Exogenous Production of N-acetylmuramyl-L Alanine Amidase (LysM2) from Siphoviridae Phage Affecting Anti-Gram-Negative Bacteria: Evaluation of Its Structure and Function

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Abstract

Background: To obtain endolysin with impact(s) on gram-negative bacteria as well as gram-positive bacteria, N-acetylmuramyl L-alanine-amidase (MurNAc-LAA) from a Bacillus subtilis-hosted Siphoviridae phage (SPP1 phage, Subtilis Phage Pavia 1) was exogenously expressed in Escherichia coli (E. coli).

Methods: The sequences of MurNAc-LAA genes encoding peptidoglycan hydrolases were obtained from the Virus-Host database. The sequence of MurNAc-LAA was optimized by GenScript software to generate MurNAc-LAA-MMI (LysM2) for optimal expression in E. coli. Furthermore, the structure and function of LysM2 was evaluated in silico. The optimized gene was synthesized, subcloned in the pET28a, and expressed in E. coli/BL21(DE3). The antibacterial effects of the protein on the peptidoglycan substrates were studied.

Results: LysM2, on 816 bp gene encoding a 33 kDa protein was confirmed as specific SPP1 phage enzyme. The enzyme is composed of 271 amino acids, with a half-life of 10 hr in E. coli. In silico analyses showed 34.2% alpha-helix in the secondary structure, hydroporphic N-terminal, and lysine-rich C-terminal, and no antigenic properties in LysM2 protein. This optimized endolysin revealed impacts against Proteus (sp) by turbidity, and an antibacterial activity against Klebsiella pneumoniae, Salmonella typhi-murium, and Proteus vulgaris in agar diffusion assays.

Conclusion: Taken together, our results confirmed that LysM2 is an inhibiting agent for gram-negative bacteria.

Keywords: Antibacterial activity, Bacteriophage SPP1, Endolysin, Siphoviridae

Introduction

Cell wall protects the cells from the turgor pressure and helps maintenance of the cell shape in bacteria. Accordingly, every bacterial cell wall destructor is known as an antibacterial agent 1. Today, the cell wall hyrolyzing enzymes from bacteriophages targeting the peptidoglycan subunits have been the main concern because of their specific action and lack of drug-resistant effects. The peptidoglycan-hydrolyzing enzyme (Endolysin) as an antibacterial agent cleaves the linkage between peptide and carbohydrates in the peptidoglycan 2. Endolysins have several important advantages in comparison to antibiotics. The enzymes lyse bacterial cell wall within minutes to a few hours 3. They are active against both growing and dormant cells, disrupt bacterial biofilms, and kill drug-resistant strains 3. Bacteriophage-derived endolysins are potentially a long-term antibacterial replacement for antibiotics 4.

The catalytic and binding domains of endolysin are connected via a short linker 5. The enzymes attach to their target by the Cell wall Binding Domains (CBDs) and digest the peptidoglycan’s linkages through Enzymatically Active Domains (EADs) 2. Gram-negative and gram-positive bacteria differ in their endolysins’ structures. Gram-positive endolysins are composed of separate CBDs and EADs while single domain globular protein forms the most gram-negative endolysin 4.5. The endolysins cannot disrupt the cell membrane of gram-negative bacteria and only their structure and/or function can lead to outer membrane penetration 6. However, the enzymes either in combination with the membrane permeability or in conjugation with a small
RNA secondary structure was used to study RNA stability \(^1\). The molecular weight of LysM2 protein, the abundance of amino acids, and half-life of protein were determined by ProtParam software (https://web.expasy.org/protparam/). The hydrophobicity of LysM2 was plotted on the Kyte-Doolittle scale using the ProtScale tool \(^1\). Secondary structure was obtained by the self-optimized prediction method (SOPMA) (https://np-3-prabi.ibcp.fr/cgi-bin/npsa_automat.pl?page=NPSA/npsasopma.html) \(^1\) and PSIPRED server (http://bioinf.cs.ucl.ac.uk/psipred/). The transmembrane helix was predicted using TMHMM v 2.0 \(^1\). The three-dimensional (3D) model for the amidase was predicted using Protein Homology/analog\(Y\) Recognition Engine V 2.0 (Phyre2) software \(^1\) and validated by PROSA-web (Protein Structure Analysis) \(^2\). The 3-D structure of molecules was analyzed by the Ramachandran plot \(^3\), FT site server (https://ftsite. bu.edu/) predicted the active-site (s) in the tertiary structure.

