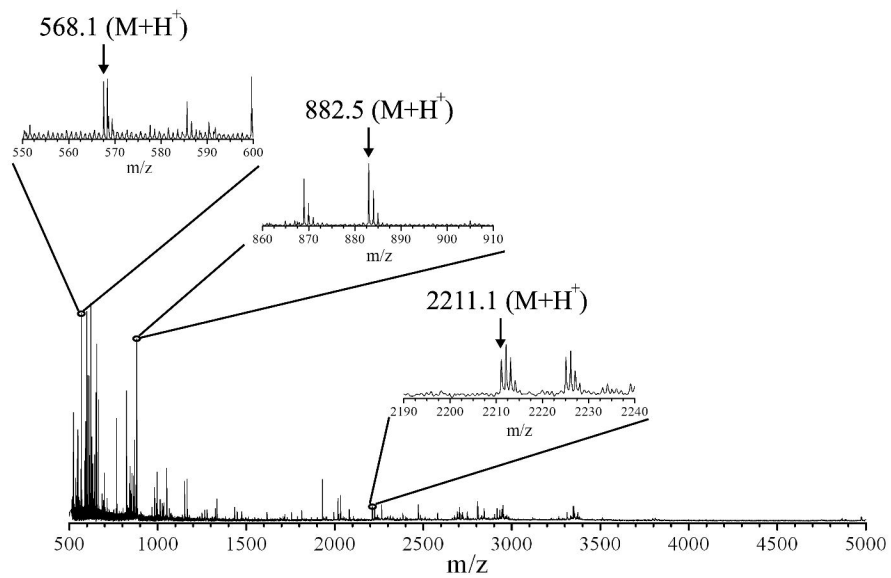


Figure 4

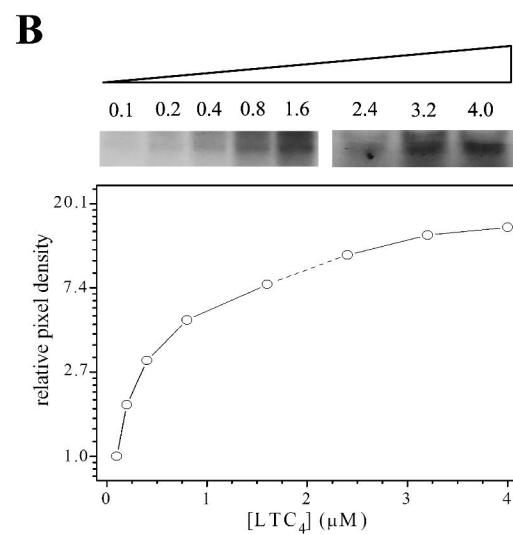
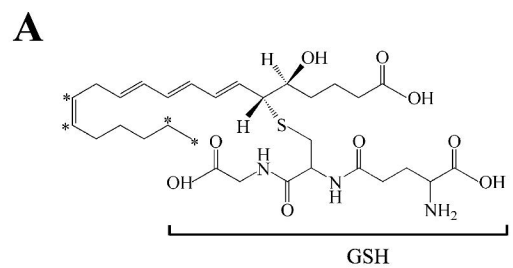


Figure 5

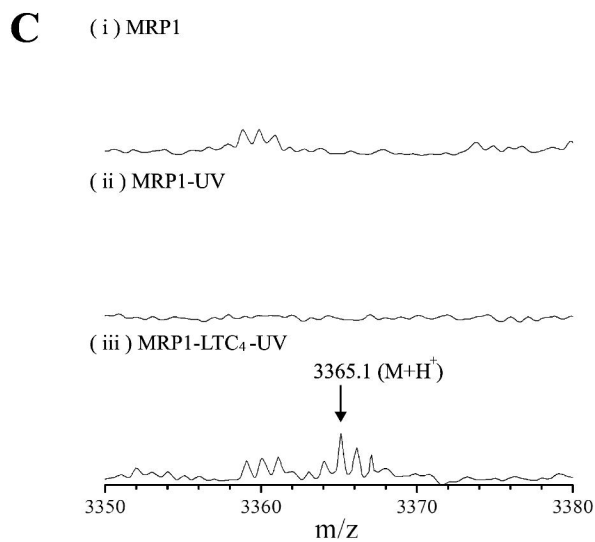
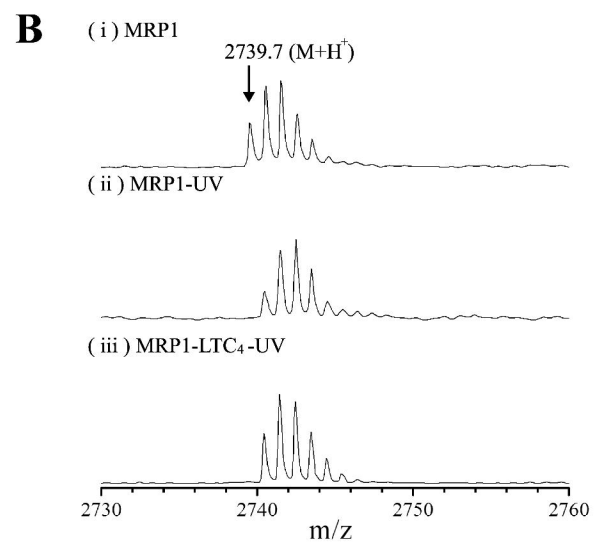
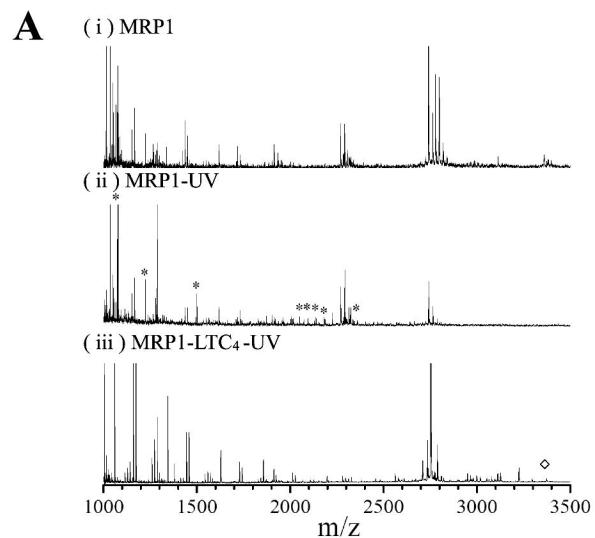


Figure 6

