A stapled chromogranin A-derived peptide is a potent dual ligand for integrins αβ6 and αβ8

Francesca Nardelli, Michela Ghitti, Giacom Quilici, Alessandro Gori, Qingqiong Luo, Andrea Berardi, Angelina Sacchi, Matteo Monieri, Greta Bergamaschi, Wolfgang Bermel, Fuxiang Chen, Angelo Corti, Flavio Curnis and Giovanna Musco

Combining 2D STD-NMR, computation, biochemical assays and click-chemistry, we have identified a chromogranin-A derived compound (5) that has high affinity and bi-selectivity for αβ6 and αβ8 integrins and is stable in microsomal preparations. 5 is suitable for nanoparticle functionalization and delivery to cancer cells, holding promise for diagnostic and/or therapeutic applications.

Integrins αβ6 and αβ8 are epithelial-specific cell-adhesion receptors, playing a fundamental role in pro-fibrotic cytokine transforming growth factor beta (TGFβ) activation in fibrosis.1 They are also highly expressed during tissue remodelling, wound healing, and cancer cell migration, invasion and growth, whereby over-expression correlates with poor patient prognosis.2,3 Hence, targeting of cells highly expressing one or both integrins through high affinity ligands with dual specificity and reduced off-targeting effects may represent a valid, yet poorly explored pharmacological strategy against cancer and/or fibrosis.

Over-expression correlates with poor patient prognosis.2,3 Hence, targeting of cells highly expressing one or both integrins through high affinity ligands with dual specificity and reduced off-targeting effects may represent a valid, yet poorly explored pharmacological strategy against cancer and/or fibrosis. 

A stapled chromogranin A-derived peptide is a potent dual ligand for integrins αβ6 and αβ8.21 A CgA-derived peptide (residues 39–63) (1) also recognizes αβ6 with nanomolar affinity and high selectivity (Kd: 15.5 ± 3.2 nM) (Table 1), herewith regulating αβ6-dependent keratinocyte adhesion, proliferation, and migration.21 Notably, 1 harbours a degenerate RGDLXXL/I motif, with a glutamate replacing a leucine after the RGD sequence (position D + 1, RGDEXXL) (Fig. S1, ESI†). Prompted by this peculiarity, we investigated the structural determinants of 1/αβ6 interaction by heteronuclear 2D-NMR STD methods and docking calculations. Intriguingly, while 1 is highly specific for αβ6, reconstitution of the canonical RGDLXXL motif, combined with a click-chemistry stapling strategy results in a novel potent ligand suitable for the dual targeting of αβ6/αβ8 for diagnostic and therapeutic purposes.

We studied the conformation of recombinant peptide 1 in physiological conditions by homonuclear and heteronuclear multidimensional NMR. Peptide 1 was expressed in E. coli as an insoluble fusion partner of ketosteroid isomerase, and subsequently cleaved with CNBr and purified by HPLC.22 Recombinant 13C/15N 1 displays the typical NOE pattern of the α-helical conformation between residue E46 to K59, with both termini being unstructured (Fig. 1a, c and Tables S1, S2, ESI†). Accordingly, the helical segment and both termini display relatively high (<0.5) and very low (<0.3) heteronuclear NOE values, respectively (Fig. 1d). The RGD motif adjacent to the α-helix is relatively flexible, and thus well suited to adapt inside the integrin-binding pocket (Fig. 1a). The first three turns of the post-RGD helix are amphiphatic, with I48, L49, I51, and group selective information on the interaction, we performed in the presence of the extracellular region of recombinant human αβ6 (4 μM) 1D-1H saturation transfer difference (STD) spectroscopy (Fig. S2a, ESI†) and heteronuclear two-dimensional STD experiments,23 exploiting isotopically labelled (13C/15N) recombinant peptide 1 (0.5 mM) (Fig. 2a and Fig. S2b, ESI†). The 2D-STD 1H-15N-HSQC resolved peak ambiguities in the 1D-1H STD spectrum and
provided residue-specific STD effect values. Hydrophobic amino acids (I48, L49, I51, and L52) of the post-RGD helix displayed the strongest STD% values (75%), suggesting their important contribution to receptor binding (Fig. 2b). Intense STD effects of the methyl groups of branched amino acids in 2D-STD-1H–13C-HSQC corroborated their involvement in the interaction, although signal overlap hampered their quantification for epitope mapping (Fig. S2b, ESI†). To exclude false positive effects, we spiked recombinant peptide 1 with bovine serum albumin as a negative control: no interaction occurred, and we did not observe any STD signal (Fig. S3a and b, ESI†). 2D-STD-1H–15N-HSQC performed with αvβ6 pre-incubated with 20 mM of EDTA resulted in depletion of the STD effects, thus confirming the presence of the electrostatic clamp between the receptor metal ion and the aspartate side chain of the RGD motif (Fig. S3c, ESI†). This result is in line with competitive binding assays using a peptide with RGE instead of RGD (2), yielding a $K_i > 50 \mu M$ (Table 1).

