

On the Activation of Integrin α Ib β 3: Outside-in and Inside-out Pathways

Mehrdad Mehrbod,[△] Stephen Trisno,[△] and Mohammad R. K. Mofrad*

Molecular Cell Biomechanics Laboratory, Departments of Bioengineering and Mechanical Engineering, University of California, Berkeley, California; and Physical Biosciences Division, Lawrence Berkeley National Laboratory, Berkeley, California

ABSTRACT Integrin α Ib β 3 is a member of the integrin family of transmembrane proteins present on the plasma membrane of platelets. Integrin α Ib β 3 is widely known to regulate the process of thrombosis via activation at its cytoplasmic side by talin and interaction with the soluble fibrinogen. It is also reported that three groups of interactions restrain integrin family members in the inactive state, including a set of salt bridges on the cytoplasmic side of the transmembrane domain of the integrin α - and β -subunits known as the inner membrane clasp, hydrophobic packing of a few transmembrane residues on the extracellular side between the α - and β -subunits that is known as the outer membrane clasp, and the key interaction group of the β A domain (located on the β -subunit head domain) with the β TD (proximal to the plasma membrane on the β -subunit). However, molecular details of this key interaction group as well as events that lead to detachment of the β TD and β A domains have remained ambiguous. In this study, we use molecular dynamics models to take a comprehensive outside-in and inside-out approach at exploring how integrin α Ib β 3 is activated. First, we show that talin's interaction with the membrane-proximal and membrane-distal regions of integrin cytoplasmic-transmembrane domains significantly loosens the inner membrane clasp. Talin also interacts with an additional salt bridge (R734-E1006), which facilitates integrin activation through the separation of the integrin's α - and β -subunits. The second part of our study classifies three types of interactions between RGD peptides and the extracellular domains of integrin α Ib β 3. Finally, we show that the interaction of the Arg of the RGD sequence may activate integrin via disrupting the key interaction group between K350 on the β A domain and S673/S674 on the β TD.

INTRODUCTION

Integrins are a family of extracellular matrix (ECM) binding proteins that consist of 25 heterodimeric members. Each integrin molecule is composed of a α and a β noncovalently associated subunits. Each integrin subunit consists of a large extracellular domain (ectodomain), a single-pass transmembrane helix, and a short cytoplasmic tail (1,2). Integrins play a host of crucial roles in a variety of cell functions, including linking focal adhesion assemblies to the ECM, facilitating cell migration, transmitting signals bidirectionally, and controlling cell growth, differentiation, and apoptosis (2–6). Additionally, clustering of integrins is known to be a critical regulator of the focal adhesion size (7–9). Integrin α Ib β 3, which is the major integrin type expressed on the surface of platelets, plays a critical role in platelet aggregation and blood clotting (10,11). Therefore, integrin α Ib β 3 malfunction is marked by several diseases such as thrombosis in myocardial infarction, ischemic stroke, peripheral arterial disease, and Glanzmann thrombasthenia bleeding disorder (11,12). Integrin α Ib β 3 is activated via inside-out and/or outside-in signaling mechanisms, and these two pathways are reported to be discrete while having mutual effects on each other (1,2,13).

The inside-out activation of integrins is defined as the process of activation that is triggered by a cytoplasmic signal and leads to increased affinity of the integrin head

domain for the ligand. Inside-out activation processes modulate integrin α Ib β 3 affinity for extracellular ligands (i.e., fibrinogen) through binding of key cytoplasmic proteins (see Fig. 1). Among the various proteins that bind integrins and link them to the actin cytoskeleton, talin and kindlin are reported to activate integrin via associating with the cytoplasmic tail of the integrin β -subunit (4,14). The most well-known inside-out activation cascade for integrin α Ib β 3 is triggered by binding of cleaved thrombin to proteinase-activated receptor 1 (PAR1) located on the plasma membrane of human platelets. This binding leads to phospholipid hydrolysis, which results in the generation of inositol trisphosphate (IP3) and diacylglycerol (DAG), and an increase in cytosolic free Ca^{2+} . The elevated concentration of Ca^{2+} and DAG, which in turn activates CALDAG-GEF1 and protein kinase C (PKC), converts RAP1 from a GDP-bound to a membrane-attached, GTP-bound form. Activation of RAP1 leads to recruitment of its effectors, RAP1-GTP-interacting adaptor molecule (RIAM), and its binding partner, talin 1, to the plasma membrane. This facilitates access of talin to the integrin β 3 tail and talin-induced activation of integrin α Ib β 3 (4). Two major interactions attach the transmembrane domains of the α - and β -subunits: the outer membrane clasp (OMC) embedded within the lipid bilayer and the inner membrane clasp (IMC) located near the membrane-proximal (MP), cytoplasmic tail between the integrin subunits (2). Upon release of these clasps, the transmembrane-cytoplasmic domains of integrin are separated and activated, causing the extracellular domains to become more receptive to ECM ligand binding. Binding

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[△]Mehrdad Mehrbod and Stephen Trisno contributed equally to this work.

*Correspondence: mofrad@berkeley.edu

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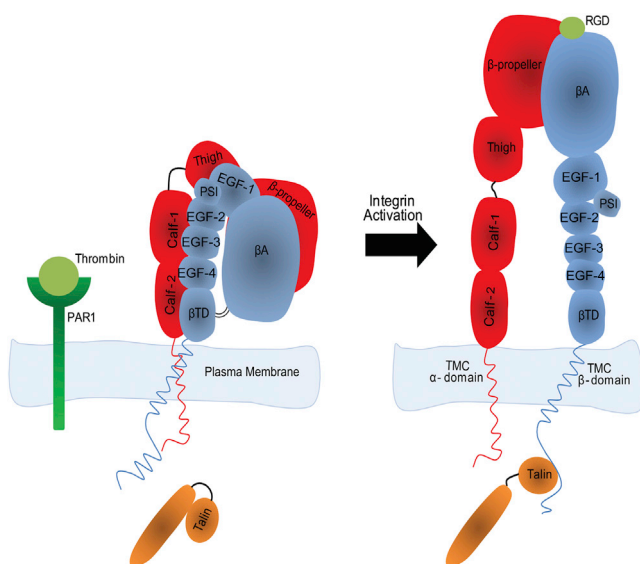


FIGURE 1 A schematic of one of the main pathways of integrin α Ib β 3 inside-out activation. Binding of thrombin to PAR1 causes separation of the talin head and tail domains. Consequently, the talin head domain associates with the β 3 subunit cytoplasmic domain, activating integrin α Ib β 3.

of the integrin β 3 subunit to talin-1 is one of the major factors that disrupts the interactions between the two integrin subunits, separating the transmembrane-cytoplasmic domains (14). The current study provides molecular-resolution simulations that show how talin head domain binding to the transmembrane-cytoplasmic domain of the integrin β 3 subunit mechanically loosens the IMC.

