Analysis of Electroblotted Proteins by Mass Spectrometry: Protein Identification after Western Blotting*§

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We describe a new approach for the identification and characterization by mass spectrometry of proteins that have been electroblotted onto nitrocellulose. Using this method (Blotting and Removal of Nitrocellulose (BARN)), proteins can be analyzed either as intact proteins for molecular weight determination or as peptides generated by on-membrane proteolysis. Acetone is used to dissolve the nitrocellulose and to precipitate the adsorbed proteins/peptides, thus removing the nitrocellulose which can interfere with MS analysis. This method offers improved protein coverage, especially for membrane proteins, such as uroplakins, because the extraction step after in-gel digestion is avoided. Moreover, removal of nitrocellulose from the sample solution allows sample analysis by both MALDI- and (LC) ESI-based mass spectrometers. Finally, we demonstrate the utility of BARN for the direct identification of soluble and membrane proteins after Western blotting, obtaining comparable or better results than with in-gel digestion. Molecular & Cellular Proteomics 7:308–314, 2008.

In-gel enzymatic digestion of gel-separated proteins followed by MS analysis is a powerful tool for protein identification and characterization of posttranslational modifications (1). However, this method has several major shortcomings, including low accessibility of proteases and other digestive reagents to the gel-entrapped proteins as well as a low recovery of large and/or hydrophobic peptides from the gels (2). These shortcomings can be especially problematic for the study of membrane proteins that typically contain hydrophobic peptides, and for the location and determination of posttranslational modifications, because modified residues and protein segments may escape detection (3). Several alternatives have therefore been developed to overcome these shortcomings, including the transfer of the gel-resolved proteins by electroblotting onto nitrocellulose (NC) (4–6) or PVDF membranes (7–9). An additional advantage of using electroblotted proteins is the possibility of analyzing intact proteins (3, 5) by avoiding inefficient and time-consuming gel extraction methods such as electroelution (10) and passive diffusion (11, 12).

After electroblotting, proteins usually are either digested on the membrane followed by extraction of the peptides from the polymer bands (4) and subsequent MS analysis, or the NC bands are dissolved directly in MALDI matrix solution after on-membrane digestion for MS analysis (5, 13). The first procedure suffers, however, from a similar limitation as in-gel digestion because the recovery of large and/or hydrophobic peptides can be low. The second procedure solves this problem because the peptides adsorbed onto the membrane are dissolved together with the NC. Acetone was originally used to dissolve the NC membrane, but the yield is low because of partial precipitation of proteins/peptides in acetone (5). We demonstrated in a previous paper (3) that this problem can be solved simply by replacing acetone with a mixture of 70:30 acetonitrile/methanol as the MALDI matrix solution. Compared with in-gel digestion, this improved method provided a doubling of the amino acid sequence coverage and better digestion efficiencies for integral membrane proteins such as uroplakins (3).

Although small amounts of NC have been added to the MALDI matrix solution to obtain homogeneous matrix crystalization and to enhance peptide detection (14, 15), high concentrations of nitrocellulose can interfere with MALDI-MS performance (3, 5). In addition, the presence of nitrocellulose in a sample mixture prevents the use of ESI-MS for analysis. In this article, we present a novel approach for the analysis of electroblotted proteins by both MALDI- and ESI-based mass spectrometers. This approach is based on the removal of the NC from the solution before MS analysis (Fig. 1), thus increasing the sensitivity and allowing the use of ESI-MS by direct infusion or after LC. This method (Blotting and Removal of Nitrocellulose [BARN]) also allows the identification of electroblotted proteins after Western blotting on the same NC.

The abbreviations used are: NC, nitrocellulose; α-CHCA, α-cyano-4-hydroxycinnamic acid; BARN, Blotting and Removal of Nitrocellulose; FA, formic acid; PVP-40, Poly (vinylpyrrolidone); UPII, uroplakin II; UPIII, uroplakin III; BSA, bovine serum albumin.
with (OM) or without (OM/NC-Free) removal of the nitrocellulose acetone/4 mm² NC), mixed by vortexing, and incubated for 30 min at room temperature. The acetone containing the dissolved NC was carefully removed and the precipitated peptides were air-dried. Resuspension of the peptides was carried out depending on the nature of the protein(s) and the mass spectrometer used for further analysis. For proteins analyzed by MALDI-MS, resuspension was carried out by adding 20 μl of 10 mg/ml of α-CHCA in either 1% TFA in 50:50 acetonitrile/water for soluble proteins or 1% TFA in 25:75 acetonitrile/methanol for membrane proteins. For soluble and membrane protein digests analyzed by LC-ESI-MS, the peptides were resuspended in 20 μl of 2% acetonitrile in 0.1% FA. All solutions were sonicated for 10 min before MS analysis.