**Localization of LysM2 protein in the host cell and antigenicity**

The subcellular location of LysM2 protein in the host cell was predicted by the Virus-mPLoc software (https://www.psort.org). The antigenicity of LysM2 protein was evaluated by the Vaxijen software 2 (http://www.ddgpharmfac.net/vaxijen/VaxiJen/VaxiJen.html) \(^2\). The potential for toxicity of LysM2 was predicted using the BTXpred (Prediction of Bacterial Toxins) server (http://crdd.osdd.net/raghava/btxpred/).

**Cloning and expression of LysM2 gene**

The cutting sites for BamHI (Sinaclon, Iran) and SacI (Termo Fisher Scientific, USA) restriction enzymes were respectively introduced at 5' and 3' end of the coding sequence. The LysM2 gene was restricted using BamHI/SacI from pUC57/LysM2, and ligated into pET28a vector with the same enzymes. The generated construct, pMM2 (pET28a/LysM2), was introduced into the E. coli B121 (DE3) cells. The transformed cells were selected on LB agar supplemented with 40 \(\mu\)g/ml kanamycin (Sigma-Aldrich, USA). The cloning procedure was confirmed by BamHI/SacI digestion analysis.

The expression of pMM2 was induced by 1 \(mM\) isopropyl\(\beta\)-galactoside (IPTG) (DNAbiotech, Iran) at 28°C for 20 hr. The cells were suspended in 20 \(mM\) NaH\(\text{PO}_4\), 500 \(mM\) NaCl, and 50 \(mM\) Imidazole (Merck, Germany) buffer (pH=7.2-7.4), sonicated on ice for 10 min (90 w, 30 s at 7 s interval), and centrifuged at 15000xg for 20 min. The supernatant was collected. As a negative control, all the above steps were carried out for an uninduced E. coli BL21(DE3) harboring pMM12. Fractions were analyzed on sodium dodecyl sulfate-polyacrylamide gel electrophoresis (SDS-PAGE) for protein expression of pMM12. Protein purification was done by NI-NTA affinity chromatography (DNAbiotech, Iran). The column was eluted with a range of Imidazole concentrations as 20-150.
mM (50 mM NaH2PO4; 300 mM NaCl; pH=7.7), dia-
lyzed against Phosphate-Buffered Saline (PBS), and
analyzed on SDS-PAGE. The amount of LysM2 pro-
tein was measured by Bradford assay.

Evaluation of the enzyme activity

The lysed cell wall of the indicator bacteria, Strept-
tococcus pyogenes (S. pyogenes) (ATCC 19615), Ba-
cillus subtilis (B. subtilis) (ATCC 12711), Bacillus (sp)
(SUBC1001), Staphylococcus aureus (S. aureus) (ATCC-
25923), Pseudomonas aeruginosa (P. aeruginosa) (AT-
CC27853), E. coli (ATCC25-922), Salmonella (sp.)
(SUBC1002), Proteus (sp.) (SUBC1003), Klebsiella
pneumonia (K. pneumonia) (ATCC13883), Salmonella
typhimurium (S. typhimurium) (SUBC1005), Proteus
vulgaris (P. vulgaris) (SU-BC1006), and a clinical K.
pneumoniae (SUBC1004) was prepared for evaluating
the enzyme activity as previously described 23. Briefly,
the heat-killed indicator bacteria were added to LB
medium. The plates were punched to make 8
wells that reduced the turbidity of the heat
incubated at 37°C for 70 min. A volume of the enzyme
that reduced the turbidity of the heat-killed indicators
to 50% was introduced as the enzyme activity.

Results

LysM2 gene construction

The LysM2 gene with 828 nucleotides in length was
subcloned from pUC57 in pET28a. The codon prefer-
ence was adjusted for E. coli and the conservation of
the LysM2 sequence was evaluated by GenScript soft-
ware.

In silico study of LysM2 protein

Sequence analysis: The most similar protein to Mur-
NAC-LAA from B. subtilis phage was found in Firmic-
utes bacteria upon a comparison among 100 endolysins
harboring the MurNAC-LAA domain in the GenBank
(Figure 1A). BLASTp homology analyses revealed a
conservativity (86% to 96% identity) among MurNAC-
LAA enzymes from Bacillus phages. The catalytic
domain of LysM2 protein against the bacterial cell wall
was investigated in silico (Figure 1B). The whole gene
similarity was 80% at nucleotide level within the Mur-
NAC-LAA family. The prediction of the mRNA struc-
ture for LysM2 confirmed the availability of enough
free energy for the optimum expression.