On the other hand, the outside-in activation is identified by interactions of the integrin extracellular head domain with the ECM ligand or divalent cations that lead to partial unfolding of the extracellular domain and separation of integrin subunits. The integrin β 3 subunit is known to be the major regulator of activation for integrin α Ib β 3 and α v β 3 (15,16). Binding of divalent cations with the integrin head domain (i.e., β A and β -propeller domains on the extracellular side) is reported to determine the integrin activation state. There exist three divalent metal ion binding sites on the integrin β A domain. The first one, termed as the metal ion-dependent adhesion site (MIDAS) is coordinated with Mg^{2+} , although the two other cation binding sites, called the adjacent to MIDAS (ADMIDAS) and ligand-induced metal binding site (LIMBS) located on the opposite sides of MIDAS, are coordinated with Ca^{2+} (15,17,18). High concentrations of Ca^{2+} reinforce the bent, inactive state of integrin α v β 3, whereas in the presence of Mn^{2+} , a cation that activates integrins, most integrin α Ib β 3 molecules observed by electron microscopy were in an extended conformation (19). It is proposed by some researchers that the RGD ligand and divalent cation share a common binding pocket on the integrin β 3 head domain on the interface of the β A and β -propeller domains (20,21). Importantly, external force has also been shown to directly activate

certain types of integrin and prolong their ligand-bound lifetime (20,21). Last but not least, the integrin head domain interaction with the ligand at the metal ion-dependent binding sites is shown to activate integrins though its details are not yet fully agreed upon. Furthermore, whether an interaction between the CD loop of the β TD and the β 6- α 7 loop of the β A domains regulates integrin activation remains highly controversial (22,23). Hence, we explored potential effects of RGD-binding to integrin α Ib β 3 through positioning two soluble RGD peptides proximal to the metal ion-dependent binding sites and one near the β A- β TD domains interface.

Two mechanistic models are widely invoked to describe the behavior of integrins: the switchblade and the deadbolt model (24). According to the switchblade model, integrins take on three distinct conformations, corresponding to their inactive, active, and ligand-bound states. The inactive state of integrin is featured by a bent-over configuration wherein the molecule shows a low affinity for ECM ligands (see Fig. 1) (24). Furthermore, in the inactive state, IMCs and OMCs hold the transmembrane domains of integrin together (1). Integrin activation results in a stretched conformation and breakage of the IMCs and OMCs, most likely via presence of a competing molecule (e.g., talin and kindlin) that occupies these binding sites on the transmembrane domain of the integrin β -subunit (2,4). Activated integrin is known to have a significantly higher affinity for ECM ligands (19). Finally, the ligand-bound state takes place when the integrin head domain engages in an interaction with an ECM molecule (e.g., fibronectin and fibrinogen). The ligand-bound conformation differs from the nonbonded active state in that the integrin head domain introduces an opening between the α - and β -subunits when in the ligand-bound state (23,25). Alternatively, the deadbolt model suggests a significantly smaller conformational change, wherein a hairpin loop between β -strands C and D of the β 3 tail domain (i.e., the CD loop), located on the β -subunit proximal to the plasma membrane, functions as a dead bolt. Upon release of the CD loop, the integrin molecule is activated, as the bonding between the β TD (proximal to the plasma membrane) and the β A domains on the integrin head domain is lost (23,26,27).

Despite numerous experimental studies conducted to shed light on the elaborate mechanism of integrin α Ib β 3 activation from inside-out as well as outside-in perspectives, the atomistic details of either of these mechanisms have remained ambiguous (4,13). In this study, we developed molecular dynamics (MD) models to probe details of inside-out and outside-in activation of integrin α Ib β 3 via integrin-talin interactions. It has been shown previously that outside-in signaling pathways of integrin α Ib β 3 are spatially distinct from those of inside-out activation in platelets (13). Hence, this study chose to dissect two of the most established pathways for integrin α Ib β 3 activation in molecular details: Talin binding to the cytoplasmic

domain of the β_3 subunit to represent the inside-out activation, and RGD binding to the ectodomain to simulate the outside-in activation. First, we estimated the strength of the integrin transmembrane bonds (i.e., IMCs and OMCs) and showed that the presence of the talin head domain bound to the cytoplasmic domain of the integrin β -subunit markedly loosens the IMC such that a lower external force is required to separate the transmembrane domains of the α - and β -subunits. We focused our attention on the talin-integrin β_3 interaction as the last step of a major cascade of events that leads to integrin activation to show, in molecular details, the contribution of this critical event in dissociating the integrin transmembrane domains. Furthermore, using the full-length crystal structure of integrin including the ectodomain and transmembrane-cytoplasmic domains for the first time to the best of our knowledge, we identified a number of potential binding sites of the soluble RGD ligand to the integrin head domain. Based on these results, three likely mechanisms are proposed for integrin-ligand binding. Finally, we explored the dead-bolt model in atomic details, mapping out three key residues that act as the dead bolt.

METHODS

Interactions of RGD peptides with full-length integrin

All MD simulations were carried out with the program NAMD (28), using CHARMM27 force field. The integrin $\alpha\text{Ib}\beta_3$ ectodomain (PDB ID: 3FCS chains A and B (29)) and the transmembrane-cytoplasmic domains (PDB ID: 2KNC (46)) were obtained from the Protein Data Bank (PDB) and combined to build the full-length integrin $\alpha\text{Ib}\beta_3$ structure (except residues 954–959 of the α -subunit and 684–690 of the β -subunit), assuming covalent bonds between residues C959 and G955 on the α -subunit and G684 and G690 on the β -subunit. The integrin structure was embedded in a patch of POPC (1-palmitoyl-2-oleoyl-sn-glycero-3-phosphocholine) lipid bilayer with dimensions of $152 \times 113 \text{ \AA}$, using the software VMD (30). In all simulations, lipid chains overlapping with the transmembrane domain were removed afterward. PDB files of three RGD peptides were manually produced and positioned in proximity of the integrin head domain as shown in Fig. 2. The system was solvated afterward in a water box with an ionic KCl concentration of 150 mM (31).