Next, we incorporated the 2D-STD experimental information in data driven docking calculations (HADDOCK2.2)15 to determine the binding mode of 1 with the extracellular head of αvβ6 (PDB: 5FFO).16 The model highlights receptor–ligand interactions highly reminiscent of those observed for the proTGFRβ1/αvβ6 complex (Fig. 2c and Fig. S4a, ESI†).18 On one hand, the guanidinium of R43 forms electrostatic interactions with Asp129 and Asp150v; on the other hand, the carboxylate of D45 coordinates the metal ion-dependent adhesion site (MIDAS) and interacts with the amide of Ser1276v and Asn2186v. I48, L49, I51, and L52, located respectively on the second and the third turn of the post-RGD amphipathic α-helix, make extensive hydrophobic interactions with β6 residues of the specificity determining loops (SDLs), including Ala1266v, Asp1296v (SDL1), Ile1836v, Tyr1856v (SDL2), and Ala2176v (SDL3) (Fig. 2c), thus explaining the selectivity of 1 towards αvβ6 with respect to the other αv integrins (Table 1). Since in our model residue E46 points towards the receptor interior, we reasoned that the preformed α-helix of 1 might entropically compensate the unfavourable electrostatic contribution of the negative charge within the hydrophobic binding pocket. Thus, we synthesized a shorter peptide containing the hydrophobic residues important for the interaction, without ten C-terminal residues supposed to be crucial for the helical propensity (3). Indeed, 3 showed a drastic reduction both in α-helical content (Fig. S5, ESI†) and binding to αvβ6 ($K_i: 277 \pm 77 \text{ nM}$) (Table 1), supporting the notion that the stability of the preformed four-turn amphipathic helix adjacent to the RGD motif is fundamental for effective αvβ6 recognition.18,26 We next predicted that restoring the canonical LXXL motif might increase the affinity of 1 for αvβ6. Indeed, the replacement in position $D + 1$ of E46 with a leucine (4) lowered the $K_i$ by one order of magnitude ($K_i: 1.6 \pm 0.3 \text{ nM}$) (Table 1).

Structurally, αvβ6 and αvβ8 share a similar wide lipophilic SDL pocket, suitable for hydrophobic interactions with the

---

**Table 1** Inhibition constants ($K_i$, nM) and the associated standard error of the mean of compounds 1–6 for integrins as determined by the competitive binding assay (ESI)

| Code | Peptide‡ | $K_i$ | n | $K_i$ | n | $K_i$ | n | $K_i$ | n | $K_i$ | n |
|------|----------|-------|---|-------|---|-------|---|-------|---|-------|---|
| 1    | FETLRGERILSRHQLLKELQD  | 15.5 ± 3.2  | 6  | 7663 ± 1704  | 6  | 9206 ± 1810  | 5  | 3600 ± 525  | 4  | 2192 ± 690  | 4  |
| 2    | FETLRGERILSRHQLLKELQD‡  | > 50 000  | 1  | > 50 000  | 1  | > 50 000  | 1  | > 50 000  | 1  | > 50 000  | 1  |
| 3    | FETLRGERILSRHQLLKELQD  | 277 ± 74  | 4  | 31 174  | 1  | 10 110  | 1  | 2039  | 1  | 1250  | 3  |
| 4    | FETLRGERILSRHQLLKELQD  | 1.6 ± 0.3  | 3  | 8.5 ± 3.7  | 2  | 924 ± 198  | 3  | 2405 ± 592  | 4  | 1928 ± 226  | 3  |
| 5    | FETLRGERILSRHQLLKELQD  | 0.6 ± 0.1  | 6  | 6.2 ± 1.2  | 1h | 1310 ± 389  | 3  | 2741 ± 615  | 3  | 2453 ± 426  | 3  |
| 6    | NAVPNLRLDGVLQAQKVART  | 0.9 ± 0.2  | 8  | 69 ± 12  | 2  | 2317 ± 10  | 5  | 15 449 ± 218  | 5  | 26 197 ± 7387  | 3  |