The study of physico-chemical parameters

ProtParam analyses demonstrated that LysM2 is a
protein of 271 amino acids in length with the alpha-
index of 83.87, half-life of more than 10 hr in E. coli,
20 hr in yeast, and 30 hr in mammalian reticulocytes
(in vitro), and the molecular weight of 29.7 kDa. The
LysM2 protein showed a stability index of 40.48 where
a value of more than 20.48 indicates stability in protein
life of more than 10

Figure 1. A) The phylogenetic tree for the optimized LysM2, based on the Neighbor-Joining method. B) In silico investigation of the catalytic domain of LysM2
LysM2 is a stable protein in structure.

**Evaluation of the secondary and tertiary structure**

The secondary structure of the LysM2 enzyme exhibited a proportion of 34.2% of alpha-helix, 23.23% of extended strand, 4.43% of beta-turn, and 36.9% of random coil (Figures 2A and 2B). A total residue of 248 (91.5%) was modeled with 100.0% confidence in the crystal structure of the MurNAc-LAA from *E. coli*. The frequency of positively charged amino acids is higher than the N-terminal end of the protein (aa 1-150) (Figure 2C). LysM2 was found as a hydrophobic nonpolar molecule due to the presence of hydrophobic residues at the N-terminal end. The PI value was detected as 9.67 for the lysine and alanine. These two amino acids have tendency to form alpha helices. The active sites for LysM2 enzyme are demonstrated in figure 2D. The FT software predicted three active sites in the tertiary structure of the LysM2 enzyme. The second active site was similar to the active sites predicted by NCBI-tool. Using RAMPAGE server, the proposed model for LysM2 protein was evaluated. The results showed that 2.2% of the residues were in the outlier region, 5.6% in the allowed area, and 92.1% of amino acids in the favored region. Consequently, 97.7% of the amino acids were located in a stable situation. Z-score was measured as -6.12 in comparison with the pre-determining structures (Figures 3A and 3B).

**Localization of LysM2 protein in the host cell and the antigenicity**

LysM2 protein was predicted to localize in the protoplasm of the host cells. The antigenic properties were analyzed using Vaxijen software 2. The value of 0.4, lower than 0.5038, suggests no antigenic properties for LysM2. The BTXpred server predicted the toxicity of LysM2 protein for bacteria based on analyzing the primary structure (SVM model).

**Cloning and expression of LysM2 gene**

The construct of LysM2 gene (pMMI2) was transformed into *E. coli* BL21(DE3). The purified protein was run on a 12% polyacrylamide SDS-PAGE. The protein of 33 kDa related to LysM2 was detected on the SDS-PAGE (Figure 4). The yield of protein from *E. coli* was obtained as 0.8 mg protein per 1 gr cell and the specific activity was 2 U per 0.2 mg/ml protein.

**Antibacterial activity assay**

The enzyme activity was measured by monitoring the cell wall lysis via agar well-diffusion method. The results of the agar diffusion assay showed a relatively optimal antimicrobial activity of 2950 AU in diameter against *K. pneumoniae*, 6010 AU for *S. typhi* murium, and 6730 AU for *P. vulgaris* (Figure 5A).

The culture turbidity of the indicator strains was reduced subject to the natural extraction of the LysM2 protein. The lytic activity was determined only on the...
Exogenous Production of LysM2 from Siphoviridae Phage

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Proteus sp. as depicted in figure 5B. The unit activity was calculated as 2 Unit/ml.

Discussion

Endolysins lyse the cell wall of gram-positive bacteria, while an outer membrane protein supports gram-negative bacteria. However, endolysins either in companion with holins or with a cationic N or C-terminal tail kill the gram-negative bacteria.

In this study, an endolysin called LysM2, from a Siphoviridae phage was exogenously expressed in E. coli. The 29.7 kDa amidase was analyzed in silico. The presence of 34.2% alpha-helix with positive hydrophobic amino acids in the N-terminal end of the enzyme confirmed LysM2 as a nonpolar molecule similar to lipopolysaccharide molecules in the membrane. These data suggest the possible interaction(s) between the N-terminal region and lipopolysaccharide in the outer membrane of the bacteria.

