

In silico Analysis and Molecular Modeling of RNA Polymerase, Sigma S (RpoS) Protein in *Pseudomonas aeruginosa* PAO1

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Abstract

Background: Sigma factors are proteins that regulate transcription in bacteria. Sigma factors can be activated in response to different environmental conditions. The *rpoS* (RNA polymerase, sigma S) gene encodes sigma-38 (σ_{38} , or RpoS), a 37.8 kDa protein in *Pseudomonas aeruginosa* (*P. aeruginosa*) strains. RpoS is a central regulator of the general stress response and operates in both retroactive and proactive manners; not only does it allow the cell to survive environmental challenges; it also prepares the cell for subsequent stresses (cross-protection).

Methods: The significance of RpoS for stress resistance and protein expression in stationary-phase *P. aeruginosa* cells was assessed. The goal of the current study was to characterize RpoS of *P. aeruginosa* PAO1 using bioinformatics tools.

Results: The results showed that RpoS is an unstable protein that belongs to the sigma-70 factor family. Secondary structure analysis predicted that random coil is the predominant structure followed by extended alpha helix. The three-dimensional (3D) structure was modeled using SWISS-MODEL Workspace.

Conclusion: Determination of sequence, function, structure, and predicted epitopes of RpoS is important for modeling of inhibitors that will help in the design of new drugs to combat multi-drug-resistant (MDR) strains. Such information may aid in the development of new diagnostic tools, drugs, and vaccines for treatment in endemic regions.

Keywords: Bioinformatics, *In silico*, *Pseudomonas aeruginosa*, RpoS, Therapy

Introduction

Pseudomonas aeruginosa (*P. aeruginosa*) is of increasing concern in hospital settings because of frequently-emerging antibiotic resistant strains implicated in nosocomial infections. *P. aeruginosa* is a gram-negative opportunistic pathogen and a major cause of nosocomial infections in immunocompromised individuals and patients with severe burns and cystic fibrosis (1). *P. aeruginosa* can persist during feast, famine, and stress conditions in many different environments including soil, water,

plants, animals, and humans. The alternative sigma factor, RpoS, positively regulates many genes in stationary phase and is considered to be a master stress-response regulator (2, 3). The *rpoS* gene encodes sigma factor RpoS (also called σ_{38} and σ_{70}), which was identified in several gram-negative bacteria (4). As in *Escherichia coli* (*E. coli*), the RpoS level in *P. aeruginosa* increases upon entry of the cells into the stationary phase (2, 5). RpoS affects and regulates the production of several virulence factors

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including extracellular alginate, exotoxin A, and biofilm formation (6, 7). Furthermore, RpoS influences the expression of more than 40% of individual genes that are controlled by quorum sensing, the cell-cell communication device in gram-negative bacteria, which was identified by transcriptome analysis (8, 9). Quorum sensing has been demonstrated to be involved in the control of rpoS transcription in *P. aeruginosa* (5). In addition, *P. aeruginosa* RpoS mutants form biofilms of increased biomass and enhanced resistance to the antibiotic tobramycin (7). RpoS alters RNA polymerase core specificity and switching gene expression in the stationary phase (5, 10). The study of protein structures provides valuable information that aids in the design and development of specific inhibitors (11-13). No experimental structural information is available for most protein sequences; thus, protein structure prediction has received considerable interest in recent years. Improved understanding of protein structures will aid in the design of drugs and inhibitors for the treatment of pathogens (14, 15). The purpose of this study was to characterize RpoS of *P. aeruginosa* using on- and off-line computational tools to aid in the development of new diagnostic tools, drugs, and vaccines for treatments in endemic regions.

Materials and Methods

Sequence analysis of RpoS

P. aeruginosa was selected as the candidate organism for the present study. Its complete genome sequence (GI: 110227054) is available at <http://www.ncbi.nlm.nih.gov>. The protein sequence of RpoS (NP_252312) was downloaded from NCBI (<http://www.ncbi.nlm.nih.gov>). The RpoS sequence was analyzed for similar sequences using BlastP at <http://www.ncbi.nlm.nih.gov>. Proteins that were most similar to RpoS were selected and multiple alignments were performed using the ClustalW web tool (<http://www.genome.jp/tools/clustalw/>). A phylogenetic tree was obtained using Mega4 Software.

