



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, hydrophobic 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 typhimurium*, and *Proteus vulgaris* in agar diffusion assays.

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

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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 agent¹. Today, the cell wall hydrolyzing 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 peptidoglycan². Endolysins have several important advantages in comparison to antibiotics. The enzymes lyse bacterial cell wall within minutes to a few hours³. They are active against both growing and dormant cells, disrupt bacterial biofilms, and kill drug-resistant strains³. Bacteriophage-derived endolysins are poten-

tially a long-term antibacterial replacement for antibiotics³.

The catalytic and binding domains of endolysin are connected *via* a short linker⁴. The enzymes attach to their target by the Cell wall Binding Domains (CBDs) and digest the peptidoglycan's linkages through Enzymatically Active Domains (EADs)⁵. 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 penetration⁶. However, the enzymes either in combination with the membrane permeability or in conjugation with a small

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protein, holin, kill the gram-negatives. Holin makes a hole in the cell membrane of gram-negative bacteria ⁷.

Although the new sequencing methods and types of equipment have entailed a revolution in genome data, less than 1000 endolysins have been characterized ⁸. The limited knowledge about the mode of action plus the specific targeting of endolysins has sparked the idea to produce recombinant endolysins with desired features ⁸. They are suitable in two different aspects. The first, as mentioned above, is the specific digestion of the cell wall, which does not lead to antibacterial resistance impacts. The second is the possibility to engineer the endolysin domains for a new desired feature. Endolysin as a functional protein can be rearranged *via* normal genetic engineering methods whereas altering non-peptide antibacterial compounds is more difficult and complicated. Studying the evolution of phage lysins has revealed modular domain exchanges that lead to new catalytic binding properties ⁹. Novel endolysins can be developed with optimized stability, specificity, and lytic function ¹⁰.

Recently, recombinant endolysin as a bio-control agent has been investigated in a variety of gram-negative pathogens. Since N-acetylmuramyl L-alanine-amidase (MurNAc-LAA) specifically destroys the bacterial cell wall by cutting muramic acid-peptide bond ¹¹, and muramic acid as a substrate is present in bacterial cell wall but not in higher organisms, amidase MurNAc-LAA was proposed as a biocontrol agent to limit the pathogenic gram-negative bacteria. To obtain an amidase with impact(s) on gram-negative bacteria as well as gram-positive bacteria, in this study, MurNAc-LAA from *Bacillus subtilis* (*B. subtilis*)-bacteriophage Siphoviridae was heterologously expressed in *Escherichia coli* (*E. coli*). The antibacterial properties of the endolysin were investigated in relation to its secondary and tertiary structure.

Materials and Methods

Muramyl- N-Acetyl -L-Alanine Amidase (*LysM2*) gene construction

The gene and protein sequences of *MurNAc-LAA* from the *Bacillus* phage SPP1 in *B. subtilis* (Accession number: X97918) were obtained from the Virus-Host database (GenBank number CAA66518, NCBI). The GC content was adapted for expression in *E. coli* by GenScript codon optimization software (<http://www.genscript.com/>). The optimized *MurNAc-LAA* gene in our laboratory, *MurNAc-LAA-MMI* (*LysM2*, appendix 1), was synthesized by Gene Transfer Pioneer company (GTP, Iran) and cloned into pUC57.

In silico study of *LysM2* protein

Using NCBI Conserved Domain Database (CDD) ¹² and InterPro database, the functional domain of *LysM2* was investigated ¹³. Tree Viewer v 1.17.4 software was used to generate a *MurNAc-LAA* cladogram containing the *LysM2* endolysin ¹⁴.

