

Early Endosomal Escape of a Cyclic Cell-Penetrating Peptide Allows Effective Cytosolic Cargo Delivery

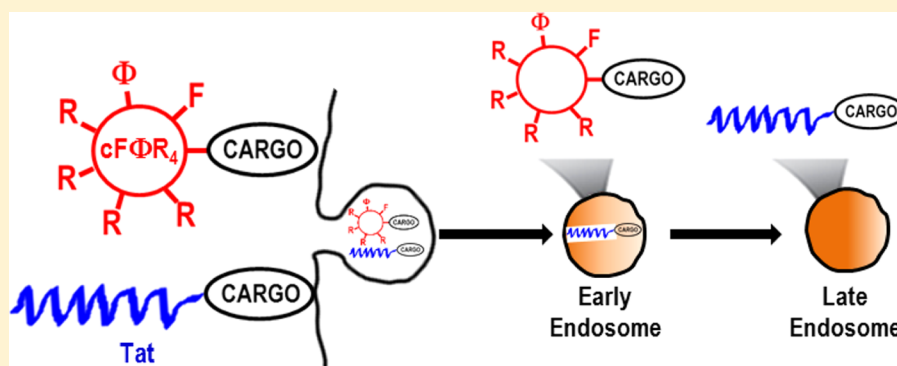
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S Supporting Information



ABSTRACT: Cyclic heptapeptide cyclo(FΦRRRRRQ) (cFΦR₄, where Φ is L-2-naphthylalanine) was recently found to be efficiently internalized by mammalian cells. In this study, its mechanism of internalization was investigated by perturbing various endocytic events through the introduction of pharmacologic agents and genetic mutations. The results show that cFΦR₄ binds directly to membrane phospholipids, is internalized into human cancer cells through endocytosis, and escapes from early endosomes into the cytoplasm. Its cargo capacity was examined with a wide variety of molecules, including small-molecule dyes, linear and cyclic peptides of various charged states, and proteins. Depending on the nature of the cargos, they may be delivered by endocyclic (insertion of cargo into the cFΦR₄ ring), exocyclic (attachment of cargo to the Gln side chain), or bicyclic approaches (fusion of cFΦR₄ and cyclic cargo rings). The overall delivery efficiency (i.e., delivery of cargo into the cytoplasm and nucleus) of cFΦR₄ was 4–12-fold higher than those of nonarginine, HIV Tat-derived peptide, or penetratin. The higher delivery efficiency, coupled with superior serum stability, minimal toxicity, and synthetic accessibility, renders cFΦR₄ a useful transporter for intracellular cargo delivery and a suitable system for investigating the mechanism of endosomal escape.

The plasma membrane presents a major challenge in drug discovery, especially for biologics such as peptides, proteins, and nucleic acids. One potential strategy for subverting the membrane barrier and delivering the biologics into cells is to attach them to “cell-penetrating peptides” (CPPs). Since the initial observation that HIV *trans*-activator of transcription, Tat, internalizes into mammalian cells and activates viral replication in the late 1980s,^{1,2} a large number of CPPs consisting of 6–20 residues have been reported.^{3–8} CPPs have been used to deliver small-molecule drugs,^{9,10} DNA,^{11,12} RNA,^{13–16} proteins,^{17–19} and nanoparticles^{20–22} into mammalian cells and tissues through either covalent attachment or electrostatic association. Many CPPs display minimal toxicity and immunogenicity at physiologically relevant concentrations,^{23,24} and the incorporation of specific unnatural

amino acids²⁵ and other chemical moieties^{26,27} has been found to increase the stability and extent of cytosolic delivery.

Despite three decades of investigation, the fundamental basis for CPP activity remains elusive. Two distinct and non-mutually exclusive mechanisms have been proposed for the CPPs whose primary sequences are characterized by multiple arginine residues. In the first mechanism (direct membrane translocation), the arginine guanidinium groups interact with phospholipids of the plasma membrane to generate neutral ion pairs that passively diffuse across the membrane^{28,29} or promote the formation of transient pores that permit the CPPs to traverse the lipid bilayer.^{30,31} In the second

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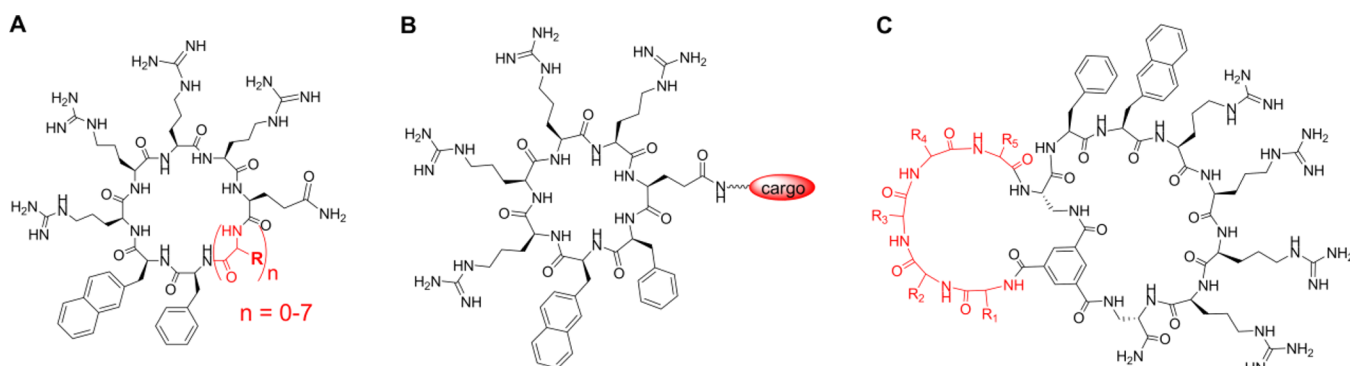


Figure 1. Structures showing cargo attachment during endocyclic (A), exocyclic (B), and bicyclic (C) delivery of cargos (colored red) by cΦR₄.

mechanism, CPPs associate with cell surface glycoproteins and membrane phospholipids, internalize into cells through endocytosis,^{32–36} and subsequently exit from endosomes into the cytoplasm. Taken together, a majority of data show that at low CPP concentrations, cellular uptake occurs mostly through endocytosis, whereas direct membrane translocation becomes prevalent at concentrations above 10 μM.³⁷ However, the mechanism(s) of entry and the efficiency of uptake may vary with CPP identity, cargo, cell type, and other factors.^{38,39}

CPPs that enter cells via endocytosis must exit from endocytic vesicles to reach the cytosol. Unfortunately, the endosomal membrane has proven to be a significant barrier toward cytoplasmic delivery by these CPPs; often a negligible fraction of the peptides escapes into the cell interior.^{40–42} For example, even in the presence of the fusogenic hemagglutinin peptide HA2, which has been demonstrated to enhance endosomal cargo release, >99% of a Tat–Cre fusion protein remains entrapped in macropinosomes 24 h after initial uptake.³⁵ Recently, two new types of CPPs with improved endosomal escape efficiencies have been discovered. Appelbaum et al. showed that folded miniature proteins containing a discrete pentaarginine motif were able to effectively overcome endosomal entrapment and reach the cytosol of mammalian cells.⁴² This motif consists of five arginines across three turns of an α -helix, and proteins containing this motif were released from early (Rab5⁺) endosomes into the cell interior. We and others found that cyclization of certain arginine-rich CPPs enhances their cellular uptake.^{43–46} Small amphipathic cyclic peptides such as cyclo(F Φ RRRRRQ) (cΦR₄, where Φ is L-2-naphthylalanine) are internalized by mammalian cells in an energy-dependent manner and enter the cytoplasm and nucleus with efficiencies 2–5-fold higher than that of nonarginine (R₀).⁴³ Moreover, membrane impermeable cargos such as phosphopeptides can be inserted into the cΦR₄ ring, resulting in their delivery into the cytoplasm of target cells. However, insertion of a cargo into the cyclic peptide ring, which we term the “endocyclic” delivery method (Figure 1A), is limited to relatively short peptides (no more than seven amino acids), as large rings, for yet unknown reasons, display poor internalization efficiency.⁴³