The pressure and temperature of the system were held constant at 1 atm and 310 K, respectively, using Langevin's piston and Hoover's method (28). The time step was taken as 2 fs. The cutoff distance for nonbonded interactions was 1.2 nm. For all simulations, the particle mesh Ewald method was used for electrostatic force calculations (28). The cutoff distance for nonbonded interactions was 1.2 nm. The hydrogen atom bond length was constrained using the SHAKE method. The SHAKE method fixes bond lengths between large atoms and hydrogen atoms, preventing unnecessary calculation of irrelevant interactions (32). The system was minimized, at 2000 steps, and equilibrated six times with RGD peptides present and once with no RGD peptide in the system as control, each time for ~ 13 ns.

Integrin-talin binding

The crystal structure of the transmembrane and cytoplasmic domains of integrin $\alpha\text{Ib}\beta_3$ was embedded in a patch of POPC. The first step in our simulations was to induce the talin-1 FERM head domain to bind to integrin

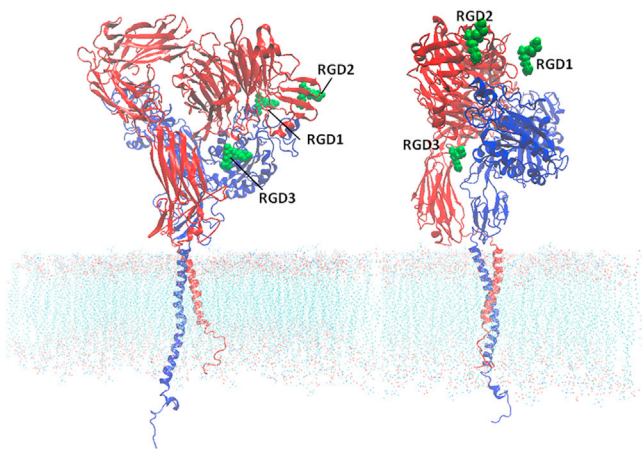


FIGURE 2 Crystal structure of integrin $\alpha\text{Ib}\beta_3$ embedded in the plasma membrane. Three RGD peptides (green) are positioned in potential binding regions of integrin. The only RGD sequence that interacted with the integrin molecule was the one located near the βTD - βA pocket (RGD3). The αIb and β_3 subunits are depicted in red and blue, respectively.

$\alpha\text{Ib}\beta_3$, which are known to bind to each other (33,34). A model was created, using the molecular graphics software VMD, with the transmembrane-cytoplasmic regions of integrin $\alpha\text{Ib}\beta_3$ (PDB ID: 2KNC (35)) embedded in a POPC lipid bilayer (30). The Talin-1 FERM head domain (PDB ID: 3IVF (36)) was placed with the F3 (PTB-like) domain, facing the integrin β_3 subunit with a 27 \AA distance between the center of mass of the F3 domain (L320) to β_3 residue W739. The system was solvated, then neutralized and ionized to a concentration of 150 mM NaCl. The system underwent minimization (2000 steps) and equilibration for 7 ns, before each center of mass in the F0–F3 talin domains was given a nudge for 1 ns ($k = 0.07 \text{ kcal/mol/\AA}^2$; velocity = 17.5 \AA/ns) in the direction that minimizes the mentioned 27 \AA distance. Following that, the system was allowed 28 ns to equilibrate. At the end of the total 36 ns, we nudged the F0 domain of talin for 1 ns ($k = 0.06 \text{ kcal/mol/\AA}^2$, velocity = 12.5 \AA/ns) to tilt the F3 domain of talin toward the integrin β_3 subunit. This was performed to promote the MP interactions between F727 and F730 on the β_3 subunit to the S1-S2 loop of talin F3 (33). Following that, the system was equilibrated for 9.5 ns.

Simulation and analysis of integrin-talin interactions using full-length integrin structure

Having obtained a full-length integrin $\alpha\text{Ib}\beta_3$ structure, we placed it inside a membrane, solvated and ionized it with 150 mM NaCl, and ran a minimization and equilibration simulation for 6 ns. Next, with our equilibrated full-length integrin structure, a similar model consisting of integrin and talin-1 FERM head domain was built, with a similar orientation and initial distance maintained between the integrin β_3 subunit and F3 domain of talin-1. This model was minimized and equilibrated for 4 ns, 10 times to get a random sample of velocities and trajectories. From the simulations, we measured the final distance (at ~ 4 ns) between R734-E1006, between the αIb and β_3 extracellular domains, between the βTD and βA domains, and between the center of masses of selected regions of the β_3 subunit of integrin and talin-1 F3 domain. Finally, the Spearman's tests of dependence were performed to further pinpoint which region of the β_3 subunit tail is correlated to the weakening of this additional interaction and whether the degree of talin binding to the integrin β_3 subunit affected integrin's extracellular conformation. (Details for the comparison of the IMC interactions and other results in integrin versus integrin-talin systems are included in the Supporting Material.)

RESULTS

Interactions between the soluble RGD and integrin potentially activates integrin α IIB β 3

To probe likely binding sites of the soluble ligand, RGD sequences were placed at three locations proximal to the integrin head domain previously reported as potential binding spots of integrin for fibrinogen (15,18,23). Depicted in Fig. 2 are locations of the three soluble RGD ligands relative to the integrin molecule. Two RGD peptides were positioned in the vicinity of the interface between the β -propeller domain of the α -subunit and the β A domain of the β -subunit, whereas another RGD peptide was located in proximity of the pocket formed by the β A and β TD domains of the β -subunit. Fibrinogen is a large macromolecule with a low transformational and rotational diffusion coefficient (37). Therefore, identifying the potential binding sites of the fibrinogen on the integrin head domain requires an excessive amount of computational time, i.e., several seconds or even longer, which is beyond the timescale of current MD models. Hence, merely a functional part of the fibrinogen molecule, i.e., the RGD sequence, was located close to the integrin head domain and allowed to diffuse freely.

The integrin molecule embedded in the lipid bilayer was solvated in a water box, minimized in 2000 steps of 2 fs, and equilibrated for no less than 13 ns. The three RGD peptides diffused throughout the water box until they formed interactions at various regions on the integrin head domain. The simulation was repeated seven times, corresponding to a total of \sim 104 ns. RGD peptide 3 (RGD3) interacted with various binding sites located on the integrin head domain and/or within the inner pocket formed by the bent molecule (see Fig. S1). However, RGD peptide 1 and 2 (RGD1 and RGD2) combined interacted with a more limited number of binding sites on the interface of the β A and β -propeller domains. Intriguingly, RGD3 was confined to the β A- β TD pocket region in all simulations, whereas RGD1 and RGD2 remained associated with the head domain only in half of the simulations. Interactive residues on each subunit are shown in Table S1.

