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Citation for published version:

Digital Object Identifier (DOI):
10.1371/journal.ppat.1000226

Link:
Link to publication record in Edinburgh Research Explorer

Document Version:
Publisher's PDF, also known as Version of record

Published In:
PLoS Pathogens

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A Structural Model of the *Staphylococcus aureus* ClfA–Fibrinogen Interaction Opens New Avenues for the Design of Anti-Staphylococcal Therapeutics

Vannakambadi K. Ganesh1,a, Jose J. Rivera1,a,b, Emanuel Smeds1, Ya-Ping Ko1, M. Gabriela Bowden1, Elisabeth R. Wann1, Shivasankarappa Gurusiddappa1b, J. Ross Fitzgerald2, Magnus Höök1,a

1 Center for Extracellular Matrix Biology, Institute of Biosciences and Technology, Texas A & M University Health Science Center, Houston, Texas, United States of America, 2 Centre for Infectious Diseases, School of Biomedical Sciences, The University of Edinburgh, Edinburgh, United Kingdom

Abstract

The fibrinogen (Fg) binding MSCRAMM Clumping factor A (ClfA) from *Staphylococcus aureus* interacts with the C-terminal region of the fibrinogen (Fg) γ-chain. ClfA is the major virulence factor responsible for the observed clumping of *S. aureus* in blood plasma and has been implicated as a virulence factor in a mouse model of septic arthritis and in rabbit and rat models of infective endocarditis. We report here a high-resolution crystal structure of the ClfA ligand binding segment in complex with a synthetic peptide mimicking the binding site in Fg. The residues in Fg required for binding to ClfA are identified from this structure and from complementing biochemical studies. Furthermore, the platelet integrin αIIbβ3 and ClfA bind to the same segment in the Fg γ-chain but the two cellular binding proteins recognize different residues in the common targeted Fg segment. Based on these differences, we have identified peptides that selectively antagonize the ClfA-Fg interaction. The ClfA-Fg binding mechanism is a variant of the “Dock, Lock and Latch” mechanism previously described for the *Staphylococcus epidermidis* SdrG–Fg interaction. The structural insights gained from analyzing the ClfANFg peptide complex and identifications of peptides that selectively recognize ClfA but not αIIbβ3 may allow the design of novel anti-staphylococcal agents. Our results also suggest that different MSCRAMMs with similar structural organization may have originated from a common ancestor but have evolved to accommodate specific ligand structures.

Introduction

*Staphylococcus aureus* is a Gram-positive commensal organism that permanently colonizes 20% of healthy adults and transiently colonizes up to 50% of the general population [1]. For many years, *S. aureus* has been a major nosocomial pathogen causing a range of diseases from superficial skin infections to life-threatening conditions, including septicemia, endocarditis and pneumonia [1,2]. Within the last decade a dramatic increase in the number of invasive infections caused by community-acquired *S. aureus* has been recorded in otherwise healthy children and young adults [3,4]. This outbreak together with the continued increase in antibiotic resistance among clinical strains underscores the need for new prevention and treatment strategies [1].

A detailed characterization of the molecular pathogenesis of *S. aureus* infections may expose new targets for the development of novel therapeutics. Several staphylococcal virulence factors have been identified including capsule, surface adhesins, proteases, and toxins (reviewed in [5,6,7,8]). One of these virulence factors is the MSCRAMM (microbial surface components recognizing adhesive matrix molecules) clumping factor A (ClfA). ClfA is the major staphylococcal fibrinogen (Fg) binding protein and is responsible for the observed clumping of *S. aureus* in blood plasma [9,10]. Essentially all *S. aureus* clinical strains carry the clfA gene [11]; ClfA is a virulence factor in a mouse model of septic arthritis [12] and in rabbit and rat models of infective endocarditis [13,14,15].

ClfA generates strong immune responses and has shown potential as a vaccine component in active and passive immunization studies. In one study, mice vaccinated with a recombinant ClfA segment containing the Fg-binding domain and subsequently challenged with *S. aureus* showed significantly lower levels of arthritis compared to mice vaccinated with a control protein [12]. In another study, mice passively immunized with polyclonal or monoclonal antibodies against the ClfA Fg-binding domain were protected in a model of septic death [16]. The humanized monoclonal antibody, Aurexis®, has a high affinity for ClfA and inhibits ClfA binding to Fg [17]. Aurexis is currently in clinical trials in combination with antibiotic therapy for the treatment of *S. aureus* bacteremia [18]. Thus ClfA is a viable target for both vaccine and therapeutic strategies.

ClfA belongs to a class of cell wall-localized proteins that are covalently anchored to the peptidoglycan [5,19,20]. Starting...
from the N-terminus, ClfA contains a signal sequence followed by the ligand-binding A region composed of three domains (N1, N2, and N3), the serine-aspartate repeat domain (R region), and C-terminal features required for cell wall anchoring such as the LPXTG motif, a transmembrane segment and a short cytoplasmic domain [21,22,23]. A crystal structure of a Fg binding ClfA segment (residues 221–559) which includes two of the domains (N2N3) demonstrates that each domain adopts an IgG-like fold [24]. This domain architecture was also determined from the crystal structure of the ligand binding segment of SdrG from Staphylococcus epidermidis, an MSCRAMM that binds to the N-terminal region of the Fg β-chain [25].