To gain insight into the cΦR₄ mechanism of action and potentially design cyclic CPPs of still higher efficiency, in this study we investigated the internalization mechanism of cΦR₄ through the use of artificial membranes and pharmacologic agents as well as genetic mutations that perturb various endocytic events. Our data show that cΦR₄ binds directly to the plasma membrane phospholipids and enters cells through endocytosis. Like the miniature proteins displaying the

pentaarginine motif,⁴² cΦR₄ escapes from the early endosomes into the cytosol. We also examined the ability of cΦR₄ to deliver a wide range of cargo molecules, including linear peptides of varying charges, cyclic peptides, and large proteins, into the cytoplasm of mammalian cells by exocyclic [attachment of cargo to the Gln side chain (Figure 1B)] or bicyclic [fusion of the cΦR₄ and cyclic cargo rings (Figure 1C)] delivery methods. We found that cΦR₄ is remarkably tolerant to the size and nature of cargos and efficiently transported all of the cargos tested into the cytoplasm and nucleus of mammalian cells. In addition, cΦR₄ exhibits superior stability against proteolysis over linear CPPs but minimal cytotoxicity. cΦR₄ therefore provides a practically useful transporter for cytosolic cargo delivery as well as a system for investigating the mechanism of early endosomal cargo release.

MATERIALS AND METHODS

Materials. Reagents for peptide synthesis were purchased from Advanced ChemTech (Louisville, KY), NovaBiochem (La Jolla, CA), or Anaspec (San Jose, CA). 2,2'-Dipyridyl disulfide, Lissamine rhodamine B sulfonyl chloride, fluorescein isothiocyanate (FITC), dexamethasone (Dex), coenzyme A trilithium salt, FITC-labeled dextran (dextran^{FITC}), and human serum were purchased from Sigma-Aldrich (St. Louis, MO). Cell culture media, fetal bovine serum (FBS), penicillin/streptomycin, 0.25% trypsin-ethylenediaminetetraacetic acid, Hoechst 33342, Alexa488-labeled dextran (dextran^{Alexa488}), Dulbecco's phosphate-buffered saline (DPBS) (2.67 mM potassium chloride, 1.47 mM potassium phosphate monobasic, 137 mM sodium chloride, and 8.06 mM sodium phosphate dibasic), and Lipofectamine 2000 were purchased from Invitrogen (Carlsbad, CA). PD-10 desalting columns were purchased from GE-Healthcare (Piscataway, NJ). Nuclear staining dye DRAQ5 was purchased from Thermo Scientific (Rockford, IL), while the cell proliferation kit [3-(4,5-dimethylthiazol-2-yl)-2,5-diphenyltetrazolium bromide (MTT)] was purchased from Roche (Indianapolis, IN). The anti-phosphotyrosine (pY) antibody (clone 4G10) was purchased from Millipore (Temecula, CA).

Peptide Synthesis and Labeling. The details of peptide synthesis are described in the Supporting Information. Peptide labeling with FITC was performed by dissolving the purified peptide (~1 mg) in 300 μL of 1:1:1 (v/v/v) dimethyl sulfoxide (DMSO)/dimethylformamide (DMF)/150 mM sodium bicarbonate (pH 8.5) mixture and mixing that solution with 10 μL of FITC in DMSO (100 mg/mL). After 20 min at room temperature, the reaction mixture was subjected to reversed-phase high-performance liquid chromatography (HPLC) on a

C₁₈ column to isolate the FITC-labeled peptide. To generate rhodamine- and Dex-labeled peptides (Figure S1 of the Supporting Information), an N^ε-4-methoxytrityl-L-lysine was added to the C-terminus. After solid-phase peptide synthesis, the lysine side chain was selectively deprotected using 1% (v/v) trifluoroacetic acid in CH₂Cl₂. The resin was incubated with Lissamine rhodamine B sulfonyl chloride and DIPEA (5 equiv each) in DMF overnight. The peptides were fully deprotected as described in the Supporting Information, triturated with diethyl ether, and purified by HPLC. The Dex-labeled peptide was produced by incubating the resin with a mixture of dexamethasone-21-thiopropionic acid, HBTU, and DIPEA (5, 5, and 10 equiv, respectively) in DMF for 3 h.⁴² The peptide was then deprotected, triturated, and purified by HPLC. Bicyclic peptides, phosphocoumaryl aminopropionic acid (pCAP), and pCAP-containing peptides (PCPs) were synthesized as previously described.^{47–49} The authenticity of each peptide was confirmed by matrix-assisted laser desorption ionization time-of-flight mass spectrometry.

Preparation of cFΦR₄-Protein Conjugates. Peptide cFΦR₄ containing a C-terminal cysteine [cFΦR₄-SH, ~10 μmol (Figure S2 of the Supporting Information)] was dissolved in 1 mL of degassed DPBS and mixed with 2,2'-dipyridyl disulfide (5 equiv) dissolved in acetone (0.5 mL). After 2 h at room temperature, the reaction product cFΦR₄-SS-Py was purified by reversed-phase HPLC. The product was incubated with coenzyme A (2 equiv) in DPBS for 2 h. The resulting cFΦR₄-SS-CoA adduct was purified again by reversed-phase HPLC. Green fluorescent protein (GFP) containing an N-terminal ybbR tag (VLDSLEFIASKL) and a C-terminal six-histidine tag was expressed in *Escherichia coli* and purified as previously described.⁵⁰ Next, ybbR-GFP (30 μM), cFΦR₄-SS-CoA (30 μM), and phosphopantetheinyl transferase Sfp (0.5 μM) were mixed in 50 mM HEPES (pH 7.4) and 10 mM MgCl₂ (total volume of 1.5 mL) and incubated at 37 °C for 15 min. The labeled protein, cFΦR₄-S-S-GFP (Figure S2 of the Supporting Information), was separated from unreacted cFΦR₄-SS-CoA by passing the reaction mixture through a PD-10 desalting column. GFP conjugated to Tat (Tat-S-S-GFP) and cFΦR₄-conjugated PTP1B (cFΦR₄-PTP1B) were prepared in a similar fashion (Figure S3 of the Supporting Information).

Cell Culture and Transfection. HEK293, HeLa, MCF-7, NIH 3T3, and A549 cells were maintained in medium consisting of Dulbecco's modified Eagle's medium (DMEM), 10% FBS, and 1% penicillin/streptomycin. H1650 and H1299 cells were grown in RPMI-1640 supplemented with 10% FBS and 1% penicillin/streptomycin. Cells were cultured in a humidified incubator at 37 °C with 5% CO₂. For the transfection of HeLa cells, cells were seeded onto a 96-well plate at a density of 10000 cells/well. Following attachment, cells were transfected with plasmids encoding the Rab5-green fluorescent protein fusion (Rab5-GFP, a gift from P. Di Camilli), Rab7-GFP (Addgene plasmid 28047, Q. Zhong), the glucocorticoid receptor (C638G)-GFP fusion (GR-GFP),⁵¹ DsRed-Rab5 WT (Addgene plasmid 13050, R. Pagano), or DsRed-Rab5^{Q79L} (Addgene plasmid 29688, E. DeRobertis) following manufacturer's protocols for Lipofectamine 2000.

Confocal Microscopy. To examine the colocalization between rhodamine-labeled cyclic peptide (cFΦR₄^{Rho}) and Rab5⁺ or Rab7⁺ endosomes, HeLa cells transfected with Rab5-GFP or Rab7-GFP were plated (200 μL, 10⁴ cells/well, 96-well glass bottom MatriPlates) the day prior to the experiment. On

the day of the experiment, HeLa cells were treated with 1 μM cFΦR₄^{Rho} in DMEM supplemented with 300 nM Hoescht 33342 for 30 min. After that, the cells were washed with HKR buffer [10 mM HEPES (pH 7.4), 140 mM NaCl, 2 mM KCl, 1 mM CaCl₂, and 1 mM MgCl₂] and imaged using a PerkinElmer LiveView spinning disk confocal microscope.