Functional analysis of RpoS

Functional characterizations of the RpoS sequence obtained from the Uniprot site (<http://www.expasy.org/>) are described next.

RpoS primary, secondary, and three-dimensional structure predictions

The primary structure was predicted using the Expasy ProtParam server (<http://expasy.org/cgi-bin/protparam>). Post-translational modifications were predicted by the <http://www.cbs.dtu.dk/researchgroups/PTM.php> web site.

Physicochemical parameters such as theoretical isoelectric point, molecular weight, number of atoms, and number of positively- (Lysine, Arginine, Histidine) and negatively- (Aspartic acid, Glutamic acid) charged amino acids were determined. Hydrophobic, hydrophilic, and aromatic amino acids were identified. The instability index, estimated charge at pH 7.00, isoelectric point (pI), aliphatic index, grand average of hydropathy (GRAVY), and half-life were predicted. All physicochemical properties were predicted using the PBIL-IBCP Lyon-Gerland server (<http://pbil.ibcp.fr/htm/index.php>) and the ExpASY prediction tools (<http://web.expasy.org/>). Conserved domains were predicted by the NCBI's Conserved Domain Database (<http://www.ncbi.nlm.nih.gov/Structure/cdd/wrpsb.cgi>). Locations of transmembrane, intracellular, and extracellular regions were predicted by the TMHMM data bank (<http://www.cbs.dtu.dk/services/TMHMM/>).

The secondary structure was predicted using GOR IV and SOPMA tools and results acquired from these two banks were compared. The 3D structure of RpoS was obtained from the <http://www.ncbi.nlm.nih.gov/Structure/VAST/>.

Epitope prediction for RpoS

To predict potential RpoS immune epitopes we used the immune epitope database analysis resource (IEDB-AR) web-based tools (<http://tools.immuneepitope.org>).

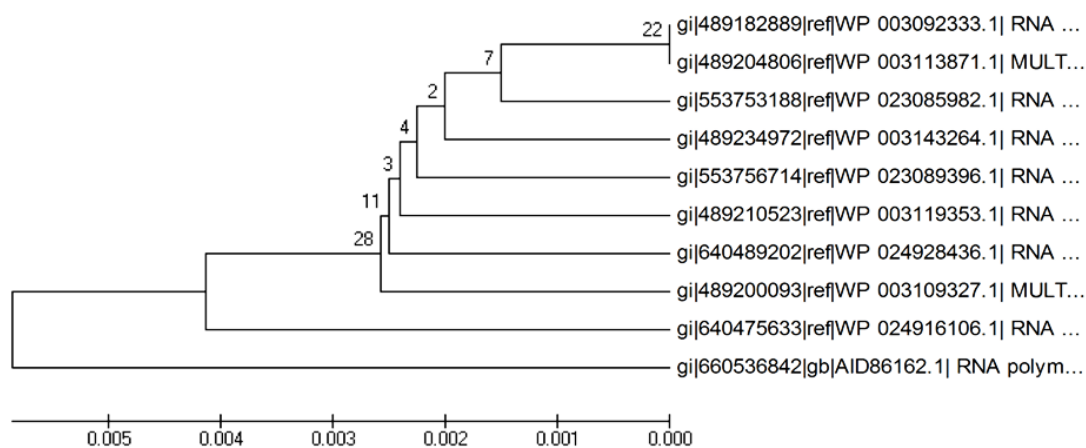
Results

In silico analysis is a suitable option for finding drug targets and choosing strategies to treat and control diseases. In first step, we used BlastP and selected for further analyses 10 sequences with the greatest identities and similarities with RpoS (Table 1). Multiple alignment performed on the 10 sequences identified nine groups. Using the ClustalW alignment

Table 2. The nine alignment groups determined by ClustalW

Group	Sequences	Score
1	2	5457
2	3	5451
3	4	5447
4	5	5445
5	6	5447
6	7	5445
7	8	5440
8	9	5435
9	10	5421

Alignment Score = 90605

**Fig. 2.** RpoS phylogenetic tree based on bootstrap values, by MEGA4 software

Functionality analysis of RpoS identified characteristic domains (Table 3). Two motifs were identified; these are the 20-amino acid HTH motif and the four-amino acid motif that interacts with the RpoC polymerase core subunit. RpoS contains four domains of 34, 71, 76, and 54 amino acids for the Sigma-70 factor. Sigma

factors are initiation factors that promote the attachment of RNA polymerase to specific transcription initiation sites. This sigma factor is the master transcriptional regulator of the stationary phase and the general stress response.