A dynamic mechanism of Fg binding termed “Dock, Lock and Latch” (DLL) has been proposed for SdrG based on a comparison of the crystal structures of SdrG N2N3 as an apoprotein and in complex with a synthetic peptide mimicking the targeted site in Fg [25]. In the SdrG DLL model, the apo-form of the protein adopts an open conformation that allows the Fg ligand access to a binding trench between the N2 and N3 domains. As the ligand peptide docks into the trench, a flexible C-terminal extension of the N3 domain is redirected to cover the ligand peptide and “lock” it in place. Subsequently the C-terminal part of this extension interacts with the N2 domain and forms a β-strand complementing a β-sheet in the N2 domain. This inserted β-strand serves as a latch to form a stable MSCRAMM ligand complex.

ClfA binds to the C-terminus of the Fg γ-chain [10,23] and a synthetic 17 amino acid peptide corresponding to this region was shown to bind to ClfA. Interestingly, the A-region of the staphylococcal MSCRAMM FnbA protein also binds to the same region in Fg [23]. Moreover residues in this Fg segment are also targeted by the platelet integrin αIIbβ3 integrin [26,27,28] and a recombinant form of ClfA has been shown to inhibit platelet aggregation and the binding of platelets to immobilized Fg [10,29,30].

The current study was undertaken to characterize the interaction of ClfA and Fg to define in detail the binding of the C-terminus of Fg’s γ-chain and to explore if compounds can be constructed that antagonize the ClfA-Fg interaction but do not affect the Fg interaction with the platelet-integrin αIIbβ3.

Author Summary


Staphylococcus aureus (S. aureus) is a common pathogen that can cause a range of diseases from mild skin infections to life-threatening sepsis in humans. Some surface proteins on S. aureus play important roles in the S. aureus disease process. One of these bacterial surface proteins is clumping factor A (ClfA) that binds to the C-terminal region of one of the three chains of fibrinogen (Fg), a blood protein that plays a key role in coagulation. We carried out biochemical and structural studies to understand the binding mechanism of ClfA to Fg and to define the residues in Fg that interact with ClfA. Interestingly, the platelet integrin, which is important for platelet aggregation and thrombi formation, also binds to the same region of Fg as ClfA. Despite the fact that the two proteins bind at the same region, the mode of recognition is significantly different. Exploiting this difference in recognition, we have demonstrated that agents could be designed that inhibit the ClfA-Fg interaction but do not interfere with the interaction of Fg with the platelet integrin. This opens the field for the design of a novel class of anti-staph therapeutics.


Results/Discussion

Identification of critical residues in Fg required for binding to ClfA

In previous studies, a segment of ClfA composed of residues 221–539 was shown to bind to the C-terminal end of the human Fg γ-chain [10]. We designed, based on structural similarities with SdrG, a smaller ClfA construct (229–545) predicted to be composed only of the N2 N3 domains and showed that ClfA229–545 retained the Fg-binding activity. To identify specific residues in Fg that are important for binding to ClfA229–545, a panel of peptides (Fig. 1A) based on the Fg γ-chain sequence 395–411 (referred to as ζ1–17) were synthesized in which each position was sequentially substituted with an alanine residue (alanes 11 and 14 were changed to serines). These peptides were tested as inhibitors in solid-phase binding assays, using a peptide concentration giving about 50% inhibition by the wild-type peptide. Peptides ζ1–17H6A, ζ1–17H7A, ζ1–17G10A, ζ1–17Q13A, ζ1–17A14A, ζ1–17V17A, and ζ1–17D16A were significantly less potent inhibitors than the native sequence suggesting that the Fg residues H6, H7, G10, Q13, A14 and G15 interact with ClfA (Fig. 1B). Remarkably, peptides ζ1–17A11S, ζ1–17D16A, and ζ1–17V17A showed enhanced inhibition of ClfA binding to a recombinant form of residues 395–411 of the Fg γ-chain fused to a GST protein (GST-Fg ζ1–17) compared to a peptide with the wild-type sequence, indicating a higher affinity of the peptide variants for ClfA.

The ability of ClfA229–545 to bind to the peptide containing the ζ1–17D16A mutation was further characterized. In solid-phase assays, ClfA binds to immobilized GST-Fg ζ1–17 fusion protein with a lower affinity (Kd = 657 nM) compared to the mutated GST-Fg ζ1–17D16A (Kd = 35 nM) (Fig. 1C). In solution, using isothermal titration calorimetry (ITC) assays, (Fig. 1D), ClfA also binds with a lower affinity to the native ζ1–17 peptide (Kd of 5.8 μM) compared to the mutant ζ1–17D16A (Kd of 3 μM). Thus, although the apparent dissociation constants differ according to the assays used to estimate them, similar trends in affinity between the wild-type and the D16A mutation were observed.