For the GR translocation assay, HeLa cells transfected with GR-GFP were plated as described above.⁵¹ The cells were treated for 30 min with DMEM containing 1 μM Dex or Dex-peptide conjugate and 300 nM Hoescht 33342 and imaged using a Zeiss Axiovert 200M epifluorescence microscope outfitted with a Zeiss AxioCam mRM camera and an EXFO-Excite series 120 Hg arc lamp. The translocation ratio (the ratio of mean GFP intensity in the nuclear and surrounding regions) for individual cells was measured as described in the Supporting Information. To examine the effect of endocytosis inhibitors, transfected HeLa cells were pretreated for 30 min with clear DMEM containing the inhibitors before incubation with Dex or Dex-peptide conjugates. To test whether Rab5 activity is required for endosomal escape, HeLa cells were transfected with GR-GFP and DsRed-Rab5 WT or DsRed-Rab5^{Q79L} before being treated with Dex or the Dex-peptide conjugate and imaged as described above.⁴²

To examine the internalization of rhodamine-labeled peptides, 5 × 10⁴ HEK293 cells were plated in a 35 mm glass-bottom microwell dish (MatTek). On the day of the experiment, the cells were incubated with the peptide solution (5 μM) and 0.5 mg/mL dextran^{FITC} at 37 °C for 2 h. The cells were gently washed with DPBS twice and imaged on a Visitech Infinity 3 Hawk 2D-array live cell imaging confocal microscope. To detect the internalization of pCAP-containing peptides, HEK293 cells were similarly plated and incubated with the peptide solution (5 μM) at 37 °C for 60 min. After removal of the medium, the cells were gently washed with DPBS containing sodium pervanadate (1 mM) twice and incubated for 10 min in DPBS containing 5 μM nuclear staining dye DRAQ5. The resulting cells were washed with DPBS twice and imaged on a spinning disk confocal microscope (UltraView Vox CSUX1 system). To monitor GFP internalization, 5 × 10⁴ HEK293 cells were seeded in a 35 mm glass-bottom microwell dish and cultured overnight. Cells were treated with CPP-S-S-GFP (1 μM) at 37 °C for 2 h. After removal of the medium, the cells were incubated in DPBS containing 5 μM DRAQ5 for 10 min. The cells were washed with DPBS twice and imaged on a Visitech Infinity 3 Hawk 2D-array live cell imaging confocal microscope.

Flow Cytometry. To quantify the delivery efficiencies of pCAP-containing peptides, HeLa cells were cultured in six-well plates (5 × 10⁵ cells per well) for 24 h. On the day of the experiment, the cells were incubated with 10 μM pCAP-containing peptide in clear DMEM with 1% FBS at 37 °C for 2 h. The cells were washed with DPBS containing 1 mM sodium pervanadate, detached from plate with 0.25% trypsin, suspended in DPBS containing 1% bovine serum albumin, and analyzed on a BD FACS Aria flow cytometer with excitation at 355 nm. Data were analyzed with Flowjo (Tree Star) The experimental procedure for estimating the effect of the cyclic peptide on endocytosis is described in the Supporting Information.

Immunoblotting. NIH 3T3 cells were cultured in full growth medium to reach 80% confluence. The cells were starved in serum free medium for 3 h and treated with different concentrations of cFΦR₄-PTP1B or untagged PTP1B for 2 h,

followed by a 30 min incubation in medium supplemented with 1 mM sodium pervanadate. The solutions were removed and the cells washed twice with cold DPBS. The cells were detached and lysed in 50 mM Tris-HCl (pH 7.4), 150 mM NaCl, 1% NP-40, 10 mM sodium pyrophosphate, 5 mM iodoacetic acid, 10 mM NaF, 1 mM ethylenediaminetetraacetic acid, 2 mM sodium pervanadate, 0.1 mg/mL phenylmethanesulfonyl fluoride, 1 mM benzamidine, and 0.1 mg/mL trypsin inhibitor. After being incubated on ice for 30 min, the cell lysate was centrifuged at 15000 rpm for 25 min in a microcentrifuge. The total cellular proteins were separated by sodium dodecyl sulfate–polyacrylamide gel electrophoresis (SDS–PAGE) and transferred electrophoretically to a polyvinylidene fluoride membrane, which was immunoblotted using anti-pY antibody 4G10.

RESULTS AND DISCUSSION

cF Φ R₄ Enters Cells via Endocytosis. We previously observed that cF Φ R₄ fails to enter cells at 4 °C or in the presence of sodium azide, suggesting that energy-dependent endocytic processes mediate its cell entry.⁴³ However, other cyclic CPPs have been reported to enter cells by direct membrane translocation.^{44,45} To further test the role of endocytosis and intracellular trafficking during the cellular uptake of cF Φ R₄, we examined the extent of colocalization between cF Φ R₄^{Rho} (Table 1, compound 1) and GFP-tagged Rab proteins that have been demonstrated to localize to vesicles of the endocytic system. Rab5 is a small Rab family GTPase that is primarily localized to early endosomal membranes, whereas Rab7 is predominantly localized to the membranes of late endosomes.^{52,53} HeLa cells overexpressing GFP-Rab5 or GFP-Rab7 were incubated with 1 μ M cF Φ R₄^{Rho} for 30 min and examined by spinning-disk confocal microscopy (Figure 2A). A large fraction of rhodamine B fluorescence overlapped with that of Rab5-GFP ($R_{\text{GFP, rhodamine}} = 0.703$) and Rab7-GFP ($R_{\text{GFP, rhodamine}} = 0.591$), indicating that cF Φ R₄^{Rho} is present in both early (Rab5⁺) and late (Rab7⁺) endosomes.

To further delineate the endocytic events required for the cytosolic delivery of cF Φ R₄, we made use of a novel GR-GFP translocation assay^{42,51,54} and examined the effects of various endocytic inhibitors on the cytosolic delivery of Dex-labeled peptides cF Φ R₄^{Dex} and Tat^{Dex} (Figure S1 of the Supporting Information and Table 1, compounds 2 and 3). In resting cells, GR (glucocorticoid receptor) is maintained in the cytoplasm through interactions with host chaperones.⁵⁵ Upon cytoplasmic delivery of Dex or Dex-peptide conjugates, association with the GR activates translocation from the cytoplasm into the nucleus.⁵⁶ Thus, the ratio of GR-GFP fluorescence intensity in the nucleus to that in the cytoplasm, or the translocation ratio (TR), provides a semiquantitation of the cytosolic Dex or Dex-peptide concentration. It should be noted that this assay is ideal for comparing the cytosolic concentrations of a Dex derivative under different conditions (e.g., in the absence and presence of an endocytosis inhibitor); for different Dex derivatives (e.g., cF Φ R₄^{Dex} and Tat^{Dex}), the TR may also be affected by their solubility, metabolic stability, and/or binding affinity for GR.^{42,51} Incubation of HeLa cells expressing a GR-GFP fusion protein with 1 μ M cF Φ R₄^{Dex} increased the TR from 1.17 \pm 0.23 in untreated cells to 3.50 \pm 0.66, confirming that a significant amount of cF Φ R₄^{Dex} reached the cytoplasm. Treatment of HeLa cells before and during cF Φ R₄^{Dex} incubation with the cell-permeable dynamin inhibitor Dynasore (Dyna), the cortical actin remodeling inhibitor *N*-ethyl-