‡ Mutated residues and triazole-stapled residues (X$_i$ and X$_{2i}$, as defined in Fig. S6a, ESI). $n$, number of independent experiments (each performed with 6 different concentrations of competitor in technical duplicates). $K_i$ of 2 as determined in ref. 21. $P$ value versus 1: $p < 0.05$; two tailed test. $P$ value versus 1: $p < 0.01$, two tailed t test. $P$ value versus 1: $p < 0.05$; two tailed t test. $P$ value versus 4: $p < 0.05$; two tailed t test. $P$ value versus 4: $p < 0.1$; two tailed t test.
amphiphilic helix of 4. Of note, minor changes in the shape and in the sequence of the SDL2 of K170 and T171 in β6 and S159 and I160 in β8, respectively (Fig. S4c, ESI†), might explain why the presence of E46 in the ligand is tolerated by β6 and not by β8 (Table 1). Prompted by these results, we hypothesized that chemical stabilization of the α-helix via stapling, i.e. “side-chain-to-side-chain” cyclization,27 might further improve the binding properties of 4. Based on a 5/αβ6 model (Fig. 2d) we constrained this peptide via a triazole-bridged macrocyclic scaffold between residues in position 54 (propargylglycine) and 58 (azidolysine) through copper-catalyzed azide–alkyne cycloaddition (5) (Fig. S6a and b, ESI†).27,28

Indeed, the structural constraint boosted the α-helical content of 5, compared to 4, (Fig. S6c, ESI†), resulting in a significant 2 to 3-fold increase in αβ6 binding (K_i: 0.6 ± 0.1 nM), comparable to the reference compound foot and mouth disease virus-derived peptide A20FMDV2 (6, K_i: 0.9 ± 0.2 nM) (Table 1).11,18 Stapling maintained nM binding to αβ8 (K_i: 3.2 ± 1.2 nM), thus generating, to the best of our knowledge, the strongest bi-selective ligand for αβ6/αβ8 described so far.6,29 Importantly, peptides 1, 4, 5 and 6 were able to recognize αβ6 in its physiological context, as they bound αβ6 expressed on the cell-surface of human bladder 5637 cells and human keratinocytes (HaCat) with a relative binding potency similar to that observed with the purified recombinant αβ6 (Fig. S7, ESI†). 5 was the most effective with an activity comparable to the reference compound 6 (Fig. 3a and Fig. S8, ESI†).30 Notably, both 4 and 5 were not cytotoxic in vitro. To assess whether 5 was suitable for nanoparticle functionalization and delivery to cancer cells, we coupled it to fluorescent quantum dot nanoparticles via an N-terminal cysteine (5-Qdot) and evaluated its binding to 5637 cells. Flow cytometry and fluorescence microscopy showed that 5-Qdot, but not a control nanoconjugate without the targeting ligand (*Qdot), bound the cells, indicating that 5 maintains its receptor-tailored properties also after conjugation (Fig. 3b and c). Finally, ELISA stability assays of 4 and 5 conjugated to hors eradish peroxidase (4-HRP, 5-HRP) in human serum showed that >50% of 4-HRP and 5-HRP were still present after 24 hours of incubation at 37 °C, supporting their
proteolytic stability in biological fluids (Fig. S10, ESIV1). Importantly, stability assays with mouse liver microsomes showed that 5 was more stable than 4 (t1/2 = 4.3 h and t1/2 = 1.3 h, respectively, Fig. S11, ESIV1).