In-gel digestion and the alternative on-membrane digestion method used to validate the NC-free approach were carried out according to previously published protocols (1, 3).

Western Blotting and Antibody Removal—A total of 0.1–1 μg of purified bovine asymmetric unit membranes (18–20) containing four major uroplakins (la, lb, II, and III) were dissolved in SDS loading buffer. Proteins were resolved by SDS-PAGE and transferred onto a nitrocellulose membrane. Uroplakin II (UPII) was detected by a monospecific polyclonal antibody against UPII and uroplakin III (UPIII) by a mouse monoclonal antibody against UPIII. Horseradish peroxidase-conjugated goat antirabbit or goat antimouse sera were used as secondary antibodies (Sigma), respectively, and visualized by ECL reagent (Pierce). Clean new dishes were used to avoid contamination by bovine serum albumin (BSA) or casein from previous Western blots (Pierce). Protein-free blocking buffer was used during incubation with primary and secondary antibodies.

The developed film was superimposed onto the original nitrocellulose membrane, and the proteins of interest were excised according to the Western blot signal. Antibody removal was carried out by three washes of the NC bands with 1.5 ml of 20 mM sodium bicarbonate buffer (pH 7.4) for 5 min each at room temperature, followed by three additional washes with 1.5 ml of 100 mM glycine (pH 2.4) for 10 min each at room temperature. Finally, the bands were washed again with 1.5 ml of 20 mM bicarbonate buffer (pH 7.4) for 5 min. Subsequent on-membrane digestion was carried out as described above.

MALDI Mass Spectrometry—Linear and reflectron mode MALDI-TOF mass spectra were acquired using a Micromass ToF Spec-2E mass spectrometer using standard parameters: a nitrogen laser (λ = 337 nm), laser pulse 39 ns, and accelerating voltage 20 kV. External calibration was carried out using angiotensin I (average mass, 1296.5 Da), corticotropin-like intermediate lobe peptide (ACTH clip 18–39, average mass, 2465.7 Da) for peptides mass measurements, or cytochrome c (average mass, 12230 Da), and bovine serum albumin (average mass, 66430 Da) for analyses of intact proteins. Typically, 100–200 laser shots were summed into each mass spectrum. The spectra obtained were processed using MassLynx MaxEnt 3 (Micromass) software.

Nanoflow LC-MS/MS was also used for the analysis of peptide mixtures from tryptic on-membrane and in-gel digestions. The peptides were loaded onto a 0.3 × 1-mm C18 nano-precolumn (LC Packings) and then washed 5 min with 2% acetonitrile in 0.1% FA at a flow rate of 20 μl/min. After washing, flow was reversed through the precolumn and the peptides eluted with a gradient 2–90% acetonitrile in 0.1% FA. The gradient was delivered over 120 min by a CapLC (Waters) HPLC system at a flow rate of 200 nl/min, obtained by a 15:1 gradient from 0 to 90% acetonitrile in 0.1% FA over 12 min. The Q-TOF micro (Micromass) data acquisition involved MS survey scans and automatic data-dependent MS/MS acquisition, which were invoked after selected ions met preset parameters of minimum signal intensity of 12 counts per second, ion charge state +2, +3, or +4, and

Fig. 1. Steps required for in-gel and on-membrane digestion with (OM) or without (OM/NC-Free) removal of the nitrocellulose membrane.
appropriate retention time. Survey scans of 1 s were followed by CID of the three most intense ions for up to 6 s each, or until 5000 total MS/MS ion counts per precursor peptide were achieved. The raw MS data were subsequently processed using manufacturer-supplied ProteinLynx 3.5 software, with the following settings: Background subtraction of polynomial order 10 below a 10% curve, 1 smooth with a window of two channels in Savitzky Golay mode, followed by centroid calculation of the top 80% of peaks based on a minimum peak width of 4 channels at half-height. On the basis of these parameters, pkf files incorporating parent ion mass and retention time as well as peak lists for each corresponding MS/MS spectrum were generated. In-house Mascot software (version 2.0.00, Matrix Science) was used for database searching and protein identification using the mammalian database from National Center for Biotechnology Information with a minimum parent-ion and fragment-ion mass accuracy of 0.3 Da.

RESULTS

Optimization of the Variables—We first wanted to optimize the conditions such as the composition and volume of the organic solvent used for dissolving the NC membrane and the precipitation of the proteins/peptides, the time and temperature of the precipitation step, and the solution used for redissolving the precipitated proteins/peptides before MS analysis.