Table 1. Sequences of Peptides Used in This Work

peptide	abbreviation	peptide sequence ^a
1	cF Φ R ₄ ^{Rho}	cyclo(F Φ RRRRQ)-K(Rho)-NH ₂
2	cF Φ R ₄ ^{Dex}	cyclo(F Φ RRRRQ)-K(Dex)-NH ₂
3	Tat ^{Dex}	H-K(Dex)-GRKKRRQRRRPPQY-NH ₂
4	cF Φ R ₄ ^{FITC}	cyclo(F Φ RRRRQ)-K(FITC)-NH ₂
5	cF Φ R ₄ -R ₅	cyclo(F Φ RRRRQ)-RRRRR-K(Rho)-NH ₂
6	cF Φ R ₄ -A ₅	cyclo(F Φ RRRRQ)-AAAAA-K(Rho)-NH ₂
7	cF Φ R ₄ -F ₄	cyclo(F Φ RRRRQ)-FFFF-K(Rho)-NH ₂
8	cF Φ R ₄ -PCP	cyclo(F Φ RRRRQ)-miniPEG-DE(pCAP)LI-NH ₂
9	PCP	Ac-DE(pCAP)LI-NH ₂
10	R ₉ -PCP	Ac-RRRRRRRRR-miniPEG-DE(pCAP)LI-NH ₂
11	Tat-PCP	Ac-RKKRRQRRR-miniPEG-DE(pCAP)LI-NH ₂
12	Antp-PCP	Ac-RQIKIWFQNRMMKWKK-miniPEG-DE(pCAP)LI-NH ₂
13	bicyclo(F Φ R ₄ -A ₅) ^{Rho}	[Tm(AAAAA)K(RRRR Φ F)]-K(Rho)-NH ₂
14	bicyclo(F Φ R ₄ -A ₇) ^{Rho}	[Tm(AAAAAA)K(RRRR Φ F)]-K(Rho)-NH ₂
15	bicyclo(F Φ R ₄ -RARAR) ^{Rho}	[Tm(RARAR)K(RRRR Φ F)]-K(Rho)-NH ₂
16	bicyclo(F Φ R ₄ -DADAD) ^{Rho}	[Tm(DADAD)K(RRRR Φ F)]-K(Rho)-NH ₂
17	monocyclo(F Φ R ₄ -A ₅) ^{Rho}	cyclo(AAAAAARRRR Φ F)-K(Rho)-NH ₂
18	monocyclo(F Φ R ₄ -A ₇) ^{Rho}	cyclo(AAAAAARRRR Φ F)-K(Rho)-NH ₂
19	cF Φ R ₄	cyclo(F Φ RRRRQ)
20	R ₉	H-RRRRRRRRR-OH
21	Tat	H-YGRKKRRQRRR-OH
22	Antp	H-RQIKIWFQNRMMKWKK-OH

^aAbbreviations: Φ , L-2-naphthylalanine; J, L-2,3-diaminopropionic acid; Rho, rhodamine B; Dex, dexamethasone; FITC, fluorescein isothiocyanate; miniPEG, 8-amino-3,6-dioxoactanoic acid; pCAP, phosphocoumaryl aminopropionic acid; Tm, trimesoyl.

isopropyl-amiloride (EIPA), or the cholesterol-sequestering agent methyl- β -cyclodextrin (MBCD) decreased the cF Φ R₄^{Dex} TR to 2.35 \pm 0.75, 1.86 \pm 0.46, and 1.56 \pm 0.39, respectively (Figure 2B and Figure S4 of the Supporting Information).^{57–59} These results strongly support our previous hypothesis that cF Φ R₄ enters cells predominantly through endocytosis,⁴³ and the inhibition pattern suggests the involvement of multiple endocytic mechanisms during the uptake of cF Φ R₄.

cF Φ R₄ Escapes from Early Endosomes into the Cytoplasm. The presence of intense, diffuse fluorescence throughout the cytoplasm and nucleus of cells treated with fluorescently labeled cF Φ R₄ indicates that cF Φ R₄ efficiently escapes from the endosome (ref 43 and *vide infra*). In an attempt to understand why cF Φ R₄ possesses this unusual property among CPPs, we again made use of the GR-GFP translocation assay to examine the effect of downstream endocytic perturbations on the cytoplasmic delivery of cF Φ R₄^{Dex}. Pretreatment of HeLa cells with the endosomal vesicular ATPase inhibitor bafilomycin (Baf)⁶⁰ prior to the addition of cF Φ R₄^{Dex} decreased the TR to 2.66 \pm 0.62, suggesting that endosomal acidification facilitates the release of cF Φ R₄^{Dex} into the cytoplasm. Blocking the maturation of Rab5⁺ vesicles by pretreating cells with the phosphatidylinositol 3-

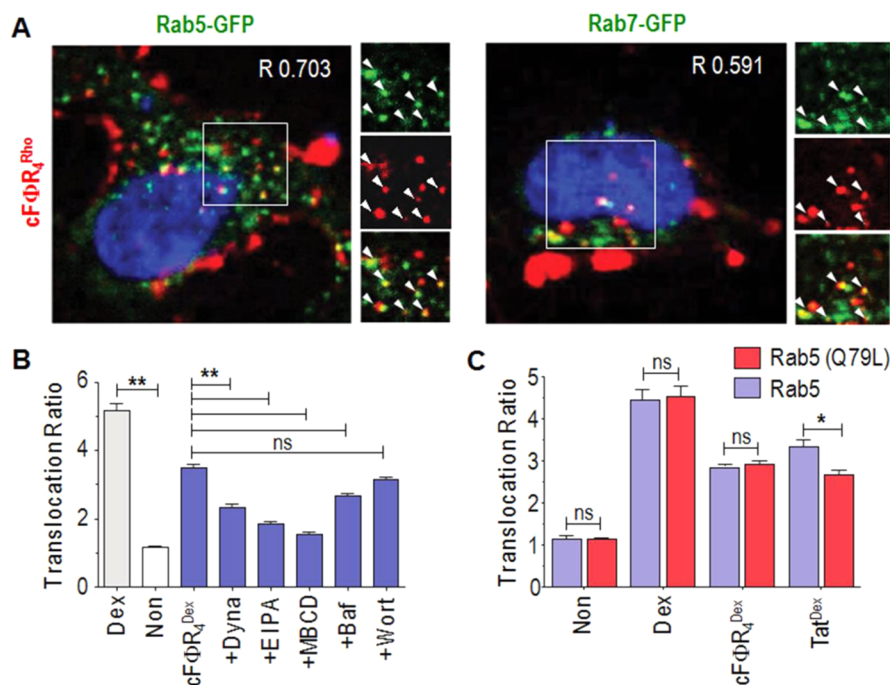


Figure 2. cFΦR₄ enters cells through endocytosis, localizes to Rab5⁺ and Rab7⁺ endosomes, and releases from early endosomes into cytoplasm. (A) Colocalization between Rab5-GFP (left) or Rab7-GFP (right) and cFΦR₄^{Rho} (red) HeLa cells stained with Hoescht 33342 (blue). (B) Translocation of GR-GFP after treatment with 1 μM Dex or cFΦR₄^{Dex} in the presence and absence of 80 μM Dynasore (Dyna), 50 μM N-ethyl-isopropyl-amiloride (EIPA), 5 mM methyl-β-cyclodextrin (MBCD), 200 nM wortmannin (Wort), or 200 nM bafilomycin (Baf). (C) Translocation of GR-GFP after treatment with 1 μM Dex or cFΦR₄^{Dex} upon overexpression of WT Rab5 or Rab5(Q79L). **p* ≤ 0.01; ***p* ≤ 0.001; ns, not significant (two-tailed *t* test).

kinase inhibitor wortmannin (Wort)⁶¹ had an only minor effect on the TR (from 3.50 ± 0.66 to 3.15 ± 0.55), supporting the idea that cFΦR₄^{Dex} is released from early Rab5⁺ endosomes. To further test whether endosomal maturation is required for cytosolic delivery, we overexpressed GTPase-inactive Rab5 mutant, Rab5(Q79L), which halts endosomal maturation at the Rab5⁺ stage.⁶² Rab5(Q79L) overexpression significantly reduced the TR for Tat^{Dex}, which has previously been shown to be released from late endosomes⁴² but had no effect on either free Dex or cFΦR₄^{Dex} (Figure 2C and Figure S5 of the Supporting Information), confirming that cFΦR₄ is released from early endosomes into the cytoplasm. Interestingly, miniature proteins containing a pentaarginine motif on an α-helix, another system shown to efficiently escape from the endosome, are also released from the early endosome.⁴² R₉ was previously shown to exit the endocytic pathway after the miniature proteins but prior to Tat.⁴² It appears that compared to other cationic CPPs, cFΦR₄ is less dependent on endosomal acidification for release and thus able to exit from the less acidic early endosomes.