In conclusion, NMR experiments allied to computational and biochemical methods elucidated the molecular details at the basis of αvβ6 recognition by CgA-derived peptides, giving first hints on the interaction between αvβ6 and CgA.19 The entropic gain, derived from the preformed four-turns α-helix adjacent to the RGD motif, combined to the hydrophobic interactions between residues in position D + 3, D + 4, and D + 7 and the β subunit, largely compensate the unfavourable electrostatic repulsion of E46 in position D + 1. Thus, the natural αvβ6 recognition motif RGDLXXL is less restrictive than previously supposed and can be extended to RGDEXXL, provided that the helix adjacent to RGD is preformed and presents an extensive hydrophobic surface for αvβ6 interaction. Importantly, the complex model inspired the design of novel peptides, including a stapled one with high stability, sub-nanomolar affinity and bi-selectivity for αvβ6 recognition motif RGDLXXL, provided that the helix adjacent to RGD is preformed and presents an extensive hydrophobic surface for αvβ6 interaction. Importantly, the complex model inspired the design of novel peptides, including a stapled one with high stability, sub-nanomolar affinity and bi-selectivity for αvβ6/αvβ8 integrins. These molecules, derived from a human protein, may represent useful and safer tools for the ligand-directed targeted delivery of diagnostic and therapeutic compounds and nanoparticles to epithelial cancers with high expression of αvβ6 and/or αvβ8, such as oral and skin squamous cell carcinoma.21 Furthermore, in light of the roles of both αvβ6 and αvβ8 in TGFβ maturation and fibrosis, the dual targeting ability of these compounds could be also conveniently used to develop anti-fibrotic drugs and tracers devices, thus adding to the still limited number of small molecules able to specifically recognize these integrins.

The authors thank M. Alfano for helpful discussion. This work was supported by EU Horizon 2020 [801126, EDIT] and AIRC (IG-19220, IG-21440, 22737). F. N. conducted this study within her PhD course at S Raffaele University, Milan.

Conflicts of interest
There are no conflicts to declare.