One of the key features of our NC-free method is that we dissolve the NC membrane using an organic solvent, which simultaneously precipitates the electroblotted proteins/peptides, thus separating them in a single step. We tested acetone, acetonitrile, methanol, and ethanol for this purpose, and we found that the use of acetone provided the best MALDI-MS results for intact myoglobin and especially for intact BSA (supplemental Fig. 1a). These data are consistent with the fact that acetone is one of the most widely used solvents for protein precipitation (21).

We tested precipitation times between 10 and 180 min. The MS signal increased after 10–30 min of precipitation but started to decrease with longer times, possibly because of partial redissolution of the proteins/peptides after longer times. Thus, 30 min was selected as optimum precipitation time for subsequent experiments (supplemental Fig. 1b).

We compared the use of acetone at room temperature (21 °C) and −20 °C. Even though most protocols use cold acetone to precipitate proteins, we found that acetone at room temperature actually gave better MS signals for both myoglobin (supplemental Fig. 1c) and BSA (supplemental Fig. 1d) (21). It is possible that, although cold acetone is more efficient for precipitating proteins, it might be less effective in dissolving the NC, leading to the partial suppression of the MS signal.

Different volumes of acetone to dissolve the NC and precipitate the proteins/peptides were also tested. Using larger volumes of acetone (30 μl/mm² NC) facilitated the dissolution of the NC membrane but probably decreased the recovery of the proteins, thus leading to reduced MS signals. We found 22.5 μl of acetone per mm² of NC to give the highest MS signals (supplemental Fig. 1, c and d).

We also tested various solutions to be used for redissolving the acetone-precipitated proteins/peptides. The optimal solution depended on whether intact proteins or peptides were analyzed and on what kind of mass spectrometer was to be used for subsequent analysis. For the analysis of intact proteins using MALDI-MS, we tested the ability of binary mixtures of acetonitrile/methanol at different ratios to redissolve soluble (myoglobin and BSA) and membrane (UP1 and UP1II) proteins. All the solutions were prepared in 10 mg/ml α-CHCA and 1% TFA (3). In all cases (supplemental Fig. 2a), we obtained the best MS signal with the 25:75 acetonitrile/methanol mixture, so this condition was used for all subsequent studies. For the analysis of digested proteins by MALDI-MS, we tested various mixtures of acetonitrile, methanol, and water (supplemental Fig. 2, c and d). We obtained different results depending on the nature of the proteins analyzed. For soluble proteins, we obtained the best MS signal (supplemental Fig. 2c) as well as the best protein coverage (supplemental Fig. 2d) when using a binary mixture of 50:50 acetonitrile/water, which we therefore used for further experiments. For membrane proteins that contained many hydrophobic peptides, although mixtures of acetonitrile/water gave the best MS signal (supplemental Fig. 2c), acetonitrile/methanol gave a better protein coverage most likely because hydrophobic peptides were better redissolved, and thus detected by MALDI-MS, in the absence of water (supplemental Fig. 2d). For this reason, we used 75:25 methanol/acetonitrile to analyze digested membrane proteins in subsequent experiments. When using direct infusion ESI-MS, the solution used must be able to redissolve the precipitated proteins/peptides and to provide a good and stable ion spray. It is well known that solutions with a moderate to high percentage of water provide a more stable spray. When we tested different mixtures of acetonitrile, methanol, and water to redissolve intact proteins before ESI-MS analysis by direct infusion, we obtained the best results using 2% acetonitrile, whereas solutions with a high organic solvent content could not be used because the spray was too unstable. Another key variable that highly increased the signal-to-noise ratio was the FA content. Different concentrations of FA were compared, and the best results were obtained with solutions containing 3% FA (supplemental Fig. 3). For LC-MS analysis, we resuspended the samples in 2% acetonitrile, 0.1% FA to maximize binding of the proteins/peptides to the reverse phase column.

Evaluation of Different Protein Digestion Strategies—After electroblotting the proteins onto the NC membrane, the intact proteins can be enzymatically digested on-membrane before removal of the NC or digested in-solution after removal of the NC prior to mass spectrometry. For the former strategy, we digested electroblotted myoglobin and BSA on-membrane with or without Rapigest. For the latter, we digested the same proteins in-solution in the presence or absence of 10% acetonitrile, urea, Rapigest, and the combination of 10% acetonitrile and urea. We obtained better coverage for both proteins using the on-membrane digestion strategy with no significant
differences observed between using Rapigest or not (supplementary Fig. 4).

**MALDI-MS Analysis after Removal of NC**—To evaluate the suitability of the NC-free method for the determination of the molecular weight of intact proteins by MALDI-MS, we compared this approach with a previously published method (3) that was based on the direct dissolution of the protein together with the NC band in the MALDI matrix solution. Myoglobin, BSA, UPII, and UPIII were used as models of soluble and integral membrane proteins. Although both methods worked quite efficiently and could detect as little as 200 fmol of myoglobin, the NC-free approach gave better signal intensity, providing almost twice the ion counts for the same protein concentration as compared with the previous method without removing the NC prior to MS (supplemental Fig. 5).