Table 3. Domains, repeats, motifs, and features of RpoS

Name	Start	End	length	E value
H-T-H motif	293	312	20	-
Pfam: Sigma-70 factor domain-1	61	94	34	4.8e-16
Pfam: Sigma-70 factor domain-2	99	169	71	3e-25
Pfam: Sigma-70 factor domain-3	179	254	76	4.9e-22
Pfam: Sigma-70 factor domain-4	267	320	54	8.4e-18
Interaction with polymerase core subunit RpoC motif	123	126	4	-

Primary structure prediction of RpoS

Analysis of the primary structure of RpoS showed that the protein contained 334 amino acids with an estimated molecular weight of 38235.3 (Table 4). Forty-seven positively-charged (Arg+Lys) and 60 negatively-charged (Asp+Glu) residues were identified.

Phosphorylation sites were predicted at serines 28, 29, 35, 47, 120, 148, 199, 228, 230, 235, and 291, and threonines 39, 44, 77, 158, 169, 191, 225, 238, 272 and 292. Tyrosines were not predicted to be phosphorylated. O-Glycosylation sites were found on serines 28, 35, 45, 47, and 226, and on other amino acids at residues 43, 44, and 225. N-glycosylation sites were identified on asparagine 165 and lysines 4, 5, 49, 97, 109, 138, 193, 316, and 324. C-mannosylation sites were identified on tryptophans 153, 154, and 267. No acetylation sites were identified.

The protein contains 5415 atoms and its chemical formula is C1680H2724N482O523S6. The isoelectric point (pI) is 5.26. The aliphatic index of a protein is defined as the relative volume occupied by aliphatic side chains, which include alanine, valine, isoleucine, and leucine, and contributes to protein thermostability. The aliphatic index of RpoS is 95.75, indicating this protein is unstable for a wide range of temperatures. The instability index of RpoS is 49.78, indicating a relatively short half-life.

The GRAVY value is -0.547, indicating that RpoS is relatively non-polar. The GRAVY value is determined by the sum of hydrophathy values of all amino acids in a protein divided by the protein length. The calculation is based on the Kyte-Doolittle scale. RpoS contains 109 hydrophobic (ALIVMW), 170 hydrophilic (DEKNQRST), 17 aromatic (FYW), and 46 hydroxyl (STY) residues. The estimated half-life is 30 hours in mammalian reticulocytes *in vitro*, >20 hours in yeast *in vivo*, and >10 hours in *E. coli*, *in vivo*.

The half-life is a prediction of the time required for half of a protein in a cell to degrade after its synthesis. ProtParam relies on the "N-end rule", which relates the half-life of a protein to the identity of its N-terminal residue; the prediction is given for three model organisms; human, yeast, and *E. coli*. Identity of the N-terminal residue of a protein plays an important role in determining its stability *in vivo*. Proteins have strikingly different half-lives *in vivo*, from seconds to hours, depending on the nature of the amino acid at the N-terminus and the different models.