Interactions that lasted for a minimum of \sim 3 ns after their initial formation were called permanent bonds as opposed to those formed only intermittently, termed temporary bonds hereinafter. Depicted in Fig. S1 is the distance between interacting residues of integrin within the β A- β TD pocket region and RGD3. It is noteworthy that interactions between the RGD peptide and extracellular domain of integrin are mainly salt bridges, as the RGD peptide is equipped with a strong basic residue and a highly acidic one (i.e., Asp and Arg) with long side chains at its two ends that are separated by a small hydrophobic spacer (i.e., Gly). For this reason, all permanent bonds shown in Fig. S1 are of \sim 4.5 Å bond length, which is the characteristic length of a salt bridge (38,39).

According to the nature of bonds in the simulated trajectories, integrin-RGD bindings were classified into three major groups; the first group (i.e., type1 bond) comprised interactions with only a single, permanent interaction between the RGD peptide and integrin as shown in Fig. S1 a and b. Permanent bonds were formed as a result of type1 bonds with minimal fluctuations in all cases. The bond distance between the Arg of RGD3 and D817 on the Calf2 domain of the α -subunit is presented in Fig. S1, whereas Fig. S1 b shows the bond distance between the Arg of RGD3 and D127 on the β A domain of the β -subunit.

The second type of binding that occurred in two of our simulations included bindings in which one side of the soluble RGD peptide interacted permanently with the β A domain on the integrin head domain, whereas the other end only showed temporary engagement with membrane proximal domains of integrin. In one simulation, the Arg side of the soluble RGD formed a permanent bond with E312 on the β A domain (see Fig. S1 c). This interaction served as an anchorage for the ligand while the other side interacted temporarily with K650 on the β TD. Another permanent interaction formed between the Arg of RGD3 and D232 of the β -propeller domain of the α IIB subunit, whereas the Asp side of RGD3 formed a temporary interaction with N313 on the β A domain (see Fig. S1 d).

The other, and the most complex, type of interactions involved one permanent binding site and two temporary interactions on the integrin molecule that competed with each other. This group of interactions featured one end of the free RGD peptide tethering to the β -subunit permanently with other short-term bindings also taking place at the other end of the RGD peptide. For instance, Fig. S1 e shows a permanent bond between the Arg of RGD3 and D628 on the Calf1 domain of the α -subunit (*blue*) as well as the temporary bonds between the Asp of RGD3 with R897 on the Calf1 domain of the α -subunit (*green*), and K600 on the linker region between the EGF-1 and β TD (*red*). Although partial detachments were seen in a few of the simulations, a full separation of the β TD and β A domains was only observed in one out of six RGD-included simulations, when RGD3 interacted with three binding sites as depicted in Fig. S1 f. A permanent, polar interaction (as shown in *blue* in Fig. S1 f) was formed between the Arg of RGD3 and E671 on the β TD. Importantly, it was observed that the electrostatic interactions of S673 and S674 on the β TD with K350 serve as a key for activation of integrin α IIB β 3, as depicted by Fig. 3. This simulation was run for \sim 21 ns. The key residues on the β TD (i.e., S673 and S674) continued to interact with K350 until $t = 7.5$ ns (see Fig. 3 c). However, as the Arg of the RGD peptide reached the vicinity of S674 at $t = 7.5$ ns, the Arg of the RGD peptide competed with K350 for S674 and the key interaction was highly disturbed (Fig. 3 d). Finally, the key interaction was fully removed as the Asp of the RGD peptide engaged in a competitive interaction with K600

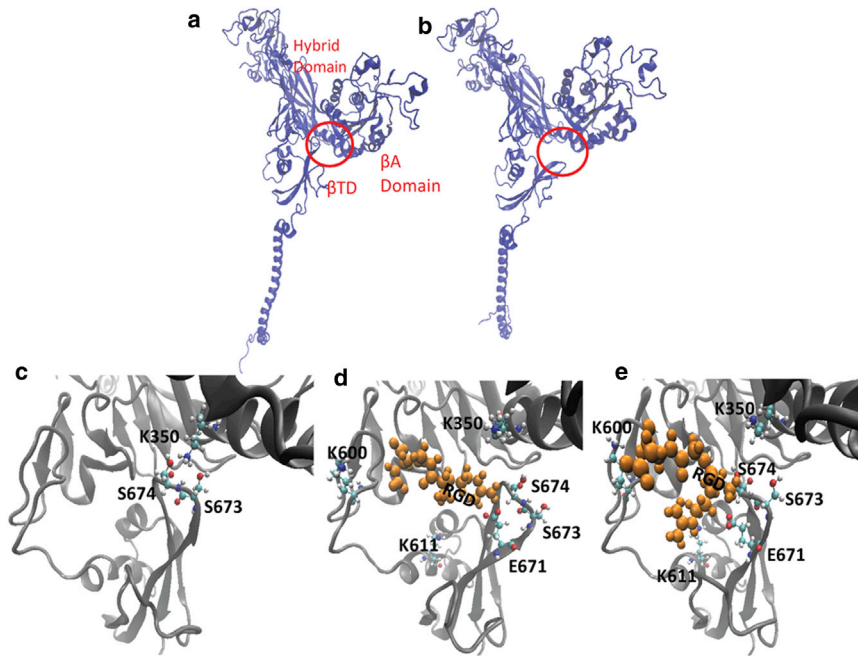


FIGURE 3 The Arg of the RGD peptide disrupts the β A- β TD interactions via competing with K350 on the β A domain for S673. (a) The β A and β TD are attached in the inactive, bent state of integrin. (b) The β TD swings open and separates apart from the β A domain, which leads to integrin activation. (c) Focusing further into the β TD- β A pocket shows the key interaction between K350 and S673/S674 that keeps integrin inactive. (d) The RGD peptide approaches S674 and interacts with it, disrupting the key interaction between the β TD and β A domains. (e) Although the Arg of the RGD peptide is bound to E671 and S674, the Asp of the RGD peptide switches back and forth between K600 and K611. This competitive interaction on the Asp side of the RGD peptide shifts the β TD further toward the EGF3/4 domains and apart from the β A domain.

and K611, pulling the β TD away from the β A domain (Fig. 3 e). As a result of the RGD peptide replacing K350 on the β A domain, the β TD swung open, separating from the β A domain (see Fig. 3 a and Fig. 4 b). The open conformation of the β TD appeared to be stable insofar as the β TD remained open for another 4.5 ns until the end of the simulation, as shown in Fig. S2. Finally, we repeated the simulation one more time without any RGD peptides included. As expected, the β TD and β A domains remained attached in the absence of an RGD peptide.