cFΦR₄ Binds to Membrane Phospholipids. It was previously observed that incubation of 1 μM FITC-labeled cyclic peptide cFΦR₄^{FITC} (Table 1, compound 4) with vesicles containing negatively charged phospholipids [90% phosphatidylcholine (PC) and 10% phosphatidylglycerol (PG)] resulted in quenching of the peptide fluorescence, consistent with direct binding of cFΦR₄ to phospholipids.⁴³ To test the potential role of membrane binding during endocytic uptake of CPPs, we prepared SUVs that mimic the outer membrane of mammalian cells (45% PC, 20% phosphatidylethanolamine, 20% sphingomyelin, and 15% cholesterol) and tested them for binding to FITC-labeled cFΦR₄, R₉, and Tat (each at 100 nM) by a

fluorescence polarization (FP) assay. cFΦR₄ bound to the neutral SUVs with an EC₅₀ value (lipid concentration at which half of cFΦR₄^{FITC} is bound) of 2.1 ± 0.1 mM (Figure 3A). R₉ showed much weaker binding to the artificial membrane (EC₅₀ > 10 mM), whereas Tat did not bind at all. We next tested the CPPs for binding to heparan sulfate, which was previously

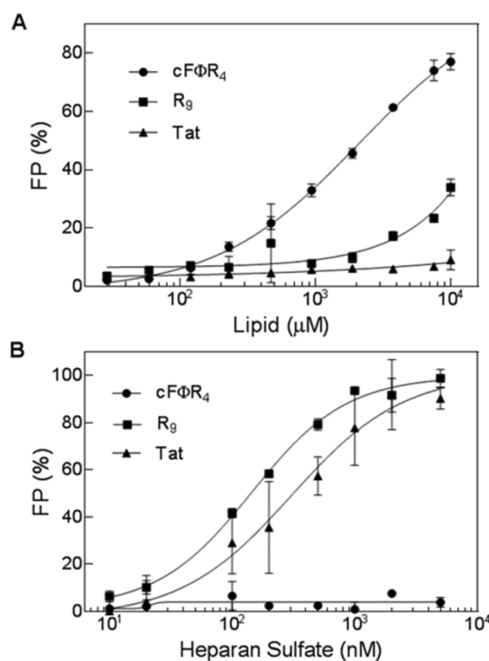


Figure 3. Binding of FITC-labeled cFΦR₄, R₉, and Tat to SUV (A) and heparan sulfate (B).

proposed to be the primary binding target of cationic CPPs.^{36,63–67} As expected, R₉ and Tat both bound to heparan sulfate with high affinity, having EC₅₀ values of 144 and 304 nM, respectively (Figure 3B). Under the same condition, cFΦR₄ showed no detectable binding to heparan sulfate. Our results are in agreement with the previous observations that nonamphipathic cationic CPPs (e.g., Tat and R₉) bind tightly with cell surface proteoglycans (e.g., heparan sulfate) but only weakly with membrane lipids.⁶⁷ The insufficient number of positive charges of cFΦR₄ is likely responsible for its lack of strong electrostatic interaction with heparan sulfate. On the other hand, the amphipathic nature and the more rigid cyclic structure of cFΦR₄ should facilitate its binding to neutral lipid membranes. These data, together with the inhibition pattern by various endocytic inhibitors described above, suggest that cFΦR₄ binds directly to the plasma membrane phospholipids and is internalized by all of the endocytic mechanisms in a piggyback manner.

Intracellular Delivery of Peptidyl Cargos. Because endocyclic delivery by cFΦR₄ is limited to a heptapeptide or smaller cargos,⁴³ in this study we tested the ability of cFΦR₄ to deliver cargos of varying sizes and physicochemical properties attached to the Gln side chain (Figure 1B, exocyclic delivery). We first covalently attached positively charged (RRRRR), neutral (AAAAA), hydrophobic (FFFF), and negatively charged [DE(pCAP)LI] peptides to cFΦR₄ (Table 1, compounds 5–8, respectively). The first three peptides were labeled with rhodamine B at a C-terminal lysine side chain (Figure S1 of the Supporting Information), and their internalization into HEK293 cells was examined by live cell confocal microscopy. Cells incubated for 2 h with 5 μM peptide cFΦR₄-A₅ (Figure 4A) or cFΦR₄-R₅ (Figure 4B) showed

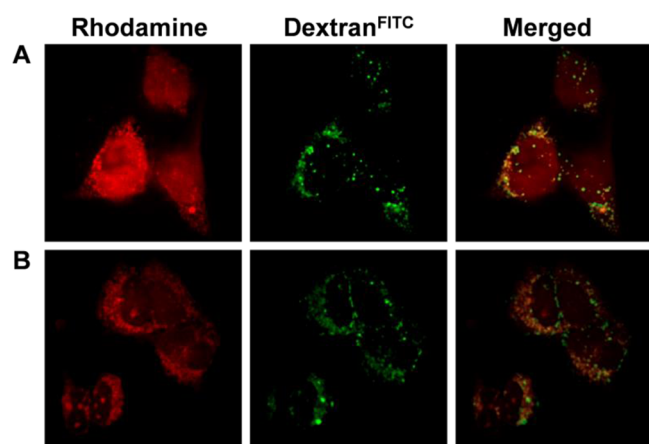


Figure 4. Representative live cell confocal images of HEK293 cells treated for 2 h with rhodamine B-labeled peptides and fluid-phase uptake marker dextran^{FITC}. (A) Cells treated with 5 μM cFΦR₄-A₅ and dextran^{FITC} in the same Z section. (B) Same as panel A but with 5 μM cFΦR₄-R₅.

evidence of both punctate and diffuse fluorescence, with the latter distributed almost uniformly throughout the cell. In contrast, the fluid-phase endocytic marker dextran^{FITC} displayed predominantly punctate fluorescence, indicative of endosomal localization. The diffuse rhodamine fluorescence suggests that a fraction of the peptides reached the cytosol and nucleus of the cells. Co-incubation of cells with cFΦR₄ (1 μM) and dextran^{Alexa488} increased the level of internalization of the endocytic marker by 15% (Figure S6 of the Supporting

Information), suggesting that cFΦR₄ activates endocytosis in cultured cells. cFΦR₄-F₄ could not be tested because of its poor aqueous solubility.