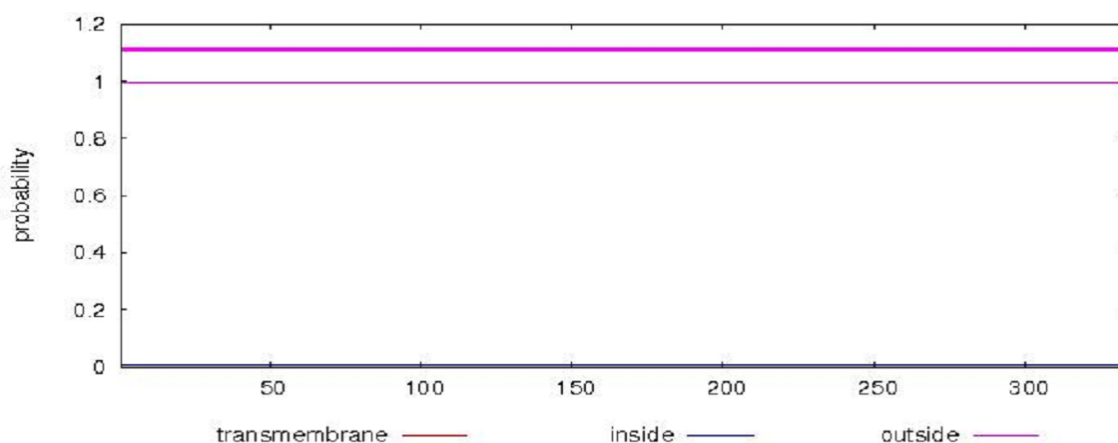
Table 4. Physicochemical properties of RpoS

Amino acid	No. of residues	% of residues
Ala (A)	19	5.7%
Arg (R)	30	9.0%
Asn (N)	9	2.7%
Asp (D)	24	7.2%
Cys (C)	1	0.3%
Gln (Q)	13	3.9%
Glu (E)	36	10.8%
Gly (G)	16	4.8%
His (H)	8	2.4%
Ile (I)	18	5.4%
Leu (L)	45	13.5%
Lys (K)	17	5.1%
Met (M)	5	1.5%
Phe (F)	9	2.7%
Pro (P)	16	4.8%
Ser (S)	20	6.0%
Thr (T)	21	6.3%
Trp (W)	3	0.9%
Tyr (Y)	5	1.5%
Val (V)	19	5.7%
Pyll (O)	0	0.0%
Sec (U)	0	0.0%

Five conserved domains were predicted in RpoS using PRS-Blast (Table 5). The first domains refer to the C-termini of four conserved domains. The second domain is the most conserved region of the protein. The third domain forms a discrete compact three helical domain within the sigma factor. The fourth domain is region 1-2. The fifth domain is RNA polymerase sigma factor RpoS; Validated. The TMHMM program predicts the locations of transmembrane, intracellular, and extracellular domains. As seen in Fig. 3, RpoS is predicted to be entirely extracellular (Fig. 3).

Table 5. Predicted conserved domains of RpoS by PRS-Blast

Name	Accession	Description	Interval	E-value
Sigma70_r4	cd06171	Sigma70, region (SR) 4 refers to the most C-terminal of four conserved domains found. ...	262-319	2.11e-10
Sigma70_r2	pfam04542	Sigma-70 region 2; Region 2 of sigma-70 is the most conserved region of the entire protein. ...	99-169	6.95e-24
Sigma70_r1_2	pfam00140	Sigma-70 factor, region 1.2	61-96	8.25e-10
PRK05657	PRK05657	RNA polymerase sigma factor RpoS; Validated	1-333	0e+00

**Fig. 3.** Graphical representation of the location of RpoS protein by TMHMM: RpoS is predicted to be entirely extracellular

Secondary structure prediction of RpoS

The secondary structure of RpoS was predicted using GOR IV and SOPMA web-site tools. Table 6 shows the results obtained from the two programs. Both programs predicted that alpha helices (50.60 and

57.78%, respectively), random coils (40.42 and 28.14%, respectively), and extended strands (8.98 and 9.28%, respectively) were the most abundant structures. This is graphically represented in Fig. 4.