RNA secondary structure was used to study RNA stability ¹⁵. 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 ¹⁶. Secondary structure was obtained by the self-optimized prediction method (SOPMA) (https://npsa-prabi.ibcp.fr/cgi-bin/npsa_automat.pl?page/NPSA/npsasopma.html) ¹⁷ and PSIPRED server (<http://bioinf.cs.ucl.ac.uk/psipred/>). The transmembrane helix was predicted using TMHMM v 2.0 ¹⁸. The three-dimensional (3D) model for the amidase was predicted using Protein Homology/analogy Recognition Engine V 2.0 (Phyre2) software ¹⁹ and validated by PROSA-web (Protein Structure Analysis) ²⁰. The 3-D structure of molecules was analyzed by the Ramachandran plot ²¹. FT site server (<https://ftsitesite.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.psорт.org>). The antigenicity of *LysM2* protein was evaluated by the Vaxijen software 2 (<http://www.ddgpharmfac.net/vaxijen/VaxiJen/VaxiJen.html>) ²². 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 *Bam*HI (Sinaclon, Iran) and *Sac*I (Termo Fisher Scientific, USA) restriction enzymes were respectively introduced at 5' and 3' end of the coding sequence. The *LysM2* gene was restricted using *Bam*HI/*Sac*I from pUC57/*LysM2*, and ligated into pET28a vector with the same enzymes. The generated construct, pMMI2 (pET28a/*LysM2*), was introduced into the *E. coli* B121 (DE3) cells. The transformed cells were selected on LB agar supplemented with 40 μ g/ml kanamycin (Sigma-Aldrich, USA). The cloning procedure was confirmed by *Bam*HI/*Sac*I digestion analysis.

The expression of pMMI2 was induced by 1 mM isopropylthio- β -galactoside (IPTG) (DNAbiotech, Iran) at 28°C for 20 hr. The cells were suspended in 20 mM NaH₂PO₄, 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 15000×rpm 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 pMMI2. Fractions were analyzed on sodium dodecyl sulfate-polyacrylamide gel electrophoresis (SDS-PAGE) for protein expression of pMMI2. 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), dialyzed against Phosphate-Buffered Saline (PBS), and analyzed on SDS-PAGE. The amount of LysM2 protein was measured by Bradford assay.

Evaluation of the enzyme activity

The lysed cell wall of the indicator bacteria, *Streptococcus pyogenes* (*S. pyogenes*) (ATCC 19615), *Bacillus subtilis* (*B. subtilis*) (ATCC 12711), *Bacillus* (sp) (SUBC1001), *Staphylococcus aureus* (*S. aureus*) (ATCC-25923), *Pseudomonas aeruginosa* (*P. aeruginosa*) (ATCC27853), *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 described²³. Briefly, the heat-killed indicator bacteria were added to LB medium. The plates were punched to make 8 mm wells followed by adding 100 µl of the purified enzyme. The strains with the clear zone were selected for evaluating their antibacterial activities. The Activity Unit (AU) of the endolysin was calculated as previously described (p<0.05)²⁴:

$$\text{Endolysin activity (mm}^2\text{/ml)} = (\text{Lz} - \text{Ls})/\text{V}$$

Lz = Clear zone area (mm)², Ls = Well area (mm)²,
V = Volume of sample (ml)

The boiled-culture of the indicator bacteria with OD600 of 0.6 was subjected to 1:2 serial dilution of the endolysin for 40 min at 25 °C. A dilution of the enzyme that reduced the turbidity of the heat-killed indicators to 50% was introduced as the activity of LysM2 enzyme.

Next, 500 µl of boiled-culture of the indicator bacteria with OD600 of 0.6 was resuspended in the volume of 20 mM Tris HCl (pH=7.5) and 500 µl of the enzyme

was mixed in a corvette, and the buffer without endolysins was used as a negative control. The mixtures were 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 preference was adjusted for *E. coli* and the conservation of the *LysM2* sequence was evaluated by GenScript software.

In silico study of LysM2 protein

Sequence analysis: The most similar protein to MurNac-LAA from *B. subtilis* phage was found in Firmicutes 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 MurNac-LAA family. The prediction of the mRNA structure 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 structure. Taken together, the results displayed that