Amphipathic peptides with a modular structure containing alpha-helix kill the bacteria by a mechanism independent of their enzyme activity. Positively charged amino acid in companion with amphipathic helical structure showed a stronger bactericidal activity.

MurNAc-LAA contains amino acids with a net positive charge (Lysine residues) at C-terminus which help them to interact with the inner layer of the cytoplasmic membrane. In this study, the 33 kDa enzyme is featured as a nonpolar protein with the hydrophobic N-terminal structure in alpha-helix similar to lipopolysaccharide of gram-negatives outer membrane. LysM2 contains a lysine rich C-terminus similar to other members of MurNac-LAA family.

Regamey and Karamata cloned and expressed blyA gene encoding 39.6 kDa MurNac-LAA. Using mutagenesis method to determine the function of blyA, the role of this enzyme in Spβ phage-mediated cell-lysis was confirmed. Furthermore, two ORFs encoding polypeptides as holins or with a cationic N or C-terminal tail kill the gram-negative bacteria.

Figure 3. A) Evaluation of LysM2 protein stability based on Ramachandran plot showed 2.2% of the residues were in the outlier region; 5.6% in the allowed area, and 92.1% of amino acids in the favored region. B) The results of analyzing LysM2 protein with the ProSA web server; Z-score plot, NMR spectroscopy (dark blue), and X-ray crystallography (light blue); the plot showed local model quality using plotting energies as a function of amino acids position in the sequence.

Figure 4. The photogram of LysM2 protein on 12% SDS-PAGE. The relevant 33 kDa band is indicated in the Lanes 1, 2: LysM2 protein, Lane 3: Control, Lanes 4, 5: Purified protein, Lane 6: Ladder protein 10-250 kDa, Lane 7: Purified control without IPTG induction, Lane 8: E. coli BL21DE3, Lane 9: Pre induction of pET28a without the insert.

Figure 5. A) Agar diffusion of LysM2 against Proteus (sp). B) The lytic activity of LysM2 against Proteus (sp).
in the gram-negative bacteria. Lai et al identified a phage lysozyme, LysAB2. Antibacterial analysis demonstrated the impact of LysAB2 on the cell wall of *A. baumannii* and *S. aureus*. The recombinant LysAB2 lysed cell wall of several gram-negative and gram-positive bacteria.

The membrane destabilizing agents such as poly-l-lysine, polymyxin B, ethylenediaminetetraacetic acid disodium (EDTA), or highly charged-hydrophobic amino acid residues increase the membrane permeability to lysins. Oliveira et al studied the endolysins from *Salmonella* phage including Lys68, SPN1S, and SPN9CC with anti-gram-negative and without anti-gram-positive activities. A *Salmonella* phage endolysin (Lys68) in combination with EDTA, citric acid, and malic acid lyse many gram-negative bacteria. The enzyme caused 3 to 5 log reductions in bacterial load/CFUs after 2 hr against *S. typhimurium* LT2 and diminished stationary-phase and bacterial biofilms by about 1 log. This evidence demonstrates that in the absence of holins, a membrane destabilizer like EDTA is required for cell wall destruction. In contrast, there are some documents showing no need for EDTA or holins to make the membrane permeable. Dong et al produced exogenous Maltocin P28, a phage-tail like bacteriocin, that harbors the conserved domain of lysozyme-like superfamily. The recombinant P28 destroys gram-negative bacteria in the absence of EDTA. A putative helix domain in the N-terminal hydrophobic region was documented for P28 similar to LysM226.

To count the endolysins as antibacterial agents, the mechanism of action for these enzymes must be determined. Investigation on the mechanism of action of the peptidoglycan cleaving enzyme was done by Yakhnina and Bernhardt. They demonstrated that the multiprotein Tol-Pal system in the envelope of gram-negative bacteria is linked with remodeling of peptidoglycan in outer membrane of *E. coli* and with the hypersensitivity to many antibiotics. *E. coli* Tol-Pal mutants have incomplete peptidoglycan layer.