Peptide cFΦR₄-DE(pCAP)LI [cFΦR₄-PCP (Figure S1 of the Supporting Information)] was designed to test the ability of cFΦR₄ to deliver negatively charged cargos as well as to compare the cytoplasmic delivery efficiency of cFΦR₄ with those of other widely used CPPs such as R₉, Tat, and penetratin (Antp). Thus, untagged PCP [Ac-DE(pCap)LI-NH₂] and PCP conjugated to R₉ (R₉-PCP), Tat (Tat-PCP), and Antp (Antp-PCP) (Table 1, compounds 9–12, respectively) were also prepared. Note that cFΦR₄-PCP carries a net charge of zero at physiological pH. pCAP is nonfluorescent but, upon entering the cell interior, should be rapidly dephosphorylated by endogenous protein tyrosine phosphatases (PTPs) to produce a fluorescent product, coumaryl aminopropionic acid (CAP, excitation at 355 nm and emission at 450 nm).^{48,49} When assayed against a PTP panel *in vitro*, all four CPP-PCP conjugates were efficiently dephosphorylated (Table S1 of the Supporting Information). This assay detects only the CPP cargo inside the cytoplasm and nucleus, where the catalytic domains of all known mammalian PTPs are localized.⁶⁸ Further, CAP is fluorescent only in its deprotonated state (pK_a = 7.8); even if some dephosphorylation occurs inside the endosome (pH 6.5–4.5) or lysosome (pH 4.5), it would contribute little to the total fluorescence (Figure S7 of the Supporting Information). Treatment of HEK293 cells with 5 μM cFΦR₄-PCP for 60 min resulted in diffuse blue fluorescence throughout the cell, suggesting that cFΦR₄-PCP reached the cell interior, whereas the untagged PCP failed to enter cells under the same condition (Figure 5A). When HEK293 cells were pretreated with the PTP inhibitor sodium pervanadate for 1 h prior to incubation with cFΦR₄-PCP (5 μM), the CAP fluorescence in the cells diminished to background levels. HEK293 cells treated with R₉-PCP, Antp-PCP, or Tat-PCP under identical conditions showed weak fluorescence, consistent with the poor ability of these peptides to access the cell interior (Figure 5A). To quantify the relative intracellular PCP delivery efficiency, HeLa cells were treated with each peptide and analyzed by fluorescence-activated cell sorting (Figure 5B). cFΦR₄-PCP was most efficiently internalized by the HeLa cells, with a mean fluorescence intensity (MFI) of 3510 arbitrary units (AU), whereas R₉-PCP, Antp-PCP, Tat-PCP, and untagged PCP produced MFI values of 960, 400, 290, and 30 AU, respectively (Figure 5C). Again, when cells were treated with cFΦR₄-PCP in the presence of sodium pervanadate, the amount of CAP fluorescence was reduced to near background levels (70 AU). Thus, cFΦR₄ is capable of delivering peptidyl cargos of varying physicochemical properties into the cytoplasm with efficiencies 3.7–12-fold higher than those of R₉, Antp, and Tat.

Intracellular Delivery of Cyclic Peptides. In recent years, there has been much interest in cyclic peptides as therapeutic agents and biomedical research tools.^{69,70} For example, cyclic peptides are effective for inhibition of protein–protein interactions,^{47,71–73} which are challenging targets for conventional small molecules. A major obstacle in developing cyclic peptide therapeutics is that they are generally impermeable to the cell membrane.^{74–76} Our attempt to deliver cyclic peptides by cFΦR₄ by the endocyclic method had only limited success; an increase in cargo size from one to seven residues led to progressively poorer cellular uptake, likely because the larger, more flexible rings bind more poorly to the cell membrane.⁴³

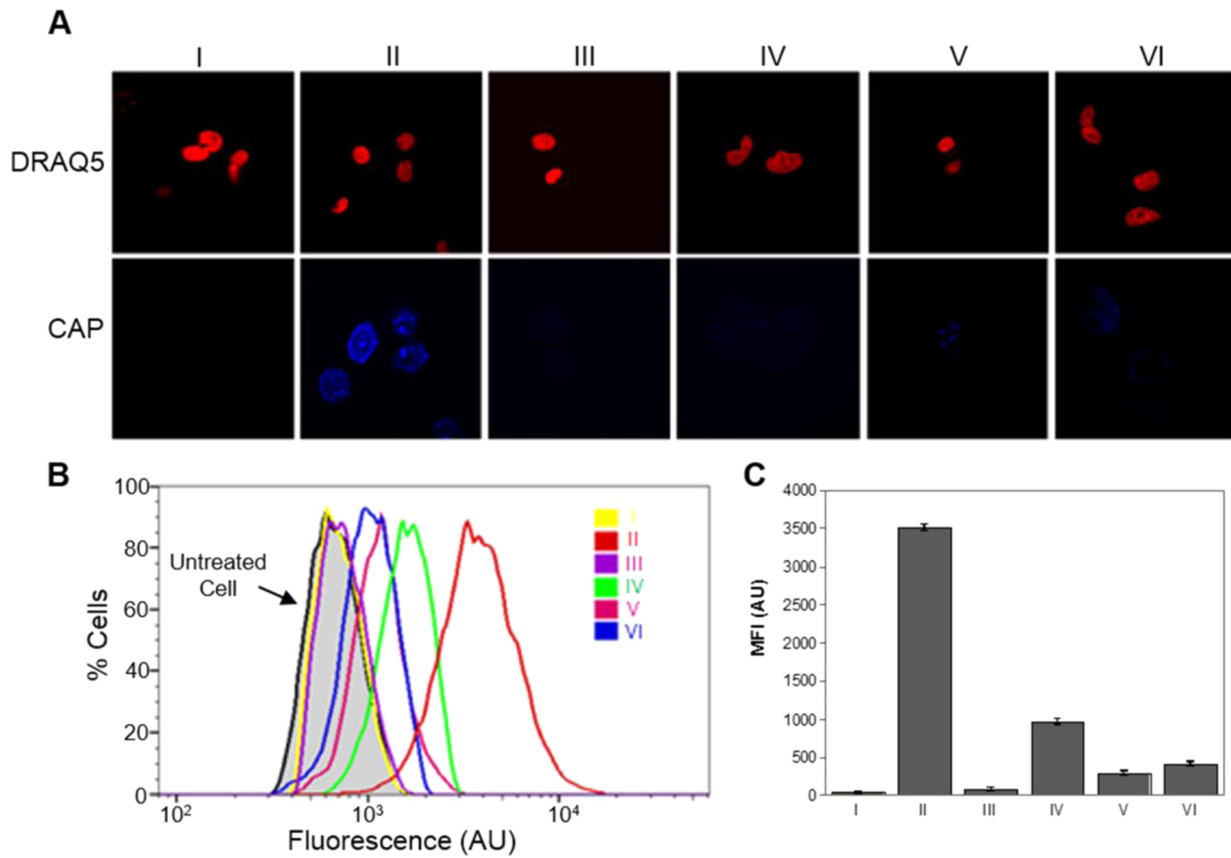


Figure 5. Internalization of pCAP-containing peptides into cultured cells: (I) untagged PCP, (II) cF Φ R₄-PCP, (III) cF Φ R₄-PCP and Na₃VO₄, (IV) R₉-PCP, (V) Tat-PCP, and (VI) Antp-PCP. (A) Representative live cell confocal images of HEK293 cells treated with 5 μ M peptides. The top panel shows the nuclear stain with DRAQ5 and the bottom panel CAP fluorescence in the same Z section. (B) Flow cytometry of HeLa cells treated with 0 or 10 μ M peptides. (C) CAP fluorescence from panel B after subtraction of background fluorescence (untreated cells).