We also compared MALDI-TOF MS of digested membrane proteins prepared using the on-membrane digestion followed by NC-removal, in-gel digestion, or the previous on-membrane digestion method without NC removal (3). The NC-free on-membrane digestion method provided the same protein coverage as the previous on-membrane digestion method (almost double when compared with in-gel digestion for UPII and UPIII) but with a better signal-to-noise ratio, similar to that obtained after in-gel digestion (Fig. 2). We conclude that the NC-free approach is as sensitive as in-gel digestion but with the advantage of allowing the identification of large and/or hydrophobic peptides by MALDI-MS that can be missed after in-gel digestion.

**LC-ESI-MS/MS Analysis after On-membrane Digestion Followed by Removal of NC**—The main advantage of the NC-free on-membrane digestion method is that the nitrocellulose is removed from the solution before MS analysis, thus allowing the analysis of digested proteins by LC-ESI-MS for protein identification. When we compared this method with in-gel digestion, similar results were obtained in terms of protein sequence coverage, signal-to-noise ratio, and Mascot scores obtained by LC-MS/MS analysis. The number of peptides identified and the quality of the MS/MS spectra obtained for in-gel and on-membrane digested BSA and myoglobin were very similar (Fig. 3).

**Application of the NC-free/On-membrane Digestion Method to Protein Identification after Western Blotting**—One of the most important advantages of this new method is the ability to identify proteins by MS after Western blotting, using the same NC membrane band for the identification and the Western blot. For this purpose, it is mandatory that we use a protein-free blocking agent during the Western blot procedure to avoid interfering with the subsequent mass spectrometric analysis. For this purpose, we tested a commercially available protein-free blocking buffer for the identification of UPII and UPIII by Western blot (Fig. 4). After Western blotting, we excised the NC bands containing UPII and UPIII, removed bound antibodies with several glycine washes, and digested the proteins on membrane with trypsin (see “Materials and Methods” for details). The same proteins at the same concentrations were also processed in parallel using conventional in-gel digestion for validation. Similar Mascot probability scores and protein coverage were obtained for the identification by LC-MS/MS of UPII (Table I). In the case
of UPIII, 3 peptides were identified after in-gel digestion providing a Mascot score of 227 (Table I), whereas on-membrane digestion identified five peptides leading to a Mascot score of 394 (Table I). The two additional peptides detected after Western blotting and on-membrane digestion were identified with high quality MS/MS spectra and high Mascot scores (81 and 96) (Fig. 5). As previously demonstrated by MALDI-MS, we identified by LC-MS/MS an equal or larger number of peptides after on-membrane digestion of electroblotted proteins than after in-gel digestion, even after carrying out a previous Western blot on the same protein bands.

DISCUSSION

Here we describe a novel approach for MS analysis of proteins that have been electroblotted onto NC membranes. Addition of acetone at room temperature to the blotted membranes dissolves the NC and at the same time precipitates the proteins and peptides. The precipitated proteins/peptides are then analyzed by MS after the dissolved nitrocellulose is removed and the proteins/peptides redissolved. This method has several advantages over conventional in-gel digestion, especially when dealing with membrane proteins that usually contain large and/or hydrophobic tryptic peptides. The method has been designed to minimize the amount of NC in
the final sample solution to avoid the suppression of the MS signal and to allow the use of ESI-based mass spectrometric techniques. Moreover, the method avoids the need for peptide extraction required by in-gel digestion and by some of the previously published methods for on-membrane digestion of electroblotted proteins. We demonstrated the utility of the method for both MALDI-MS and LC-MS/MS.

An important feature of this novel approach is that it enables the analysis of proteins by MS after Western blotting of the same NC band that contains the immunoreactive proteins. This can be extremely useful for determining antibody specificity, for the identification of cross-reactive as well as modified or degraded proteins, for the detection of a group of proteins with a common posttranslational modification using an antibody specific for that particular modification, and for protein crosslinking studies. Methods for analyzing proteins detected by Western blotting on NC (16, 22) or PVDF (23) membranes have been described based on peptide extraction from the NC or PVDF after on-membrane digestion. However, it is known that proteins can bind strongly to NC or PVDF (5, 24), leading to inefficient extraction from the membranes, especially for large and/or hydrophobic peptides. Our method circumvents this problem by avoiding any extraction step.

We validated our NC-free method using two membrane proteins, UPII and UPIII, and the results showed that successful on-membrane digestion of proteins after Western blotting followed by MS analysis is not only possible, but it can even provide better protein sequence coverage, and thus, more confident protein identification, than conventional in-gel digestion.

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REFERENCES