Our results showed that alanine substitution at the C-terminal but not in the N-terminal region of the peptide affected MSCRAMM binding suggesting that the ClfA binding site is located at the very C-terminus of the Fg γ-chain (Fig. 1). Results also show that certain amino acid changes in the ζ1–17 sequence enhance ClfA binding compared to the wild-type Fg sequence indicating that the human Fg γ C-terminal 17 residues may not be the optimum ligand for ClfA.

Analysis of the previously solved SdrG-Fg peptide complex crystal structure showed that only 11 out of the 18 peptide residues interacted with the MSCRAMM. Similarly, only a part of the 17-residue γ-chain segment may be required for binding to ClfA. In order to establish the minimum Fg peptide required for binding to ClfA229–545, a series of N- and C-terminal truncations of the ζ1–17D16A peptide were synthesized (Fig. 2A). Truncations of 2, 4, 6 or 8 amino acids at the N-terminus of the Fg γ-peptide resulted in a reduced but detectable binding affinity when tested using ITC. There was a direct relationship between the length of the peptide and its affinity for ClfA. The smaller the peptide, the lower was the reduced but detectable binding affinity when tested using ITC. There was a direct relationship between the length of the peptide and its affinity for ClfA. The smaller the peptide, the lower was the observed affinity for the MSCRAMM (Fig. 2B). Thus, the N-terminal residues of the Fg peptide (residues 1–8) are not critical for the interaction but may either contribute to or stabilize the binding of the peptide to ClfA. On the other hand, deletions of 2 or 4 residues from the C-terminal end of the ζ1–17D16A peptide abolished binding. These results indicate that the C-terminal amino acids of Fg are critical for binding to ClfA and are in agreement with a previous report that showed that Fg lacking the
C-terminal residues AGDV in the γ chain (corresponding to residues 14–17 in the peptide) or a Fg-variant that replaces the last four γ-chain residues with 20 amino acids lacks the ability to bind recombinant ClfA221–550 and induce Staphylococcus aureus clumping [10].

A stabilized closed conformation of ClfA229–545 binds Fg with a higher affinity than the open form.

The Fg binding mechanism of SdrG276–596 involves a transition from an open conformation, where the peptide binding trench between the N2 and N3 domains is exposed for ligand docking, to a closed conformation of the SdrG276–596 seen for the MSCRAMM in complex with the ligand peptide. The insertion of the N3 extension into the latching trench on N2, which represents the last step in the dynamic DLL binding mechanism, stabilizes the closed conformation of SdrG276–596 [31]. A closed conformation of apo SdrG N2N3, stabilized by introducing a disulfide bond between the end of the N3 latch and the “bottom” of N2, no longer binds Fg [31] demonstrating that for SdrG an open conformation is required for the initial docking of the ligand peptide. To explore if the binding of ClfA to Fg is also dependent on a movement of the latch we constructed a ClfA protein containing two cysteine substitutions. The locations of the cysteine mutations were determined using computer modeling and by sequence alignment to corresponding mutations in SdrG [31]. The mutant ClfAD327C/K541C generated a stable, closed conformation form. This recombinant His-tag fusion protein was purified by Ni⁺⁺ chelating chromatography; ion-exchange and gel permeation chromatography. The ClfAD327C/K541C open and closed conformation forms were examined by SDS-PAGE analysis (Fig. 2C).

Under non-reducing conditions, the disulfide mutant and the wild-type protein migrate at the same rate. Surprisingly, the closed conformation of the disulfide mutant ClfAD327C/K541C was able to bind Fg (Fig. 2C). Elisa-type binding assays where Fg or GST

Figure 1. ClfA229–545 binds to Fg γ chain peptides. (A) Panel of Fg γ-chain peptides. The wild-type peptide corresponds to the 17 C-terminal residues of the Fg γ-chain (395–411); the mutated peptides have individual amino acids replaced with Ala (or Ser). (B) Fg γ peptides inhibit ClfA binding to immobilized GST-Fg γ1–17 in solid phase assays. Wells were coated with 1 μg GST-Fg γ1–17 peptide. ClfA229–545 (100 nM) was preincubated with wild-type Fg γ1–17 peptide (WT γ1–17) or the P1 (G1A) to P17 (V17A) mutant peptide (50 μM) for 1 hr. (C) Binding of ClfA to immobilized GST-Fg γ1–17 and GST-Fg γ1–17D16A using a solid-phase assay. Increasing concentrations of clfA229–545 were incubated in microtiter wells containing 1 μg GST (circles), GST-Fg γ1–17 (triangles) or GST-Fg γ1–17D16A (squares). Bound ClfA was detected with anti-His monoclonal antibodies as described in Material and Methods. (D) Binding of ClfA229–545 to Fg γ1–17 and Fg γ1–17D16A peptides in solution using ITC.

doi:10.1371/journal.ppat.1000226.g001
Fg γ^{1-17} peptide were coated in microtiter wells and incubated with ClfA showed that the closed conformation ClfA D327C/K541C bound the ligand with a much lower apparent Kₐ (34 nM Fg; 20 nM GST-Fg γ^{1-17} D16A) compared to the wild-type ClfA 229–545 (apparent Kₐ 305 nM Fg; 222 nM GST-Fg γ^{1-17} D16A) (Fig. 2D). These results demonstrate that an open conformation may not be required for Fg binding to ClfA and that Fg binding by ClfA involves a mechanism that is different from the DLL mechanism employed by SdrG.