We observed that the dissociation of the β TD and β A domains caused the β TD to snap back, which induced a slight rotation in the β -subunit transmembrane domain ($\sim 3^\circ$ over the course of our simulations) in a lever-like motion. This rotation increased the angle between the α - and β -subunit transmembrane domains. We conducted energy analyses to measure the electrostatic energy between the α - and β -subunit transmembrane domains for the case where there was no RGD peptide as well as for the case where the integrin activation was observed. Interestingly, the electrostatic energy of interaction appeared to decrease dramatically after the β TD and β A domains separated (see Fig. 4 a). A tiny rotation of the long, β -subunit transmembrane domain increased the distance between acidic and basic residues on the α - and β -subunit transmembrane domains that considerably weakened the IMC.

Integrin-talin binding

To study the effect of talin on integrin activation, we first needed to create two separate conditions: the experimental condition, integrin with talin bound, and the control, integrin alone. To create our experimental condition, we pro-

moted the binding of talin to integrin through a series of equilibration and steering simulations. After the 48 ns of equilibration and nudging, we observed binding between integrin and talin. Our results match that of the suggested mode of binding in the literature (2).

First, hydrophobic packing is evident between conserved residues and motifs, W739 and NPLY (744 to 747), on the integrin β 3, and residues on the F3 domain of talin. The identified residues on the F3 domain of talin that bind to W739 on the integrin β 3 subunit are the residues R358 and A360 on the S5 β -sheet on talin, which form a pocket for W739 (40). Additionally, the NPLY motif interacts with these S5 residues and additional residues, A389, Q390, A393, and I398, on the final H1 helix of the F3 domain (Fig. 5). Finally, after the nudges to tilt talin, as expected, F727 on the β 3 subunit embedded itself into the talin S1-S2 loop region strand, consisting partly of residues K318, M319, and K320 (33).

Effect of talin binding on integrin

Using the integrin-talin and integrin-alone models, we randomized the initial velocities in 12 repetitions, equilibrated for 5 ns, and pulled apart the IMC for 5 ns. The IMC of integrin changed its conformation upon binding talin. Three parameters were used to quantify the state of the IMC. The average distance between the carbon- α atoms of D723-R995 and E726-R995 shows that talin induces a bulge in the IMC even before the steered separation. The mean distances, as indicated by distance d in Fig. S3, for both the integrin-talin and integrin alone conditions were 9.8 Å and 13.5 Å, respectively, and this difference was significant using a permuted two-sample, one-tailed, *t*-test

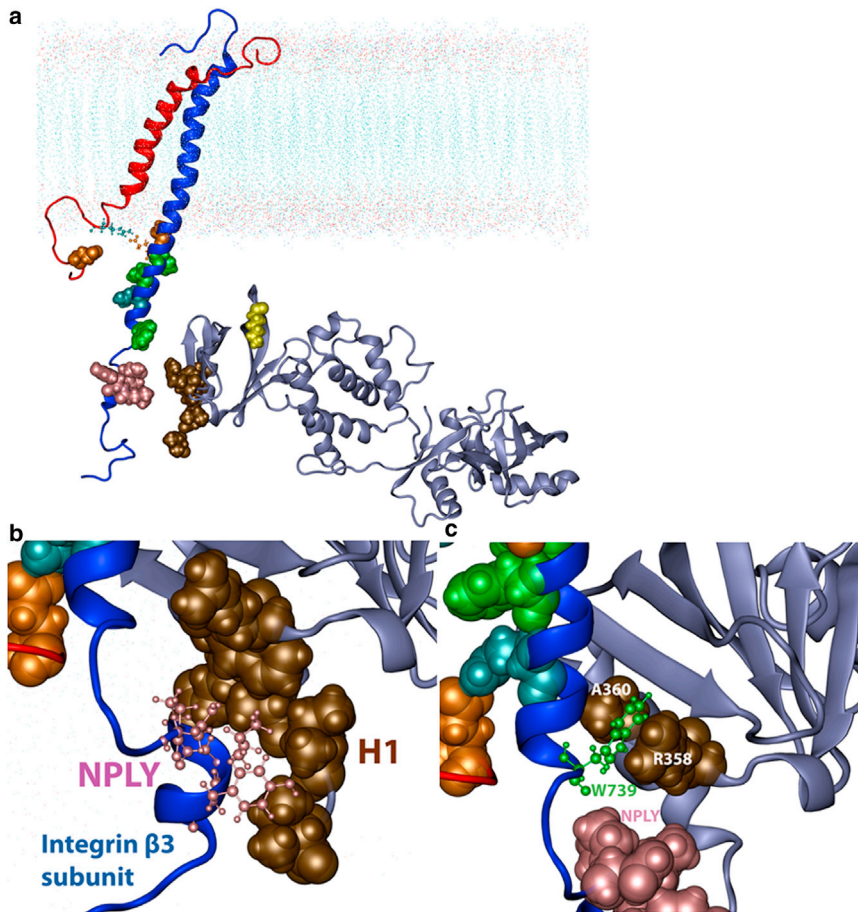


FIGURE 5 (a) Initial simulation position of the integrin α I**IIb** β 3 transmembrane-cytoplasmic domains (PDB ID: 2K9J) and talin-1 FERM domain (PDB ID: 3IVF). For the new-cartoon representations, in red is the α I**IIb** subunit of integrin, in blue is the β 3 subunit of integrin, and in silver is the talin-1 FERM domain. For van der Waals sphere representations, in orange are the acidic residues E1006 (on α I**IIb**) and D723 (on β 3) of integrin, in cyan are the basic residues and R734 (on β 3), in green are the residues F727, F730, and W739 on β 3, in pink is the NPLY motif, in brown are residues R358, A360, A389, Q390, A393, and I398 on the talin F3 domain, and in yellow is K320 of the S1-S2 loop on the talin-1 F3 domain. Note that the atoms shown with the CPK representation in cyan (R995, α I**IIb**) and orange (E726, β 3) are tightly bound to hold the IMC together. These highlighted residues play an important role as shown by our simulations. (b and c) Talin-1 F3 domain (F0–F2 not shown) binding with the NPLY motif and W739 on the integrin β 3 subunit. The left rendering (b) highlights NPLY motif binding to the H1 helix; whereas the right rendering (c) highlights W739 binding in the pocket formed by R358 and A360 in talin. The picture was taken 24 ns after the start of the simulation.