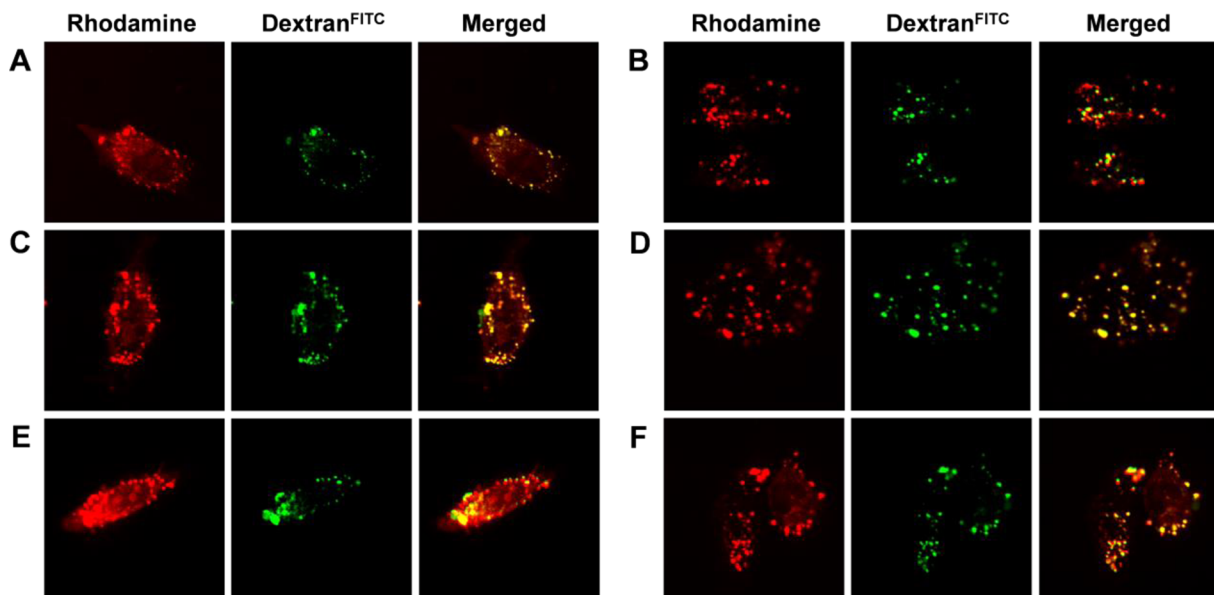


Figure 6. Representative live cell confocal microscopic images of HEK293 cells treated for 2 h with rhodamine B-labeled peptides (5 μ M each) and fluid-phase endocytosis marker dextran^{FITC} (0.5 mg/mL). The red fluorescence of rhodamine B and the green fluorescence of dextran^{FITC} from the same Z section and their merged image are shown in each panel. The enlarged images of a typical cell(s) are shown in each case to show the intracellular distribution of the internalized peptides: (A) cells treated with bicyclo(F Φ R₄-A₅)^{Rho}, (B) cells treated with monocyclo(F Φ R₄-A₅)^{Rho}, (C) cells treated with bicyclo(F Φ R₄-A₇)^{Rho}, (D) cells treated with monocyclo(F Φ R₄-A₇)^{Rho}, (E) cells treated with bicyclo(F Φ R₄-RARAR)^{Rho}, and (F) cells treated with bicyclo(F Φ R₄-DADAD)^{Rho}.

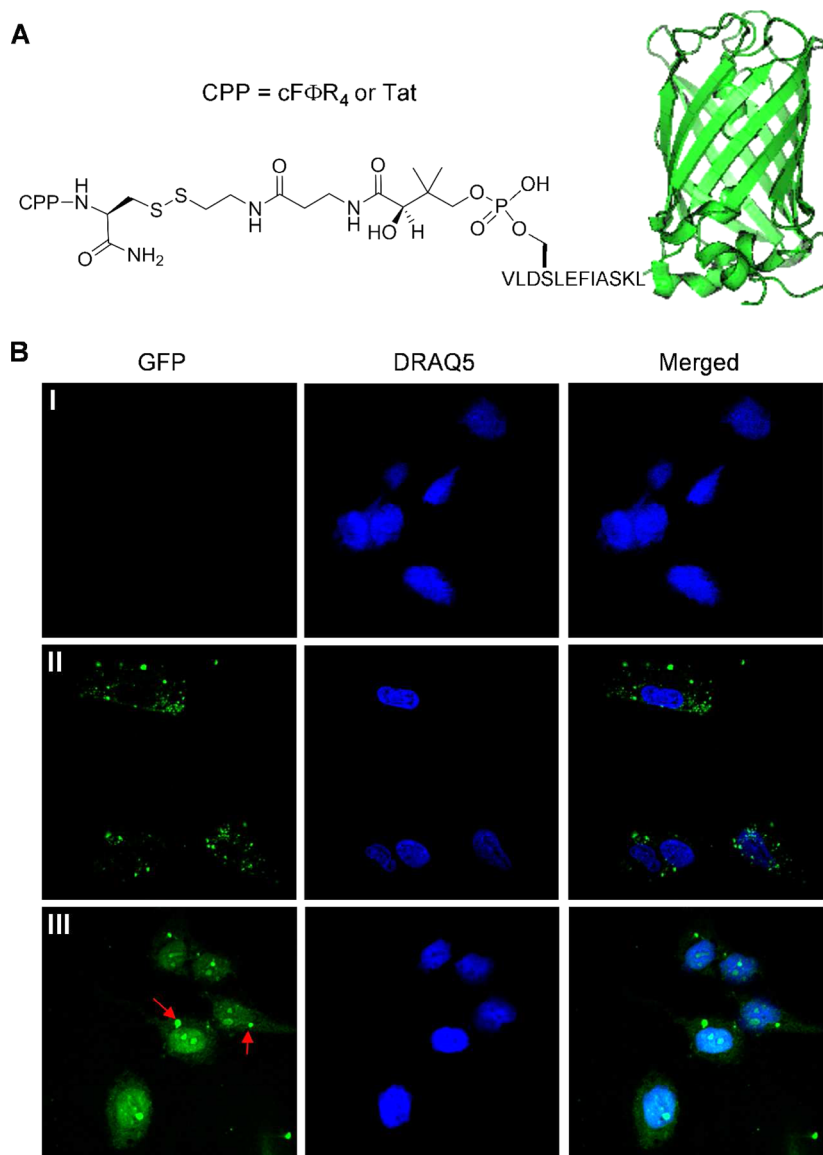


Figure 7. (A) Structures of CPP-S-S-GFP conjugates. (B) Live cell confocal images of HEK293 cells after treatment for 2 h with 1 μ M GFP (I), Tat-S-S-GFP (II), or cF Φ R₄-S-S-GFP (III) and nuclear stain DRAQ5. All images were recorded in the same Z section.

To overcome this limitation, we explored a bicyclic peptide system, in which one ring contains a CPP motif (e.g., F Φ R₄) while the other ring consists of peptide sequences specific for the desired targets (Figure 1C). The bicyclic system should in principle be able to accommodate cargos of any size, because the cargo does not change the structure of the CPP ring and should have less impact on its delivery efficiency. The additional rigidity of a bicyclic structure should also improve its metabolic stability as well as the target binding affinity and specificity. The bicyclic peptides were readily synthesized by forming three amide bonds between a trimesoyl scaffold and three amino groups on the corresponding linear peptide [i.e., the N-terminal amine, the side chain of a C-terminal diaminopropionic acid (Dap), and the side chain of a lysine (or ornithine, Dap) imbedded between the CPP and target binding motifs].⁴⁷ To test the validity of this approach, we chose F Φ R₄ in the C-terminal ring as the CPP moiety and peptides of different lengths and charges (AAAAA, AAAAAA, RARAR, and DADAD) as cargo (Table 1, compounds 13–16, respectively). For comparison, we also prepared two mono-

cyclic peptides containing F Φ R₄ as a transporter and peptides A₅ and A₇ as cargos (Table 1, compounds 17 and 18, respectively). All of the peptides were labeled at a C-terminal lysine side chain with rhodamine B (Figure S1 of the Supporting Information), and their internalization into HEK293 cells was examined by live cell confocal microscopy. Treatment of cells with 5 μ M peptide for 2 h resulted in efficient internalization of all six peptides (Figure 6), although FACS analysis indicated that the uptake of bicyclo(F Φ R₄-A₅)^{Rho} was \sim 3-fold more efficient than that of the corresponding monocyclic peptide (compound 17). The intracellular distribution of the internalized peptides was quite different between the bicyclic and monocyclic peptides. While the four bicyclic peptides showed evidence of their presence both in the cytoplasm and nucleus (as indicated by the diffuse rhodamine fluorescence) and in the endosomes (as indicated by the fluorescence puncta), the monocyclic peptides exhibited predominantly punctate fluorescence that overlapped with that of the endocytic marker dextran^{FITC}. In all cases, the endocytic marker displayed only punctate fluorescence, indicating that the

endosomes were intact in the cells treated with the peptides. These results indicate that the increased structural rigidity of the bicyclic peptides facilitates both the initial uptake by endocytosis and endosomal release, presumably because of their improved binding to the plasma and endosomal membranes. The bicyclic system may provide a general strategy for intracellular delivery of cyclic and bicyclic peptides.