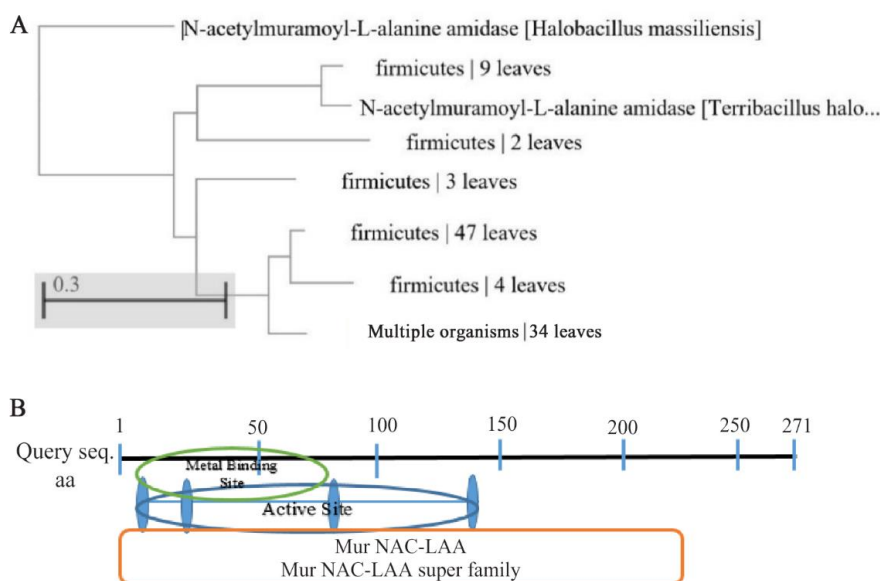


Figure 1. A) The phylogenetic tree for the optimized LysM2, based on the Neighbor-Joining method. B) *In silico* investigation of the catalytic domain of LysM2

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 BTPred 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. typhimurium*, 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

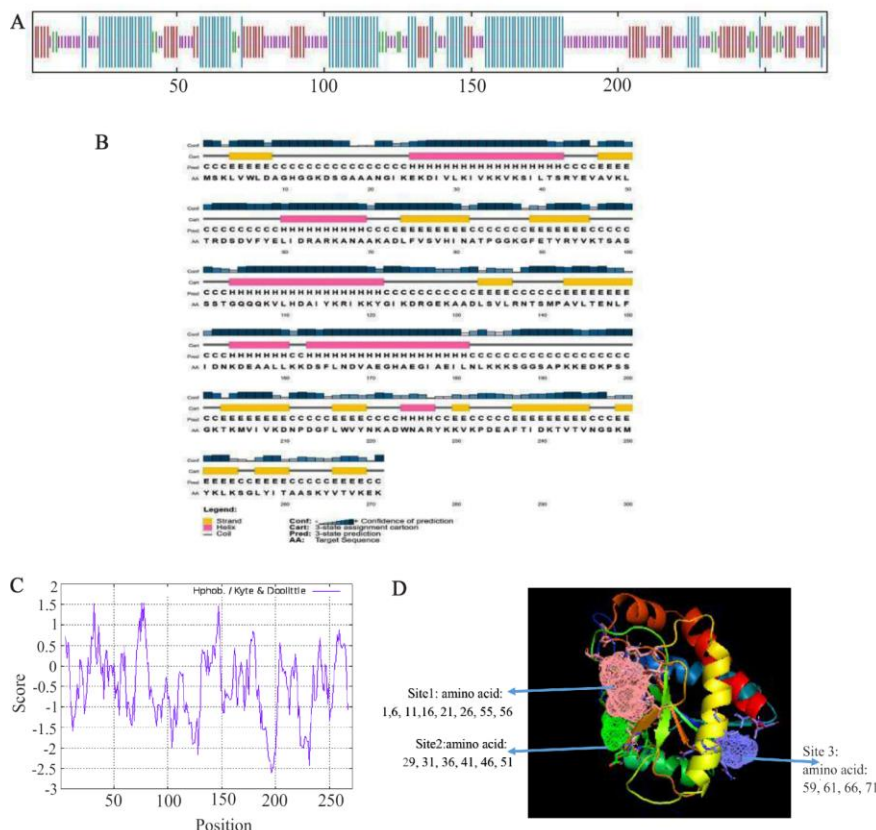


Figure 2. A, B) Secondary structure prediction for LysM2 protein. C) Frequency of positively charged amino acids is higher in the N-terminal protein. D) The three-dimensional structure of LysM2 protein. Purple, red, and blue colors indicate extended strand, coil, and helix, respectively in both figures, A and D.