Crystal structure of ClfA (229–545)D327C/K541C in complex with a 13 residue Fg-derived peptide

Crystalization screens were carried out with ClfA(229–545)D327C/K541C in complex with several N-terminal truncations of the γ^{1-17} D16A peptide that were shown to bind ClfA. Crystals of the stable closed conformation of ClfA(229–545)D327C/K541C were obtained, but structure determination was attempted for only the ClfA(229–545)D327C/K541C-γ^{5-17} D16A peptide. The crystals of the ClfA-peptide complex diffracted to a 1.95 Å resolution. Two copies of the ClfA-peptide complex were found in the asymmetric unit of the crystallographic unit cell and are referred to as A:C and B:D. Although the 13 residue Fg γ^{1-17} chain synthetic peptide was used for crystallization, only 11 residues were identified completely in both copies of the complex. The two molecules of ClfA D327C/K541C (A and B) are nearly identical with rms deviation of 0.3 Å for 312 Ca atoms and 0.55 Å for backbone atoms. As observed in the apo-ClfA(221–559) structure [24], the two molecules of ClfA D327C/K541C N2 and N3 domains adopt the DE-variant IgG fold. The overall structure of the ClfA D327C/K541C peptide complex (AcC) and the two different orientations of the complex are shown in Figure 3A and 3B respectively. The C-terminal extension of the N3 domain makes a β-sheet complementation with strand E of the N2 domain.
domain. This conformation is locked by the engineered disulfide bond as predicted by SDS-PAGE analysis (Fig. 2C) and confirmed by the crystal structure (Fig. S1). The two copies of the Fg γ-peptide molecules are nearly identical with rms deviation of 0.5 Å for 11 Ca atoms and 0.89 Å for backbone atoms. The interaction between the ClfA D327C/K541C and the peptide bury a total surface area of 1849 Å² and 1826 Å² in the A:C and B:D complex, respectively. The interaction of the peptide with the N2 domain is predominantly hydrophobic in nature, in addition to a few main-chain hydrogen bonds (Fig. 3C). Interactions between the Fg peptide and the N3 domain are both hydrophobic and electrostatic with the electrostatic contribution coming almost entirely from the main chain-main chain hydrogen bonds due to the parallel β-sheet formation of the peptide with strand G of the N3 domain (Fig. 3C). The side-chain interactions between the peptide and ClfA are predominantly hydrophobic. The 11 C-terminal residues of the Fg γ-chain peptide sequence that interact with ClfA are composed of only two polar residues, Lys12 and Gln13. Side chain atoms of Lys12 point away and do not interact with the ClfA protein whereas Gln13 makes two hydrogen bonds with the main chain atoms of Ile384 in ClfA (Fig. 3D). A water-mediated interaction is also observed between Gln13 of the peptide and Asn525 of ClfA. Tyr338 in the N2 domain and Trp523 in the N3 domain play an important role in anchoring the peptide molecule. Tyr338 and Trp523 are stacked with residues Gly15 and Gly10, respectively. In addition, Met521 and Phe529 make hydrophobic interactions with Ala7 and Val17, respectively. The C-terminal residues of the peptide Ala14, Gly15, Ala16, and Val17 are buried between the N2–N3 domain interface with the terminal Val residue, presumably threaded through a preformed

Figure 3. Representation of ClfA D327C/K541C (N2–N3)-peptide complex. (A) Ribbon representation of ClfA-peptide (Fg γ-chain analog) complex. The peptide is shown as ball and stick model. 2Fo-Fc map around the peptide contoured at 1σ is shown in the close-up view. (B) Ribbon representation of ClfA D327C/K541C –peptide complex in two orientations. The peptide molecule is shown in red and the engineered disulfide bond is shown as blue ball-and-stick object. (C) Schematic representation of ClfA-Fg γ-peptide main-chain parallel β-complementation interaction. The anti-parallel β-complementation observed in SdrG273–597-Fg γ-peptide complex is also shown for comparison. The residue numbers of both the Fg γ-chain sequence and the peptide numbering (1–17), in parenthesis, are shown. (D) Stereo-view showing the side-chain interactions of the ClfA- Fg γ-peptide complex. Carbon atoms of the peptide are shown in grey; oxygen, red; nitrogen, blue. Side chain atoms of ClfA are shown as pink stick objects. Hydrogen bonds are shown as dotted lines.