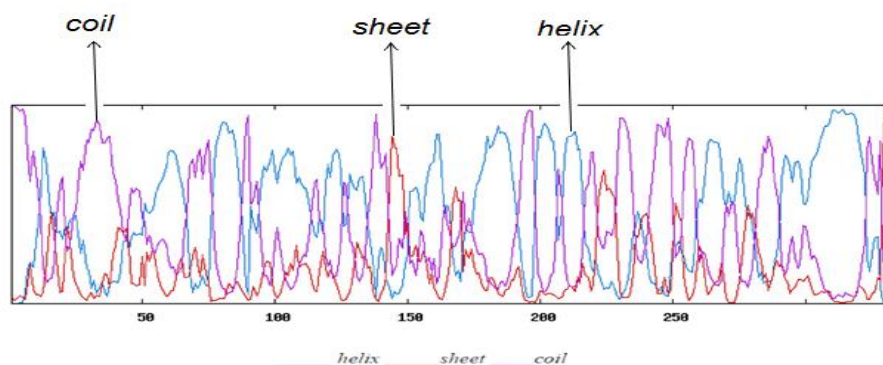
**Fig. 4.** Secondary structure prediction of RpoS by Gor IV

Table 6. Prediction of secondary structure of RpoS by SOPMA and GOR IV

Secondary structure	GOR IV		SOPMA	
	Length	Percent	Length	Percent
Alpha helix (Hh)	169	50.60%	193	57.78%
310 helix (Gg)	0	0.00%	0	0.00%
Pi helix (Ii)	0	0.00%	0	0.00%
Beta bridge (Bb)	0	0.00%	0	0.00%
Extended strand (Ee)	30	8.98%	31	9.28%
Beta turn (Ti)	0	0.00%	16	4.79%
Bend region (Ss)	0	0.00%	0	0.00%
Random coil (Cc)	135	40.42%	94	28.14%
Ambiguous states	0	0.00%	0	0.00%
Other states	0	0.00%	0	0.00%
Sequence length	334		334	

Three-dimensional structure prediction of RpoS

Because only primary sequence information about RpoS was available from NCBI, and no 3D structure information in the form of X-ray crystallographic data was available from the Protein Data Bank (PDB), modeling of RpoS was necessary to determine the protein's 3D structure. The 3D structure was predicted using the first protein obtained from the BlastP search against the PDB (Table 7). The first protein identified via this process was associated with locus 1L9U_H, encoding a protein from *Thermus aquaticus* (*T. aquaticus*) bacteria. This sequence has the greatest similarity with RpoS and its 3D structure was accessible in the PDB. 1L9U is an RNA polymerase holoenzyme containing core RNA polymerase ($\alpha_2\beta\beta'\omega$) and the promoter specificity sigma subunit, including A, B, C, D, E, and H. The H chain (1L9U_H) is sigma factor sigA in *T. aquaticus*

with the greatest similarity and identity with RpoS in the PDB BlastP analysis of RpoS, and 1L9U_H resulted in a maximum score of 204 and 46% identity.

The modeling and 3D structure of RpoS was based on 1L9U_H. Here homology modeling was predicted using SWISS PDB Viewer. The structure of the protein was refined further to improve the model (Figs. 5-7). Fig. 5 is a spatial model of RpoS using yellow ribbons and cylinders that represent α -helices and β -sheets, respectively. Fig. 6 is related to charge distribution on the RpoS Connolly surface in the form of colored spheres. In Fig. 6 the blue, red, and gray spheres represent positively, negatively, and neutrally charged amino acids, respectively. Fig. 7 displays the hydrophobicity distribution on the RpoS Connolly surface in the form of colored spheres representing hydrophobic, hydrophilic, and neutral amino acids.

Table 7. Summary of the BlastP analysis (<http://www.ncbi.nlm.nih.gov/BLAST/>) of RpoS

Seq.	Subject ID	Length	Max score	Total score	Query cover (%)	E value	Identities number (%)	Positive number (%)	Gap number (%)
1	1L9U_H	332	204	204	72%	6e-62	112.2 (46%)	163.2 (66%)	5.2 (2%)
2	1L9Z_H	438	204	204	72%	7e-61	112.2 (46%)	163.2 (66%)	5.2 (2%)
3	1IW7_F	423	202	202	72%	2e-60	110.2 (45%)	163.2 (66%)	5.2 (2%)
4	3DXJ_F	423	202	202	72%	2e-60	110.2 (45%)	163.2 (66%)	5.2 (2%)
5	4G7H_F	443	202	202	72%	5e-60	110.2 (45%)	163.2 (66%)	5.2 (2%)
6	4LJZ_F	522	201	201	78%	6e-59	107.3(40%)	166.3(62%)	7.3(2%)
7	3IYD_F	613	201	201	78%	2e-58	107.3(40%)	166.3(62%)	7.3(2%)
8	4IGC_X	613	201	201	78%	2e-58	107.3(40%)	166.3(62%)	7.3(2%)
9	4JKR_F	628	201	201	78%	2e-58	107.3(40%)	166.3(62%)	7.3(2%)
10	1KU2_A	241	155	155	41%	2e-44	78.1 (56%)	104.1 (74%)	2.1(1%)



Fig. 5. Modeled spatial configuration of RpoS representing α -helices and β -sheets.