Heidrich reported that in the presence of antibiotics, three amidases are involved in splitting murein septum during cell division in *E. coli*. The murein cross-bridges cleaves and blocks cell division. Some studies revealed that the engineering of catalytic domain in MurNac-LAA amidase presumably is not a short way to acquire the desired endolysins. Morita et al showed that both the C-terminal cell-binding and the N-terminal enzymatic domains are required for the enzymatic activity of phage endolysin from *Bacillus amyloliquefaciens*. This protein has two helical peptides at the C-terminus of endolysin that may bind to the lipopolysaccharide of *P. aeruginosa* PAO16.

Exogenous expression of amidase in *E. coli* is a promising method for the enzyme production. In this study, an *E. coli* optimized amidase, LysM2, showed anti-*Proteus* (sp), a relatively anti-*K. pneumoniae*, anti-*S. typhimurium*, and anti-*P. vulgaris* activities. Scheurwater et al studied, cloned, and expressed the N-acetylmuramoyl-L-alanine amidase gene B (AmiB) from *P. aeruginosa* in *E. coli*. AmiB (50 kDa) digests *M. luteus* peptidoglycan as a substrate in 5 mM sodium phosphate buffer at pH=6.5. The specific activity of 4.4 ∆OD.660U·min⁻¹·mg protein⁻¹ was reported for AmiB. Moreover, it degrades the purified insoluble peptidoglycan from gram-negative bacterium, *P. aeruginosa*.

Magdalena Plotka et al showed that the antibacterial spectrum of endolysins is related to the type and structure of the outer membrane. *Acinetobacter* and *Pseudomonas* were susceptible to Ts2631 endolysin. The high number of phosphate groups per lipopolysaccharide molecule in the cell wall of these two bacteria help the Ts2631 with cationic N-terminal for destabilizing action. In contrast, *Enterobacteria* lacks such a highly negative charge per lipopolysaccharide molecule, protecting against Ts2631 function. Recently, a lytic enzyme, LysC, from *Clostridium intestinale* was introduced. Its antibacterial activity is mediated by positively charged N-terminal extension.

Haddad et al designed a chimeric CHAP-amidase for improving the stability and solubility of the enzyme. Significant antibacterial activity against *S. aureus* MRSA252 was reported applying 1 µg/ml chimeric CHAP-amidase. The protein showed strong antibacterial activity against *S. epidermidis*, *S. aureus*, and *Enterococcus* (sp) while notable antibacterial activity was detected against *E. coli* and *L. lactis*. The synergistic effect of CHAP-amidase and vancomycin indicates an 8-fold decrease in the minimum inhibitory concentration of vancomycin.

The MurNac-LAA belongs to either amidase-2 or amidase-3 zinc-dependent families, cleaves the amide linkage between N-acetylmuramic acid and L-alanine. The amidase-2 domain is formed by a water molecule with the side chains of histidine, cysteine residues, and a zinc ion. The catalytic domain in PlyPSA and CD27L proteins belongs to amidase-3 family, showing a different enzymatic activity despite highly similar mode of action and 3D structure.

Furthermore, other documents demonstrate that catalytic modular domain of lysins is efficiently substituted with other lysins for the new bactericidal features. In this study, the enzyme with a catalytic domain of endolysin, LysM2, inhibited *P. vulgaris*, *K. pneumoniae*, and *S. typhimurium*. Both cell binding domain and catalytic domain contribute in the lytic activity of MurNac-LAA amidases. The cell wall binding domain in MurNac-LAA may alter the toxicity of the endolysin via increasing or decreasing the rate of enzyme-substrate contact. Therefore, engineering the binding domain in the amidase can optimize its lytic effects on the targeted bacteria. Engineering the binding domain and catalytic domain of LysM2 should be studied in further research.
Conclusion

The gene and amino acid sequences of peptidoglycan hydrolase enzymes in lysogenic phages of the Siphoviridae family hosted in *B. subtilis* were investigated in this study. The molecular weight of the protein was calculated as 33 kDa with 271 amino acids in length. The enzyme half-life was estimated to be at least 10 hr in *E. coli*. The protein secondary structure predominantly contains alpha-helix. LysM2 exhibited no antigenic properties in *in silico* analyses. LysM2 protein showed an antimicrobial activity against *K. pneumoniae*, and *S. typhimurium* in agar diffusion assay and *P. vulgaris* and *Proteus* (sp) in turbidity assay. Taken together, our results confirmed that MurNAC-LAAa-MM1 is an inhibiting agent for gram-negative bacteria.

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Conflict of Interest

The authors declare that they have no competing interest.

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