doi:10.1371/journal.ppat.1000226.g003
ligand binding tunnel after ClfA\textsubscript{D327C/K541C} adopted its closed conformation. A hydrogen bond is observed between Lys\textsubscript{389} of ClfA and the C-terminal carboxyl group of the peptide (Fig. 3D). Mutational studies showed that Tyr\textsubscript{338}Ala and Lys\textsubscript{389}Ala mutant ClfA showed significantly reduced binding to Fg [24] which corroborates with the structural results. Also an earlier study showed that E526A and V527S affected the binding [32]. The structure shows that these residues make main-chain interactions with the peptide (Fig. 3C). These residues are critical for the anchoring the peptide (Lock) and redirection of the latch.

Structural differences between the closed conformation ClfA\textsubscript{D327C/K541C}-peptide complex and the apo-ClfA\textsubscript{221–559} protein

The individual N2 and N3 domains in the apo-ClfA\textsubscript{221–559} and the closed form of ClfA\textsubscript{D327C/K541C} are almost identical with rms deviations of 0.33 and 0.42 Å for molecule A and 0.33 and 0.42 Å for molecule B, but the relative orientation of the N2 and N3 domains are significantly different (Fig. 4A). This difference affects the association of the N2 and N3 domains. In the apo conformation, the buried surface area between the N2 and N3 domains is 87 Å\textsuperscript{2} compared to 367 Å\textsuperscript{2} in the closed form of the ClfA\textsubscript{D327C/K541C}-peptide complex. In the apo-ClfA\textsubscript{221–559}, the C-terminal residues (Ala\textsubscript{528}-Glu\textsubscript{559}) of the N3 domain fold back and do not interact with the N2 domain. Moreover the folded-back segment completely occupies the binding site (Fig. 4B). Therefore, in the folded-back conformation, the ligand binding site appears not to be accessible to the peptide and thus this conformation appears to be inactive. It is presently unclear what the spatial arrangements of the N2N3 domains are in intact ClfA expressed on the surface of a staphylococcal cell. The two structures of these domains solved so far where one is active and the other inactive form suggests a possible regulation of ClfA’s Fg binding activity by external factors. One such factor may be Ca\textsuperscript{2+} which has been shown to inhibit ClfA-Fg binding [32]. Alternatively, it is possible that the folded-back conformation (which is a larger protein construct) is only one of the many possible conformations adopted by the unbound protein. Molecular modeling shows that the two domains in the folded-back conformation could adopt an orientation similar to their orientation in the ClfA-peptide complex (Fig. S2). Most likely, the structural rearrangements responsible for the transition of ClfA from an open unbound to the closed bound form are complex and involve different intermediate forms.

**Structural similarities/differences between the closed form of the ClfA-peptide and SdrG-peptide complexes**

The major difference between Fg-binding to ClfA and SdrG is that the directionality of the bound ligand peptide is reversed.
(Fig. 4C). The C-terminal residues of the ligand is docked between the N2 and N3 in ClfA and makes a parallel β-sheet complementation with strand G of the N3 domain, whereas in SdrG, the N-terminal residues of the ligand are docked between the N2 and N3 domains and form an anti-parallel β-sheet with the G strand. In both cases there are 11 ligand residues that make extensive contact with the MSCRAMM but with one residue shifted towards the N3 domain in ClfA. Of these 11 residues, 7 and 11 residues participate in the β-strand complementation of SdrG and ClfA, respectively. Although the peptide binding model of ClfA is different to that of SdrG, the inter-domain orientations of the two MSCRAMMS are very similar [25]. Superposition of 302 corresponding atoms in the N2 and N3 domains of ClfA and SdrG showed a small rms deviation of 0.65 Å indicating the high structural similarity between the two MSCRAMMS. Another striking difference is that ClfA does not require an open-conformation for ligand binding, whereas Fg can not bind to a stabilized closed conformation of SdrG. ClfA binds the C-terminal end of Fg and the last few residues of the γ-chain presumably can be threaded in to the binding pocket. In the SdrG-Fg interaction, the binding segment in Fg does not involve the seven N-terminal residues of the ligand and therefore an open conformation may be required for ligand binding.