Effect of talin binding on full integrin structure

Using the full-length integrin structure, we assessed the effects of the F3 domain of talin binding to specific local regions on the integrin β 3 cytoplasmic tail. Focusing on this additional interaction, R734-E1006, we found an overall negative correlation between the center of mass distances of the integrin β 3 cytoplasmic tail to the talin F3 domain and distance between R734 and E1006. In other words, as the talin F3 domain approaches the integrin tail, the distance between R734 and E1006 enlarges, which also results in lower interaction energy. Upon closer analysis (see Table S2), a stronger correlation is observed when selecting the dependent variable as the center of mass of a subdomain of the cytoplasmic β 3 subunit, specifically the region from the NPLY motif onward (termed NPLY-T762), to measure the distance to the center of mass of the F3 domain of talin ($\rho = -0.82$, $p = 0.0038$). This suggests a greater significance in the membrane-distal binding of the β 3 integrin to the F3 domain of talin-1. Similarly, we also examined the potential conformational changes in the integrin extracellular domain followed by the F3 domain of talin binding to the integrin β 3 cytoplasmic tail. The degree of talin binding did not show any significant effects to alter integrin extracellular conformation (Table S3).

DISCUSSION

Although integrin has been a subject of intensive study over the past two decades, molecular details of its function have remained ambiguous (3,23,24). As shown in Fig. 1, interaction of PAR1 with thrombin triggers the integrin α I**IIb** β 3 activation pathway, which finally leads to thrombosis (1,4,41). Therefore, understanding how integrin α I**IIb** β 3 functions paves the road for deciphering pathways that regulate thrombosis (41,42). We have successfully used MD techniques to model mechanosensitive focal adhesion proteins (7,43–49). Here, we performed a series of MD simulations to observe how exposing integrin α I**IIb** β 3 to soluble RGD peptides as well as the talin head domain may affect the integrin structure. Integrin α I**IIb** β 3 is a highly studied member of the integrin family, which is present in platelets, enabling them to interact with soluble fibrinogen (a specialized ligand of integrin α I**IIb** β 3 that exists abundantly in the blood stream). It is widely known that soluble fibrinogen binds the head domain of integrin α I**IIb** β 3, initiating the blood clotting process by forming a network of fibrinogen ligands with platelets trapped inside it (42,50,51).

Approaching integrin α I**IIb** β 3 from the intracellular perspective, to our knowledge, we believe that we have uncovered new biomolecular, mechanistic details on the

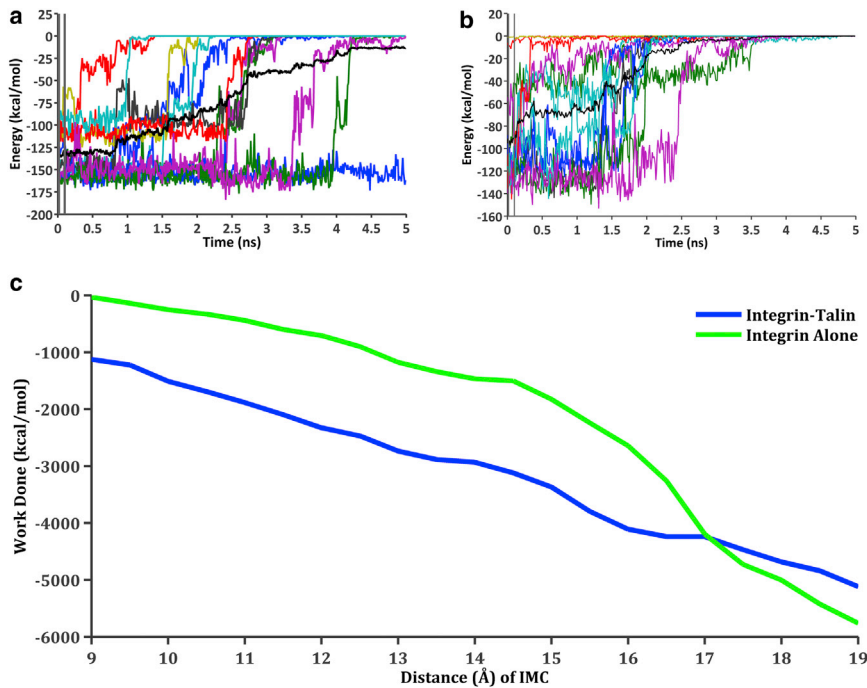


FIGURE 6 (*a* and *b*) Total nonbonding (van der Waals and electrostatic) energy between the IMC residues R995 on the α Ib, and D723 and E726 on the β 3 subunits for the steered molecular dynamics (SMD) simulations, where the α Ib R995 carbon- α atom was pulled ($k = 0.05$ kcal/mol/ \AA^2 , velocity = 10 $\text{\AA}/\text{ns}$) and the β 3 D723 and E726 carbon- α atoms were fixed. The colored lines represent the raw data from each of the 12 trials per condition, whereas the dark black line indicates the average of these trials. The two vertical dark gray bars within the first 100 ps indicate the averaged region to obtain the initial nonbonding energy before performing SMD. The graph on the left (*a*) is the integrin-alone condition, whereas the right (*b*) is with talin bound to integrin. (*c*) Work done by the SMD simulations to separate the IMC, as a function of the amount of distance between the carbon- α atoms.

inside-out activation process by talin. Although it is known that talin is required for inside-out activation of integrin, the specific mechanism of how integrin is activated by talin is uncertain (52). The current working model suggests that talin binding to the cytoplasmic tail of the β 3 subunit would occur first at the membrane-distal region, which then promotes a MP interaction to take place between talin and integrin β 3 subunit. This MP interaction is where the mechanism of activation arises (53). Our data suggest a similar mechanism, in that β 3 subunit F727 embedding in the talin S1-S2 loop may help the IMC salt bridge to loosen its grip because this allows the basic K320 residue to energetically compensate for the IMC salt bridge loss. Furthermore, in the timescale of our simulations, we did not observe significant conformational changes in the integrin extracellular domains though previous work suggested that breakage of the IMC salt bridge by talin is necessary but not sufficient to fully activate integrin (53).

Additionally, we observed a salt bridge interaction between the most membrane distal regions of the α Ib and β 3 integrin subunits with residues E1006 and R734, respectively. Interestingly, this interaction appeared in two of the four separate simulation conditions, forming in the integrin-talin bound simulations using only the cytoplasmic-transmembrane domains of integrin, and in the integrin-alone simulations using the full-length integrin α Ib β 3. We make two propositions, the first of which states that this interaction may be an artifact of using only the cytoplasmic-transmembrane domains of integrin. Second, the default presence of this interaction using full-length integrin suggests that talin plays an even more important role in integrin activation. This artifact in the cytoplasmic-

transmembrane simulations may cause the force and work required to separate the IMC under the integrin-talin conditions to be overestimated. Without this interaction, the integrin-talin conditions may be even more favorable toward IMC separation and integrin activation. More interestingly, it seems that the membrane-distal interactions of talin and integrin are important for more than solely providing an anchor for the MP interactions to weaken the IMC (53). Instead, we propose that the binding of talin to the membrane-distal region of the β 3 subunit cytoplasmic tail weakens this salt bridge E1006-R734 interaction, which is the first step in integrin inside-out activation.