Exogenous Production of LysM2 from Siphoviridae Phage

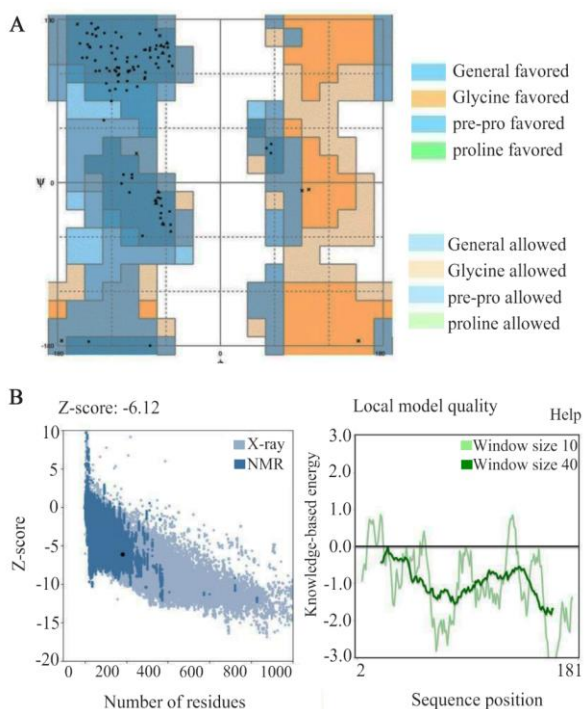


Figure 3. A) Evaluation of LysM2 protein stability based on Ramachandran plot showed 2.2% of the residues were in the outlier region; 5.6% in the allowed area, and 92.1% of amino acids in the favored region. B) The results of analyzing LysM2 protein with the ProSA web server; Z-score plot, NMR spectroscopy (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.

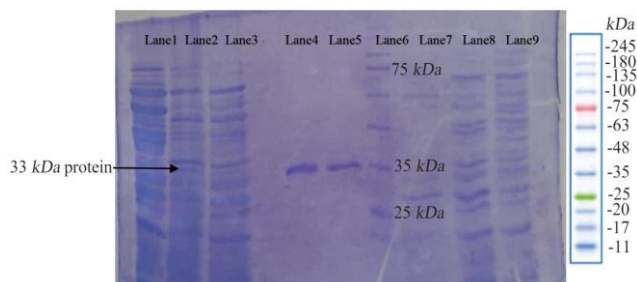


Figure 4. The photograph of LysM2 protein on 12% SDS-PAGE. The relevant 33 kDa band is indicated in the Lanes 1, 2: LysM2 protein, Lane 3: Control, Lanes 4, 5: Purified protein, Lane 6: Ladder protein 10-250 kDa, Lane 7: Purified control without IPTG induction, Lane 8: *E. coli* BL21DE3, Lane 9: Pre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

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 bacteria⁷.

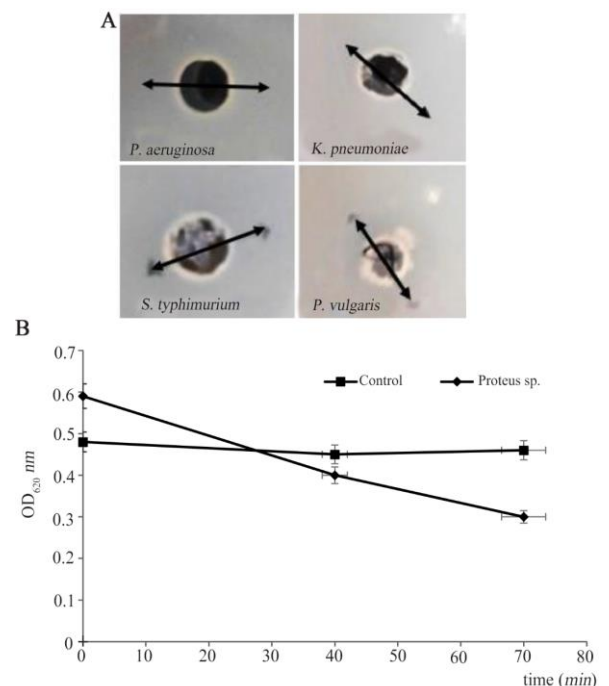


Figure 5. A) Agar diffusion of LysM2 against *Proteus* (sp). B) The lytic activity of LysM2 against *Proteus* (sp).

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 bacteria²⁵.

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 activity²⁶. 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 Sp β phage-mediated cell-lysis was confirmed. Furthermore, two ORFs encoding polypeptides as holins are located at the downstream of *blyA* gene and they are involved in releasing endolysin

in the gram-negative bacteria²⁷. 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 bacteria²⁸.

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 lysins²⁹. 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 log³⁰. 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 layer³¹.

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 division³². 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. Scheur-

water *et al* studied, cloned, and expressed the N-acetylmouramoyl-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 Δ OD.660U \cdot min⁻¹ mg protein⁻¹ was reported for AmiB. Moreover, it degrades the purified insoluble peptidoglycan from gram-negative bacterium, *P. aeruginosa*¹.