Comparison of Fg binding to ClfA and the platelet integrin αIIbβ3

The C-terminus of Fg γ-chain, which is targeted by ClfA, is also recognized by the αIIbβ3 integrin in Fg induced platelet aggregation, a vital step in thrombosis [10,33]. The Fg γ-chain complex with αIIbβ3 structure is not available but structures of related complexes provide clues on how αIIbβ3 likely interact with Fg [34]. In addition, the crystal structure of the αIIbβ3 integrin in complex with an RGD ligand provided a structural model of a similar ligand-integrin interaction [35]. In this structure, the Asp (D) residue of the RGD sequence coordinates with the metal ion in the Metal Ion Dependent Adhesion Site (MIDAS) of the integrin and thus plays a key role in the interaction. The platelet specific integrin αIIbβ3 recognizes ligands with an RGD sequence or the sequence Lys-Gln-Ala-Gly-Asp-Val found in Fg [34]. Structural studies with drug molecules that antagonize the integrin-RGD or -Fg interaction showed that each of the drug molecules contains a carboxyl group moiety that mimics the aspartic acid and a basic group that mimics the Arg (or Lys in the case of Fg) in the ligand [34]. These results suggest that the Lys and Asp residues in the C-terminal γ-chain sequence are critical for the interaction with integrin. Interestingly, our studies have shown that these Lys and Asp residues in Fg are not critical for ClfA binding (Fig. 1B). In fact, substitution of Asp with Ala (γ17-D16A) results in a higher binding affinity. Absence of a strong interaction with Lys12 in the ClfA-peptide complex structure also correlates with the biochemical data, suggesting that Arg is not a key player in the ClfA-Fg interaction. In general, our studies show that K106 and D110, which are essential for the platelet integrin αIIbβ3-Fg interaction, are dispensable for the ClfA-Fg interaction. To experimentally examine this proposed difference, the ability of the synthesized Fg WT γ1–17 and mutated peptides (γ1–17-D16A and γ1–17-K12A) to inhibit full length Fg binding to αIIbβ3 was analyzed by an inhibitory ELISA type assay (Fig. 5). The WT γ1–17 peptide completely inhibited the binding of full-length fibrinogen to αIIbβ3 whereas γ1–17-D16A and γ1–17-K12A weakly inhibited Fg binding to αIIbβ3. These results clearly demonstrated that the γ1–17-D16A and γ1–17-K12A peptides bind weakly to platelet integrin and therefore can serve as specific antagonists of Fg-ClfA interaction.

Conclusions

Based on the results presented here, we postulate that the mechanism of interaction between ClfA and Fg is a variation of the “Dock, Lock and Latch (DLL)” model of SdrG binding to Fg. In the DLL model of binding, the apo-form of the SdrG is in an open conformation to allow the ligand access to the binding cleft. A closed conformation of SdrG is unable to bind Fg. In the ClfA model, we believe that the peptide may thread into the cavity formed in a stabilized closed configuration and therefore the ClfA-Fg binding mechanism could be called “Latch and Dock”.

In the case of CNA, a collagen binding MSCRAMM from S. aureus, the collagen molecule binds to CNA through a “collagen hug” model [36] which represents yet another variant of the DLL binding mechanism. All three MSCRAMM-ligand structures determined so far, SdrG, CNA and the ClfA have different ligand binding characteristics and mechanisms, although the overall structures of the ligand binding regions of these MSCRAMMs are very similar. These observations suggest that an ancestral MSCRAMM has evolved along different paths to accommodate different ligands without greatly altering the overall organization of the proteins.

The co-crystal structure of ClfA in complex with the C-terminal region of the γ-chain of Fg will allow the design of potent antagonist of the ClfA-Fg interaction. The Fg based peptide analogs that antagonize the ClfA-Fg interaction but not affect the αIIbβ3 integrin interaction could serve as a starting point to develop novel anti-staphylococcal therapeutic agents that do not affect the αIIbβ3.

Materials and Methods

Bacterial Strains, Plasmids, and Culture Conditions

Escherichia coli XL-1 Blue (Stratagene) was used as the host for plasmid cloning and protein expression. Chromosomal DNA from S. aureus strain Newman was used to amplify the ClfA DNA sequence. All E. coli strains containing plasmids were grown on LB media with ampicillin (100 μg/ml).

Manipulation of DNA

DNA restriction enzymes were used according to the manufacturer’s protocols (New England Biolabs) and DNA manipulations
were performed using standard procedures [37]. Plasmid DNA used for cloning and sequencing was purified using the Qiagen Miniprep kit (Qiagen). DNA was sequenced by the dideoxy chain termination method with an ABI 373A DNA Sequencer (Perkin Elmer, Applied Biosystems Division). DNA containing the N-terminal ClfA sequences were amplified by PCR (Applied Biosystems) using Newman strain chromosomal DNA as previously described [33]. The synthetic oligonucleotides (IDT) used for amplifying clfA gene products are listed in Table S1.

Construction of disulfide mutants

Cysteine mutations were predicted by comparing ClfA221-559 to SdrG/273-397 disulfide mutant with stable closed conformations [31] and by computer modeling. A model of ClfA in closed conformation was built based on the closed conformation of the SdrG-peptide complex [25]. The Cβ-Cβ distances were calculated for a few residues at the C-terminal end of the latch and strand E in the N2 domain. Residue pairs with Cβ-Cβ distance less than 3 Å were changed to cysteines to identify residues that could form optimum disulfide bond geometry. The D291C/K541C mutant was found to form a disulfide bond at the end of the latch. The cystine mutations in ClfA221-559 were generated by overlap PCR [39,40]. The forward primer for PCR extension contained a BsmI restriction site and the reverse primer contained a KpnI restriction site. The mutagenesis primers contained complementary overlapping sequences. The final PCR product was digested with BsmI and KpnI and was ligated into same site in the expression vector pQE-30 (Qiagen). All mutations were confirmed by sequencing. The primers used are listed in Table S1.