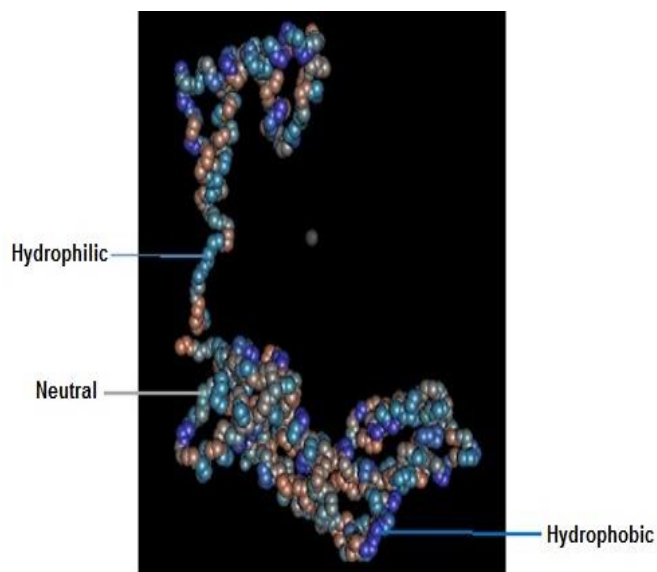


Fig. 6. Diagram of charge distribution on RpoS Connolly surface (the blue, red and grey spheres represent positively-charged, negatively-charged, and neutral amino acids, respectively).

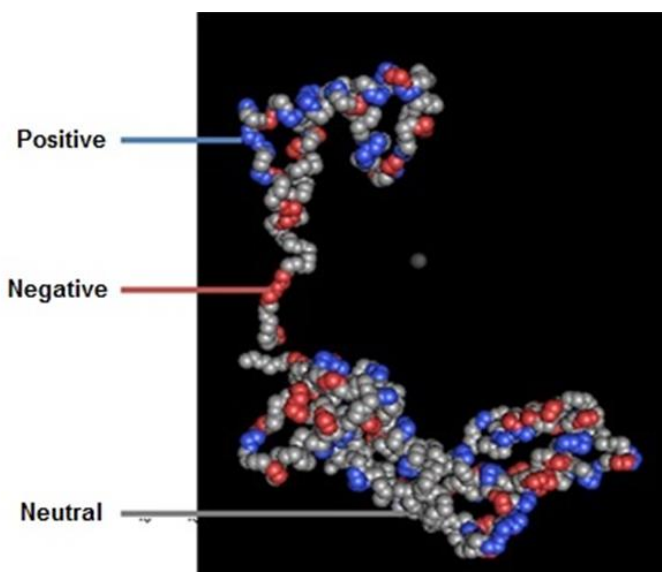


Fig. 7. Diagram of hydrophobicity distribution on RpoS Connolly surface. The dark blue, light blue and gray spheres represent hydrophobic, hydrophilic, and neutral amino acids, respectively.

An epitope, also known as antigenic determinant, is the part of an antigen that is recognized by the immune system, specifically by antibodies, B cells, or T cells. Predicted B-cell epitopes of RpoS are presented in Table 8. RpoS contains 14 epitopes with lengths from one to 24 amino acids. The longest epitope contains 24

residues, with six (25%) serines. This epitope probability can be considered as a potential binding site for an inhibitor or drug target. The shorter epitopes of one, two, and three residues are less likely to be regarded as potential inhibitor targets due to their small sizes.