Integrin is also activated via association with an extracellular ligand, a process called outside-in activation. It is reported that integrin α Ib β 3 has a high affinity for the RGD sequence of fibrinogen (3,11,54). Interactions between integrin α Ib β 3 and fibrinogen are reported to occur on the interface of the β -propeller domain of the α Ib and the β A domain of the β 3 subunit. In particular, RGD peptides are shown to associate with a region of the β 3 defined by D109 and E171 as well as another region limited to S211 and G222 (20,21). Nonetheless, a number of studies showed that the integrin α Ib β 3 head domain interacts solely with a C-terminal region of fibrinogen (i.e., γ C) rather than the RGD sequences on the fibrinogen α -subunit (15,18). To address this controversy making best use of the computational time, instead of modeling the entire fibrinogen molecule, we placed two RGD sequences at regions of the integrin α Ib β 3 head domain that had been reported to have high affinity for fibrinogen (3,15). An RGD peptide was positioned in the vicinity of the β TD- β A domain interface, another sensitive region that is suggested to contribute

to integrin activation, to explore its potential interactions especially ones that could regulate integrin function. The small size of RGD peptides conferred upon them high diffusivity and capability to sweep the space in the vicinity of the sensitive areas of integrin $\alpha\text{IIb}\beta_3$. We initiated our simulations with inactive integrin $\alpha\text{IIb}\beta_3$, wherein the βA domain of the integrin head domain is attached to the MP βTD . This forms a pocket-like configuration between the integrin head domain and MP region, which is geometrically appropriate for the long, coiled-coil molecule of fibrinogen to insert into. Because the RGD motif of fibrinogen is located on the surface of the γ -subunit of fibrinogen, it has high potency for detecting RGD-sensitive regions of integrin $\alpha\text{IIb}\beta_3$.

The association constant for the integrin-peptide interaction is

$$k_a = \frac{[IP]}{[I][P]}, \quad (1)$$

where [I], [P], and [IP] are concentrations of integrin, free RGD peptide, and integrin-RGD complex, respectively. The association constant is related to the free energy of association as follows:

$$k_a = e^{\frac{-\Delta G}{k_B T}}, \quad (2)$$

where ΔG , k_B , and T are the free energy of association per mol, Boltzmann constant, and temperature, respectively. Our simulations indicated that for the highly dynamic RGD binding sites in the βTD - βA pocket, 10 ns is a reasonable timescale for bonds to form and break down at least once (see Fig. S1). As the free energy per mol of a significant electrostatic bond in amino acids is typically taken as 5 kcal/mol (55,56), substituting that value for ΔG in Eq. 2 and solving at $T = 310$ K yields $k_a \sim 0.06 \text{ mol}^{-1}$. According to the ergodic hypothesis in statistical thermodynamics, for a stochastic system, any average of thermodynamic parameters over the entire volume of the system at any instant in time equals the average of the same parameter taken over a long time span at a single point in the system (57). Hence, as a first approximation, we can assume the free concentrations of integrin and peptide (denoted as [I] and [P] in Eq. 1) are proportional to the sum of time spans that the system experiences the unbound state. On the other hand, the concentration of the complex (denoted by [IP] in Eq. 1) is proportional to the accumulative time period that the system spends in the bound state. Therefore, the minimum association constant for significant bond formations ($k_a = 0.06 \text{ mol}^{-1}$) is corresponding to a binding time of at least 3 ns within a simulation scale of 10 ns. We defined bindings that remained associated for $> \sim 3$ ns as permanent bonds and bindings with life spans any shorter than 3 ns as temporary bonds.

Our simulations highlighted several binding sites for the RGD peptide on integrin $\alpha\text{IIb}\beta_3$, most of which were either

inside or proximal to the βA - βTD pocket. Binding sites of integrin $\alpha\text{IIb}\beta_3$ for RGD peptides in this region fell into three distinct categories, wherein permanent interactions always form at the Arg end of the RGD peptide. This could be attributed to the highly basic side chain of the Arg that facilitates formation of permanent salt bridges. The first category featured bonds formed between the Arg of the RGD peptide and integrin. Although this group included permanent bindings, these bindings did not contribute to detachment of the βA and βTD within our simulation time because they were not able to disturb the key interaction (i.e., K350 with S673 and S674). In the second type of interactions, the Arg of the RGD peptide formed a permanent bond with integrin $\alpha\text{IIb}\beta_3$, whereas the Asp of the RGD peptide formed a temporary bond, which was highly fluctuating and unstable. Finally, the third and most complex type of RGD peptide-integrin interactions were composed of a permanent interaction of the Arg of the RGD peptide with integrin $\alpha\text{IIb}\beta_3$ at one end and a competitive, temporary interaction of two other residues with the Asp of the RGD peptide at the other end. Within the timescale of our simulations (~ 13 ns), one out of two observed, type3 interactions fully detached the βA domain from the βTD , which according to both switchblade and dead-bolt models is equivalent to integrin activation.

After ~ 7.5 ns of equilibration and free diffusion of the RGD peptide in the vicinity of the βA - βTD pocket, as depicted in Fig. 3, the key βA - βTD domain interactions (i.e., K350 with S673 and S674) were disrupted as a result of the Arg of the RGD side chain taking over the OH-group on the side chain of S673. About 1 ns after the key interaction was disrupted, the βTD swung open and the conformational change continued as the Asp of the RGD peptide was engaged in two competing interactions with K600 on the EGF3-EGF4 domain linker region and K611 on the EGF4 domain of the β_3 subunit (see Fig. 3 e). These competing interactions shifted the RGD peptide more toward the EGF3 and EGF4 domains, which furthered the distance between the βA and βTD domains. It is worthwhile mentioning that because Ser residues do not have significant avidity for Lys, the two Ser residues together still do not maintain K346 on the βA domain in a permanent salt bridge (i.e., a bond distance of $\sim 4 \text{ \AA}$). Hence, this rather weak interaction combined with the strong basic identity of Arg side chains may explain how integrin $\alpha\text{IIb}\beta_3$ is activated by a soluble, RGD-containing ligand (e.g., fibrinogen).