Expression and Purification of Recombinant Proteins

E. coli lysates containing recombinant ClfA and GST-Fg γ-chain fusion proteins were purified as previously described [32]. PCR products were subcloned into expression vector pQE-30 (Qiagen) to generate recombinant proteins containing an N-terminal histidine (His) tag as previously described [10]. The recombinant ClfA His-tag fusion proteins were purified by metal chelation chromatography and anion exchange chromatography as previously described [23]. To generate recombinant ClfA229-545 and ClfA221-559 proteins, PCR-amplified fragments were digested with BsmI and KpnI and cloned into BsmI/KpnI digested pQE-30. The primers used to generate the recombinant constructs are listed in Table S1. The reactions contained 50 ng of strain Newman DNA, 100 pmol of each forward and reverse primers, 250 nM of each dNTP, 2 units of Pfu DNA polymerase (Stratagene) and 5 μl Pfu buffer in a total volume of 50 μl. The DNA was amplified at 94°C for 1 min, 48°C for 45 sec; 72°C for 2 min for 30 cycles, followed by 72°C for 10 min. The PCR products were analyzed by agarose gel electrophoresis using standard methods [37] and purified as described above.

Enzyme-linked Immunosorbent Assay

The ability of the wild-type ClfA229-545 and disulfide ClfA mutants to bind Fg was analyzed by ELISA-type binding assays. Immunol 4HBX Microtiter 96-well plates (Thermo) were coated with ψβK14β (0.25 μg/well) in TBS (25 mM Tris, 3 mM KCl, 140 mM NaCl, pH 7.4) over night at 4°C. The wells were washed with TBS containing 0.05% (w/v) Tween-20 (TBST). After blocking with 3% (w/v) BSA dissolved in TBS for 1 h at RT, 10 nM of full length Fg was applied in the presence of either WT γ1–17, γ1–17 ΔD186 or γ1–17 ΔK122 peptides and plates were incubated at RT for another hour. The bound full length Fg was then detected by goat anti human Fg (1:1000 dilution, Sigma) antibody followed by horseradish peroxidase-conjugated rabbit anti-goat IgG antibody (1:1000 dilution, Cappel). After incubation with 0.4 mg/ml of substrate, o-phenylenediamine dihydrochloride (OPD, Sigma) dissolved in phosphate-citrate buffer, pH 5.0, bound antibodies were determined in an ELISA reader at 450 nm. The proteins, antibodies and peptides were diluted in TBST containing 1% (w/v) BSA, 2 mM MgCl2, 1 mM of CaCl2 and MnCl2.

Synthesis of γ-chain Peptides

The wild-type and mutated peptides corresponding to the 17 C-terminal residues of the fibrinogen γ-chain (395–411) and truncated versions of this peptide (listed in Figure 2A) were synthesized as previously described and purified using HPLC [10].

Isothermal Titration Calorimetry

The interaction between ClfA proteins and soluble Fg peptides was analyzed by isothermal titration calorimetry (ITC) using a VP-ITC microcalorimeter (MicroCal). The cell contained 30 μM ClfA and the syringe contained 500–600 μM peptide in HBS buffer (10 mM HEPES, 150 mM NaCl, pH 7.4). All samples were degassed for 5 min. The titration was performed at 30°C using a preliminary injection of 5 μl followed by 30 injections of 10 μl with an injection speed of 0.5 μl/sec. The stirring speed was 300 rpm. Data were fitted to a single binding site model and analyzed using Origin version 5 (MicroCal) software.

Crystallization

The ClfA227C/K541C protein was purified as described earlier and concentrated to 30 mg/ml. The synthetic γ-chain peptide analogs, P16 and N-terminal truncations of P16 (P16 -2Nt, P16 -4Nt and P16 -6Nt) were mixed with the protein at 1:20 molar ratio and left for 30 min at 5°C. This mixture was screened for crystallization conditions. Small needles of the ClfA/P16 -2Nt, -4Nt and -6Nt were obtained during initial search of the crystallization condition, but we could only successfully optimize ClfA/P16 -4Nt and ClfA/P16 -6Nt. Diffraction quality crystals were obtained by mixing 2 μl of protein solution with 2 μl of reservoir solution containing 16–20% PEG 8K, 100 mM succinic acid pH 6.0.
X-ray data collection, Structure Solution and refinement