Table 8. Predicted B-cell epitopes in RpoS

No.	Start Position	End Position	Peptide	Peptide Length
1	4	13	KKEGPEFDHD	10
2	26	49	DESSADEQSPRATPKATTSFSSK	24
3	51	51	H	1
4	76	82	PLLTPEE	7
5	90	98	AQKGDPAGR	9
6	139	147	EKFDPER	9
7	196	205	HKLDHEPSPE	10
8	214	215	P	1
9	232	241	SVDVSLGPDS	10
10	247	258	DTLTDDRPTDPC	12
11	262	266	QDDDL	5
12	275	277	TEL	3
13	292	301	GLRGHESSTL	10
14	330	332	LEK	3

Discussion

P. aeruginosa is a leading cause of nosocomial infections in immune compromised individuals (16). Such infections are especially difficult to treat because of emerging antibiotic resistant strains, a trend that could be attributed to selective pressures from antibiotic treatment, as well as the organism's intrinsic ability to adapt to drug-stressed environments (17, 18). *P. aeruginosa* can persist during feast, famine, and stress conditions such as nutrient limitation, antibiotics, heat, osmotic, and high pH in many different environments (2). In particular, RpoS, a sigma factor, is a general stress response regulator that affects the transcription of genes that confer increased tolerance to stress conditions. Little information is available regarding the characterization and structure of RpoS in *P. aeruginosa* (19, 20). The focus of this study was to characterize RpoS of *P. aeruginosa* PAO1 using bioinformatics tools to apply the knowledge gained to this protein as a drug or inhibitor target. The aliphatic index of 95.75 indicates that the protein is unstable at a wide temperature range. In this work the primary, secondary, and 3D structures of RpoS were analyzed *in silico*. The primary structure determines the 3D shape known as the tertiary structure. The tertiary structure of a protein is related to protein's geometric shape and describes the folding of its secondary structural elements and specifies the position of each atom in the protein, including those of its side chains (21). The alpha-helices and beta-pleated sheets fold

into a compact globular structure (22). In addition to, globular proteins contains cores of hydrophobic amino acid residues. Also have surface regions of water-exposed, charged, hydrophilic residues. The common features of protein tertiary structures reveal much about the biological functions of the proteins and their evolutionary origins (23).

The IEDB was used to predict likely RpoS epitopes. These epitopes can be considered for the design of drugs or inhibitors. Currently, a wide range of antibiotics against the membrane, wall, enzymes, nucleic acids, ribosomes, and metabolic pathways of *P. aeruginosa* are used to treat infections caused by these bacteria. The emergence of MDR and XDR strains has resulted in resistance to many of these drugs (24); therefore, new and effective treatments are needed. Numerous *In silico* studies that examined the effects of various drugs on a variety of pathogenic bacteria indicated that the drug targets are mostly proteins and enzymes. For example, Munikumar et al., using pathway analysis, reported that the putative drug targets of the *Streptococcus pneumoniae* that causes bacterial meningitis included 26 enzymes, 8 non-enzyme proteins, and 3 conserved hypothetical proteins (25). A similar *In silico* analysis by Neema et al. identified and characterized 3986 proteins, including seven novel membrane proteins, in *Edwardsiella tarda*. One hundred and seventy-one of these proteins were proposed as potential drug targets (26). Another

In silico study by Perumal *et al.*, also using pathway analysis, identified eight putative drug targets in *P. aeruginosa* (27). Knowledge of the 3D structures of proteins will aid in the development of reasonable strategies for specific inhibitor design (28, 29). RpoS positively regulates many genes in stationary phase and is considered to be a master stress-response regulator (30). Understanding of this biosynthetic pathway and bioinformatics information are necessary for treatment of *P. aeruginosa* infections and will aid in the search for new anti-*Pseudomonas* agents. Therefore, the goal of this study was to examine the structure of *P. aeruginosa* RpoS at the

molecular level using bioinformatics tools. Using *In silico* analysis, the long-term goal is to design drugs and inhibitors against RpoS.

RpoS inhibitor modeling will aid in the design of new drugs to combat MDR strains of *P. aeruginosa*. This approach enables rapid potential drug target identification, thereby greatly facilitating the search for new inhibitors.

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