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 activity. In contrast, *Enterobacteria* lacks such a highly negative charge per lipopolysaccharide molecule, protecting against Ts2631 function^{33,34}. Recently, a lytic enzyme, LysC, from *Clostridium intestinale* was introduced. Its antibacterial activity is mediated by positively charged N-terminal extension³⁵.

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 μ g/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 indicated an 8-fold decrease in the minimum inhibitory concentration of vancomycin³¹.

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 structure¹⁰.

Furthermore, other documents demonstrate that catalytic modular domain of lysins is efficiently substituted with other lysins for the new bactericidal features²⁹. 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-LAAAn-MMI is an inhibiting agent for gram-negative bacteria.

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Conflict of Interest

The authors declare that they have no competing interest.

References

- Scheurwater EM, Pfeffer JM, Clarke AJ. Production and purification of the bacterial autolysin N-acetylmuramoyl-L-alanine amidase B from *Pseudomonas aeruginosa*. *Protein Expr Purif* 2007;56(1):128-37.
- Kashani HH, Schmelcher M, Sabzalipoor H, Hosseini ES, Moniri R. Recombinant endolysins as potential therapeutics against antibiotic-resistant *Staphylococcus aureus*: current status of research and novel delivery strategies. *Clin Microbiol Rev* 2018;31(1):e00071-17.
- Grishin AV, Karyagina AS, Vasina DV, Vasina IV, Gushchin VA, Lunin VG. Resistance to peptidoglycan-degrading enzymes. *Crit Rev Microbiol* 2020;46(6):703-26.
- Schmelcher M, Donovan DM, Loessner MJ. Bacteriophage endolysins as novel antimicrobials. *Future Microbiol* 2012;7(10):1147-71.
- Santos SB, Oliveira A, Melo LD, Azeredo J. Identification of the first endolysin Cell Binding Domain (CBD) targeting *Paenibacillus* larvae. *Sci Rep* 2019;9(1): 2568.
- Morita M, Tanji Y, Orito Y, Mizoguchi K, Soejima A, Unno H. Functional analysis of antibacterial activity of *Bacillus amyloliquefaciens* phage endolysin against Gram-negative bacteria. *FEBS Lett* 2001;500(1-2):56-9.
- Roach DR, Donovan DM. Antimicrobial bacteriophage-derived proteins and therapeutic applications. *Bacteriophage* 2015;5(3):e1062590.
- Fernández-Ruiz I, Coutinho FH, Rodríguez-Valera F. Thousands of novel endolysins discovered in uncultured phage genomes. *Front Microbiol* 2018;9:1033.
- São-José C. Correction: São-José, C. Engineering of phage-derived lytic enzymes: improving their potential as antimicrobials. *Antibiotics* 2018, 7, 29. *Antibiotics* (Basel) 2018;7(3):56.
- Love MJ, Abeysekera GS, Muscroft-Taylor AC, Billington C, Dobson RC. On the catalytic mechanism of bacteriophage endolysins: Opportunities for engineering. *Biochim Biophys Acta (BBA) Proteins Proteom* 2020; 1868(1):140302.
- Guo M, Feng C, Ren J, Zhuang X, Zhang Y, Zhu Y, et al. A novel antimicrobial endolysin, LysPA26, against *Pseudomonas aeruginosa*. *Front Microbiol* 2017;8:293.
- Marchler-Bauer A, Derbyshire MK, Gonzales NR, Lu S, Chitsaz F, Geer LY, et al. CDD: NCBI's conserved domain database. *Nucleic acids Res* 2015;43(Database issue):D222-D6.
- Quintavalla S, Vicini L. Antimicrobial food packaging in meat industry. *Meat Sci* 2002;62(3):373-80.
- Edgar RC. MUSCLE: multiple sequence alignment with high accuracy and high throughput. *Nucleic acids Res* 2004;32(5):1792-7.
- Reuter JS, Mathews DH. RNAstructure: software for RNA secondary structure prediction and analysis. *BMC Bioinformatics* 2010;11(1):129.
- Wilkins MR, Gasteiger E, Bairoch A, Sanchez JC, Williams KL, Appel RD, et al. Protein identification and analysis tools on the ExPASy server. *Methods Mol Biol* 1999;112:531-52.
- Geourjon C, Deleage G. SOPMA: significant improvements in protein secondary structure prediction by consensus prediction from multiple alignments. *Comput Appl Biosci* 1995;11(6):681-4.
- Krogh A, Larsson B, Von Heijne G, Sonnhammer EL. Predicting transmembrane protein topology with a hidden Markov model: application to complete genomes. *J Mol Biol* 2001;305(3):567-80.
- Kelley LA, Mezulis S, Yates CM, Wass MN, Sternberg MJ. The Phyre2 web portal for protein modeling, prediction and analysis. *Nat Protoc* 2015;10(6):845.
- Wiederstein M, Sippl MJ. ProSA-web: interactive web service for the recognition of errors in three-dimensional structures of proteins. *Nucleic acids Res* 2007;35(Web server issue):W407-W10.
- Laskowski RA, MacArthur MW, Moss DS, Thornton JM. PROCHECK: a program to check the stereochemical quality of protein structures. *J Appl Crystallogr* 1993;26(2):283-91.
- Doytchinova IA, Flower DR. VaxiJen: a server for prediction of protective antigens, tumour antigens and subunit vaccines. *BMC Bioinformatics* 2007;8(1):4.
- Noormohammadi H, Abolmaali S, Astaneh SDA. Identification and characterization of an endolysin-like from *Bacillus subtilis*. *Microb Pathog* 2018;119:221-4.
- Sarjoughian MR, Rahmani F, Abolmaali Sh, Darvish Alipour Sh. *Bacillus* phage endolysin, lys46, bactericidal properties against gram-negative bacteria. *Iran J Microbiol* 2020;12(6):505-12.