It has been shown that fibrinogen binds an extensive interface between the βA and β -propeller domains of the integrin $\alpha\text{IIb}\beta_3$ head domain proximal to the metal ion-dependent sites (i.e., MIDAS and ADMIDAS), which leads to integrin activation (15,18,58). Aligned with previous studies, RGD1 and RGD2 interacted with the crevice region between the βA and β -propeller on the head domain (20,21). However, we did not observe any significant conformational changes induced in integrin as a result of RGD binding to the head

domain. This is aligned with a more recent study that showed functional associations of fibrinogen with integrin occur at the RGD-lacking γ C peptide of fibrinogen (18). Our study shed light on another important binding site for the RGD motif inside the β A- β TD pocket that activates integrin. Our simulations indicated that the pocket formed by the β TD and β A domains of integrin is home to several binding spots for the RGD peptide. Short-term interactions between these binding spots and the RGD peptide increase the residence time of the soluble RGD peptide near the pocket, which escalates odds of an interaction occurring between the RGD peptide and the key bonds between the β TD and β A domains (i.e., K350 with S673 and S674), which would lead to integrin activation via disrupting the key interactions.

Two major mechanisms are reported to unlock the integrin inhibitory interactions. Although the switchblade model proposes a drastic change, from bent to fully stretched conformation upon activation, the dead-bolt model suggests more local conformational changes in the molecule due to dissociation of the β TD and β A domains (13,23,34,42). The switchblade model suggests that the interaction of the integrin cytoplasmic domain with particular focal adhesion proteins leads to a 135° rotation of the integrin head piece relative to the tail piece. This rotation causes the β A- β -propeller interface to face away from the plasma membrane, thereby becoming available to interact with the ligand (13,19). The switchblade model is corroborated for different members of the integrin family by a number of previous studies. First, when recombinant integrin α 5 β 1 was artificially constrained with disulfide bonds in a bent conformation it did not associate with immobilized ligands (59). For integrin α v β 3, a double mutation that held the head domain against the leg domains via a Cys bridge hindered activation (19). In addition, a significant increase in the protein Stokes radius has been recorded for cases where integrins were exposed to RGDFV peptides or Mn^{2+} (i.e., integrin activators) versus the case where they are in a Ca^{2+} buffer, which is an activation inhibitor (19). However, integrin α IIB β 3 activation paradigm appears to remain controversial, as detailed monoclonal antibody epitope maps for inactive and active integrin α IIB β 3 in vivo demonstrated similar compact forms consistent with the bent conformation (23,60). Furthermore, binding of different ligand mimics to integrin α IIB β 3 in intact platelets has shown distinct conformational changes in the receptor (61).

Another mechanistic explanation for integrin activation was given by the dead-bolt model. The dead-bolt model assumes that the elongated CD loop of the β TD locks the β A domain via forming bonds with it in the inactive state of the native structure, although the atomistic details of these interactions are not currently clear (23). It is important to note that the dead-bolt model does not necessarily exclude a subsequent ligand-induced switchblade-like swing-out. Interestingly enough, our simulations demonstrated

that the disruption in the interactions between the β TD and β A domains could be a trigger for integrin activation, recognizing electrostatic interactions of K350 on the β A with S673 and S674 on the β TD as a potential regulatory lock.

We observed that the dissociation of the β TD and β A domains was succeeded by the β TD snap-back, which caused the β -subunit transmembrane domain to slightly rotate ($\sim 3^\circ$) in a lever-like motion. This increase in the angle between the α - and β -subunit transmembrane domains is also reported by previous electron microscopy and biochemical data as a potential activating mechanism for integrin α IIB β 3 (21,52,54,62). However, another model is proposed for a number of other integrin family members (e.g., α 5 β 1) that suggests the hinge region for the scissors-like motion of integrin, upon activation, is located on the interface of the α - and β -subunit head domains (59). We measured the electrostatic energy between the α - and β -subunit transmembrane domains for the simulation with no RGD peptides and compared it to the one in which the integrin activation had been observed. Intriguingly, the electrostatic energy of interaction appeared to decrease dramatically after the β TD and β A domains separated. A slight rotation of the long, transmembrane domain of the β -subunit could considerably increase the distance between charged residues on the α - and β -subunit transmembrane domains, which would weaken the IMC. Therefore, we believe RGD interaction with the β TD could be a potential trigger for the complete separation of the transmembrane domains. Although this set of data proposes a key interaction that might function as a regulating dead-bolt, the loosening of the transmembrane domain clasps as a result of the β TD- β A domain separation suggests subsequent, more drastic conformational changes, and explains how ligand-binding could lead to the transmembrane domain separation as proposed by the switchblade model. On the other hand, within the timescale of our simulations, we did not observe any significant conformational changes in the ectodomain nor did we see any decreases in the β A- β TD interaction energy upon talin binding with the β 3 cytoplasmic tail. This suggests that outside-in activation via RGD association with the key residues embedded in the β A- β TD pocket occurs more rapidly than inside-out activation followed by talin binding. It is also noteworthy that distinct activation mechanisms and conformational changes might be at work for different combinations of integrin-ligand interactions.

CONCLUSION

The activated state of integrin is commonly characterized by three major dissociations: breaking of the IMC and OMC, and unbinding of the β A and β TD (1,4,23,63). This study attempted to explain the integrin α IIB β 3 function, via exploring how these key interaction groups are disrupted in specific pathways. Our observations of the

transmembrane-cytoplasmic domains of integrin $\alpha\text{IIb}\beta_3$ showed that the IMC is loosened with the presence of talin, most likely through MP interactions that result from the energetic compensation of the weakened IMC by K320 on the S1-S2 loop of talin. We also found, using the full-length crystal structure we built, that talin has a larger role in integrin activation by disrupting an additional stable clasp (R734-E1006) through the initial membrane-distal interactions that anchors talin to integrin (2). Furthermore, we used the full-length crystal structure of integrin $\alpha\text{IIb}\beta_3$ to explore binding sites of soluble RGD ligands and their ability to activate integrin $\alpha\text{IIb}\beta_3$ or maintain it in the activated state. We found three major groups of bindings with two specific binding sites corresponding to each group. According to our simulations, the major group of interactions that maintains integrin $\alpha\text{IIb}\beta_3$ in the inactive, bent state occurs between K350 on the βA domain, and S673 and S674 on the βTD . Interestingly, we observed the full dissociation of the βTD and βA domains when this interaction group was disrupted and eventually removed as a result of a competition between the Arg of the RGD peptide with S674. Therefore, we proposed this molecular scenario as a potential trigger mechanism for outside-in activation of integrin $\alpha\text{IIb}\beta_3$ by soluble RGD ligand.

SUPPORTING MATERIAL

Three tables, three figures, and supporting analysis are available at [http://www.biophysj.org/biophysj/supplemental/S0006-3495\(13\)00918-1](http://www.biophysj.org/biophysj/supplemental/S0006-3495(13)00918-1).

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