Notes and references
1 K. P. Conroy, L. J. Kitto and N. C. Henderson, Cell Tissue Res., 2016, 365, 511–519.
2 L. Kivistö, J. Bi, L. Häkkinnen and H. Larjava, Int. J. Biochem. Cell Biol., 2018, 99, 186–196.
3 M. Nieberler, U. Reuning, F. Reichart, J. Notni, H. Wester, M. Schweiger, M. Weinmüller, A. Räder, K. Steiger and H. Kessler, Cancers, 2017, 9, 116.
4 I. D. Campbell and M. J. Humphries, Cold Spring Harb. Perspect. Biol., 2011, 3, 1–14.
5 A. Ozawa, Y. Sato, T. Imabayashi, T. Uemura, J. Takagi and K. Sekiguchi, J. Biol. Chem., 2016, 291, 11551–11565.
6 F. Reichart, O. V. Maltsev, T. G. Kapp, A. F. B. Räder, M. Weinmüller, U. K. Marelli, J. Notni, A. Wurzer, R. Beck, H. J. Wester, K. Steiger, S. Di Maro, F. S. Di Leva, L. Marinelli, M. Nieberler, U. Reuning, M. Schweiger and H. Kessler, J. Med. Chem., 2019, 62, 2024–2037.
7 A. Cormier, M. G. Campbell, S. Ito, S. Wu, J. Lou, J. Marks, J. L. Baron, S. L. Nishimura and Y. Cheng, Nat. Struct. Mol. Biol., 2018, 25, 698–704.
8 O. V. Maltsev, U. K. Marelli, T. G. Kapp, F. S. Di Leva, S. Di Maro, M. Nieberler, U. Reuning, M. Schweiger, E. Novellino, L. Marinelli and H. Kessler, Angew. Chem., Int. Ed., 2016, 55, 1535–1539.
9 F. S. Di Leva, S. Tomassi, S. DiMaro, F. Reichart, J. Notni, A. Dangi, U. K. Marelli, D. Brancaccio, F. Merlino, H. J. Wester, E. Novellino, H. Kessler and L. Marinelli, Angew. Chem. Int. Ed., 2018, 44, 14645–14649.
10 M. Civera, D. Arosio, F. Bonato, L. Manzoni, L. Pignataro, S. Zanella, C. Gennari, U. Piarrulli and L. Belvisi, Cancers, 2017, 9, 128.
11 S. H. Hausner, D. DiCara, J. Marik, F. J. Marshall and J. L. Sutcliffe, Cancer Res., 2007, 67, 7833–7840.
12 R. H. Kimura, R. Teed, B. J. Hackel, M. A. Pysz, C. Z. Chuang, A. Sathirachinda, J. K. Willmann and S. S. Gambhir, Clin. Cancer Res., 2012, 18, 839–849.
13 A. Altman, M. Sauter, S. Roesch, W. Mier, R. Warta, J. Debus, G. Dyekhoff, C. Herold-Mende and U. Haberkorn, Clin. Cancer Res., 2017, 23, 1470–1480.
14 S. Krafft, B. Diefenbach, R. Mehta, A. Jonczyk, G. A. Luckenbach and S. L. Goodman, J. Biol. Chem., 1999, 274, 1979–1985.
15 X. Dong, N. E. Hudson, C. Lu and T. A. Springer, Nat. Struct. Mol. Biol., 2014, 21, 1091–1096.
16 X. Dong, B. Zhao, R. E. Iacob, J. Zhu, A. C. Koksal, C. Lu, J. R. Engen and T. A. Springer, Nature, 2017, 542, 55–59.
17 A. Kotecha, Q. Wang, X. Dong, S. L. Ilca, M. Ondiviela, R. Zihe, J. Seago, B. Charleston, E. F. Fry, N. G. A. Abrescia, T. A. Springer, J. T. Huiskonen and D. I. Stuart, Nat. Commun., 2017, 8, 15408–15416.
18 D. DiCaro, C. Rapisarda, J. L. Sutcliffe, S. M. Violette, P. H. Weinreb, I. R. Hart, M. J. Howard and J. F. Marshall, J. Biol. Chem., 2007, 282, 9657–9665.
19 A. Corti, F. Marcucci and T. Bachetti, Pflugers Arch. Eur. J. Physiol., 2018, 470, 199–210.
20 K. B. Helle, M. H. Metz-Boutigue, M. C. Cerra and T. Angelone, Pflugers Arch. Eur. J. Physiol., 2018, 470, 143–154.
21 F. Curnis, A. M. Gasparri, R. Longhi, B. Colombo, S. D’Alessio, F. Pastorino, M. Ponzoni and A. Corti, Cell. Mol. Life Sci., 2012, 69, 2791–2803.
22 J. L. Wagstaff, M. J. Howard and R. A. Williamson, Mol. BioSyst., 2010, 6, 2380–2385.
23 K. Lugardon, S. Chasserot-Golaz, A.-E. Kieffer, R. Maget-Dana, G. Nullans, B. Kieffer, D. Aunis and M.-H. Metz-Boutigue, J. Biol. Chem., 2001, 276, 35875–35882.
24 J. L. Wagstaff, S. Vallath, J. F. Marshall, R. A. Williamson and M. J. Howard, Chem. Commun., 2010, 46, 7533.
25 C. Domínguez, R. Boelens and A. M. J. J. Bonviv, J. Am. Chem. Soc., 2003, 125, 1731–1737.
26 Y. K. S. Man, D. DiCara, N. Chan, S. Vessillier, S. J. Mathier, M. L. Rowe, M. J. Howard, J. F. Marshall and A. Nissim, PLoS One, 2013, 8, e70452.
27 Y. S. Tan, D. P. Lane and C. S. Verma, Drug Discov. Today, 2016, 21, 1642–1653.
28 A. Gori, C. I. A. Wang, P. J. Harvey, K. J. Rosengren, R. F. Bhola, M. L. Gelmi, R. Longhi, M. J. Christie, R. J. Lewis, P. F. Alewood and A. Brust, Angew. Chem., Int. Ed., 2015, 54, 1361–1364.
29 T. G. Kapp, F. Rechenmacher, S. Neubauer, O. V. Maltsev, E. A. Cavalcanti-Adam, R. Zarka, U. Reuning, J. Notni, H. J. Wester, C. Mas-Moruno, J. Spatz, B. Geiger and H. Kessler, Sci. Rep., 2017, 7, 1–12.
30 X. Huang, J. Wu, S. Pong and D. Sheppard, J. Cell Sci., 1998, 111, 2189–2195.
31 H. Ahmedah, L. Patterson, S. Shnyder and H. Sheldrake, Cancers, 2017, 9, 56.