25. Dong H, Zhu C, Chen J, Ye X, Huang YP. Antibacterial Activity of *Stenotrophomonas maltophilia* Endolysin P28 against both gram-positive and gram-negative bacteria. *Front Microbiol* 2015;6:1299.
26. Tossi A, Sandri L, Giangaspero A. Amphipathic, α -helical antimicrobial peptides. *Biopolymers* 2000;55(1):4-30.
27. Regamey A, Karamata D. The N-acetylmuramoyl-L-alanine amidase encoded by the *Bacillus subtilis* 168 prophage SP β . *Microbiology* 1998;144(Pt 4):885-93.
28. Lai MJ, Lin NT, Hu A, Soo PC, Chen LK, Chen LH, et al. Antibacterial activity of *Acinetobacter baumannii* phage ϕ AB2 endolysin (LysAB2) against both gram-positive and gram-negative bacteria. *Appl Microbiol Biotechnol* 2011;90(2):529-39.
29. Ghose C, Euler CW. Gram-negative bacterial lysins. *Antibiotics* 2020;9(2):74.
30. Oliveira H, Thiagarajan V, Walmagh M, Sillankorva S, Lavigne R, Neves-Petersen MT, et al. A thermostable *Salmonella* phage endolysin, Lys68, with broad bactericidal properties against gram-negative pathogens in presence of weak acids. *PLoS One* 2014;9(10):e108376.
31. Yakhnina AA, Bernhardt TG. The Tol-Pal system is required for peptidoglycan-cleaving enzymes to complete bacterial cell division. *Proc Natl Acad Sci* 2020;117(12):6777-83.
32. Heidrich C, Templin MF, Ursinus A, Merdanovic M, Berger J, Schwarz H, et al. Involvement of N-acetylmuramyl-L-alanine amidases in cell separation and antibiotic-induced autolysis of *Escherichia coli*. *Mol Microbiol* 2001;41(1):167-78.
33. Plotka M, Sancho-Vaello E, Dorawa S, Kaczorowska AK, Kozłowski LP, Kaczorowski T, et al. Structure and function of the Ts2631 endolysin of *Thermus scotoductus* phage vB_Tsc2631 with unique N-terminal extension used for peptidoglycan binding. *Sci Rep* 2019;9(1):1261.
34. Plotka M, Kapista M, Dorawa S, Kaczorowska AK, Kaczorowski T. Ts2631 Endolysin from the extremophilic *Thermus scotoductus* bacteriophage vB_Tsc2631 as an antimicrobial agent against gram-negative multi-drug-resistant bacteria. *Viruses* 2019;11(7):657.
35. Plotka M, Szadkowska M, Håkansson M, Kovacic R, Al-Karadaghi S, Walse B, et al. Molecular characterization of a novel lytic enzyme LysC from *Clostridium intestinale* URNW and its antibacterial activity mediated by positively charged N-terminal extension. *Int J Mol Sci* 2020;21(14):4894.