Crystals of ClfA/ P16 -4Nt were flash frozen with a stabilizing solution containing 20% glycerol. Diffraction data were measured on Rigaku R-Axis IV++ detector. A total of 180 frames were collected at a detector distance of 120 mm with 1° oscillation. Data were indexed, integrated and scaled using d*terk [41]. The crystals diffracted to 1.95 Å and the data statistics were listed in Table 1. Calculation of the Matthews coefficient suggested the presence of 2 copies of the molecule in the unit cell of the triclinic cell. The structure was solved by molecular replacement (MR) with the program PHASER [42] using individual N2 and N3 domains of ClfA as search model. Solutions for the N3 domain were obtained for the two copies followed by the solutions of N2 domains. Data covering 2.5–15 Å were used for the molecular replacement solution. Electron density maps calculated during the initial rounds of refinement showed interpretable density for 11 out of 13 peptide residues in both the copies of the complex. Modeling building of the peptide and rebuilding of a few loop regions were performed using the program COOT [43]. A few cycles of ARP/WARP [44] were performed to improve the map and for the building of water model. After a few cycles of refinement using Refmac5.2 [45], electron density was clear for only the backbone atoms for two remaining N-terminal residues of the peptide molecule D and one residue for peptide C. The final model of ClfA included residues 230–299, 303–452, 456–476 and the peptide molecule D and one residue for peptide C. The final cycles of ARP/WARP [44] were performed to improve the map. A few replacement solution. Electron density maps calculated during the regions were performed using the program COOT [43]. A few cycles of ARP/WARP [44] were performed to improve the map and for the building of water model. After a few cycles of refinement using Refmac5.2 [45], electron density was clear for only the backbone atoms for two remaining N-terminal residues of the peptide molecule D and one residue for peptide C. The final model of ClfA included residues 230–299, 303–452, 456–476 and 479–545 in molecule A and 230–438, 440–476 and 479–542 in molecule B. The structure was refined to a final R-factor of 21.1% and R-free of 27.9%. Stereochemical quality of the model was validated using PROCHECK [46]. Molecular modeling studies were performed using InsightII software (Accelrys Inc). Figures were made using RIBBONS [47]. The atomic coordinates and structure factors of the complex structure have been deposited in Protein data bank with accession number; 2vr3.

Supporting Information

Figure S1 Stereo view showing the disulfide bond in the ClfAID327C/K541C. 2Fo-Fc map around the Cys327 and Cys541 contoured at 1σ is shown. Carbon atoms are colored grey and the sulfur atoms in yellow.

Figure S2 Ribbon representation of modeled ClfA229–559 in ligand bound N2–N3 orientation. Residues that make clashes are shown as stick objects. This model was built to understand if the altered N2–N3 orientation of the apo-form of ClfA (Fig. 4A) is due to the folded-back conformation, a model of the apo-ClfA221–559 was constructed with the folded-back N3 domain and the N2 domain adopting an N2–N3 orientation similar to that observed in the closed form of the ClfA-peptide complex. This model shows that Tyr338 in the N2 domain makes severe clashes with residues Ser353 and Gly534 of the folded back segment. An alternate conformation for these residues is unlikely due to spatial constraints. Additional clashes were also observed between Ala 254 and Gly 536. Thus, it is unlikely that the two domains in the folded-back conformation could adopt an orientation similar to their orientation in the ClfA-peptide complex.

Table S1

| Table 1. Crystallographic data measurement and refinement data. |
|-----------------|-----------------|
| Cell dimensions |                  |
| a, b, c (Å)     | 35.43, 61.84, 81.78 |
| α, β, γ (°)     | 85.44, 81.84, 82.45 |
| Space group     | P1               |
| Resolution (Å)  | 1.95–15.0        |
| Reflections total/unique | 86051/46090 |
| Completeness (%)| 93.9             |
| Rmerge           | 0.074            |
| Number of molecules in the asymmetric unit | 2 |
| Rfactors/ Rfree | 0.211/0.279     |
| Bond rms deviation (Å) | 0.015 |
| Angle rms deviation (°) | 1.64 |
| Average B value (Å) | 29.9 |
| No of non-hydrogen atoms | 5226 |
| Protein         | 4558             |
| Peptide         | 141              |
| Water           | 527              |
| Rms deviations from ideal values |                  |
| Bond lengths (Å) | 0.22            |
| Bond Angles (°)  | 1.95             |
| PDB ID          | 2vr3             |

* Rmerge = Σhkl-(|Fhkl|)/Σhkl |Fhkl|; where hkl is the measured and |Fhkl| is the mean intensity of reflection hkl.

** Rfree is calculated over 2% of randomly selected reflections not included in the refinement.

doi:10.1371/journal.ppat.1000226.t001

Acknowledgments

We thank Dr. Allison Bartlett for critical reading of the manuscript and Dr. James Sacchetti, Dept. of Biochemistry and Biophysics, Texas A & M University for the use of the x-ray data collection facility.

Author Contributions

Conceived and designed the experiments: VKG JJR ES YPK MGB JRF MH. Performed the experiments: VKG JJR ES YPK ERW SG. Analyzed the data: VKG JJR ES YPK ERW MH. Wrote the paper: VKG JJR ES YPK MGB JRF MH.

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