Intracellular Delivery of Protein Cargos. To test whether $c\Phi R_4$ is capable of transporting full-length proteins into mammalian cells, we chose GFP because of its intrinsic fluorescence and attached $c\Phi R_4$ to its N-terminus through a disulfide bond (Figure 7A and Figure S2 of the Supporting Information). The disulfide exchange reaction is highly specific, efficient, and reversible; upon entering the cytoplasm, the CPP-S-S-protein conjugate is expected to be rapidly reduced to release the native protein. Although $c\Phi R_4$ can be directly attached to a native or engineered surface cysteine residue(s) on a cargo protein, we employed a GFP variant containing a 12-amino acid ybbR tag at its N-terminus (which was already available in our laboratory) and used phosphopantetheinyl transferase Sfp to enzymatically attach $c\Phi R_4$ to the ybbR tag.⁵⁰ This permitted the attachment of a single $c\Phi R_4$ unit to GFP in a site-specific manner. For comparison, we also generated a Tat-S-S-GFP conjugate in the same manner. Incubation of HEK293 cells in the presence of 1 μ M $c\Phi R_4$ -S-S-GFP resulted in time-dependent accumulation of green fluorescence inside the cells (Figure 7B). The fluorescence signal was diffuse and present throughout the entire cell volume, but with higher concentrations in the nucleus. Some of the cells contained small spots of intense green fluorescence (indicated by arrows in Figure 7B), which may represent endosomally sequestered $c\Phi R_4$ -S-S-GFP or aggregated GFP inside the cell. As expected, untagged GFP was unable to enter cells, whereas Tat-S-S-GFP entered cells less efficiently than $c\Phi R_4$ -S-S-GFP (Figure 7B); FACS analysis of HeLa cells treated with 1 μ M protein revealed a 5.5-fold higher total intracellular fluorescence for the latter. Moreover, cells treated with Tat-S-S-GFP showed predominantly punctate fluorescence in the cell periphery with no detectable fluorescence in the nuclear region, suggesting that Tat-S-S-GFP is mostly entrapped in the endosomes, in agreement with previous reports.³⁵ Thus, with a protein as cargo, $c\Phi R_4$ also has an efficiency substantially higher than that of Tat with regard to both initial uptake and endosomal escape. Attempts to test R_9 -S-S-GFP with cells failed because of precipitation of the conjugate.

To demonstrate the generality of $c\Phi R_4$ for protein delivery, we chose next to deliver a functional enzyme, the catalytic domain of PTP1B (amino acids 1–321), into the cell interior. To show that a noncleavable linkage is also compatible with our delivery method, we conjugated $c\Phi R_4$ to ybbR-tagged PTP1B via a thioether bond ($c\Phi R_4$ -PTP1B) (Figure S3 of the Supporting Information). An *in vitro* assay using *p*-nitrophenyl phosphate as a substrate showed that addition of the $c\Phi R_4$ tag does not affect the catalytic activity of PTP1B (Table S2 of the Supporting Information). NIH 3T3 cells were incubated for 2 h in the presence of untagged PTP1B or $c\Phi R_4$ -PTP1B, and their global pY protein levels were analyzed by anti-pY Western blotting (Figure 8A). Treatment of the cells with $c\Phi R_4$ -PTP1B, but not untagged PTP1B, resulted in a concentration-dependent decrease in pY levels of most, but not all, proteins. The total cellular protein levels, as detected by Coomassie blue staining, were unchanged (Figure 8B), indicating that the

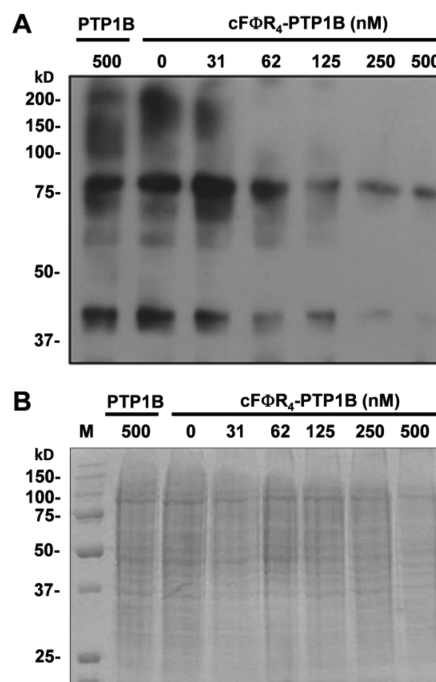


Figure 8. (A) Western blot analysis of the global pY protein levels of NIH 3T3 cells after treatment with 0–500 nM PTP1B or $c\Phi R_4$ -PTP1B (IB, anti-pY antibody 4G10). (B) The same samples as in panel A were analyzed by SDS-PAGE and Coomassie blue staining. M denotes molecular weight markers.

observed decrease in pY levels was due to dephosphorylation of the pY proteins by $c\Phi R_4$ -PTP1B and/or secondary effects caused by the introduction of $c\Phi R_4$ -PTP1B (e.g., inactivation of cellular protein tyrosine kinases). Interestingly, different proteins exhibited varying dephosphorylation kinetics. Several proteins in the 150–200 kDa range were completely dephosphorylated upon the addition of 62 nM $c\Phi R_4$ -PTP1B, whereas proteins of ~80 kDa remained phosphorylated at 500 nM $c\Phi R_4$ -PTP1B. The changes in the pY pattern are consistent with the broad substrate specificity of PTP1B⁷⁷ and very similar to that caused by overexpression of PTP1B inside the cytosol of mammalian cells.⁷⁸ Our results indicate that $c\Phi R_4$ is indeed able to deliver PTP1B into the interior of NIH 3T3 cells in the catalytically active form and to sufficient levels to dramatically perturb the cell signaling process. $c\Phi R_4$ thus provides a powerful tool for introducing other functional proteins, especially proteins that cannot be genetically expressed (e.g., toxic and chemically modified proteins), into mammalian cells for studying their cellular functions.

Stability and Cytotoxicity of $c\Phi R_4$. The relative stability of $c\Phi R_4$, R_9 , Tat, and Antp (Table 1, compounds 19–22, respectively) against proteolytic degradation was determined by incubating the CPPs in 25% human serum at 37 °C and following the disappearance of the full-length peptides by reversed-phase HPLC. The cationic tryptophan-containing peptide, Antp, was least stable among the four CPPs; it was degraded at a half-life of <20 min and was completely digested after 2 h (Figure 9A). R_9 and Tat were slightly more stable than Antp, having half-lives of ~30 min. In contrast, $c\Phi R_4$ was remarkably stable against serum proteases. There was <10% degradation after incubation for 6 h; after incubation for 24 h in the serum, >70% of $c\Phi R_4$ remained intact. Numerous other studies have also demonstrated that cyclization of peptides

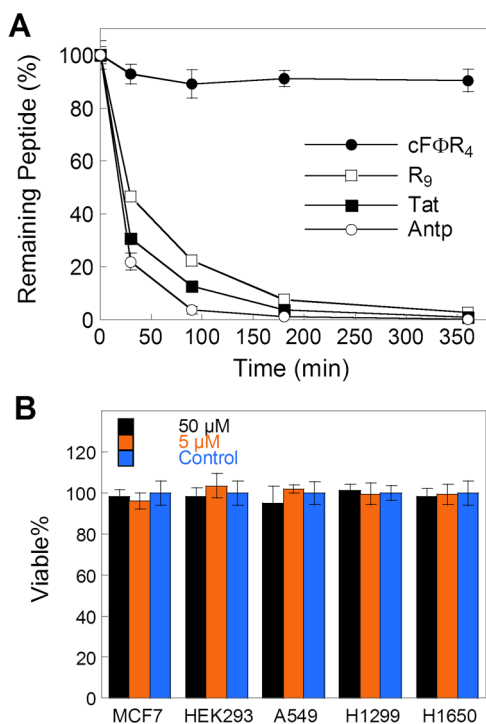


Figure 9. (A) Comparison of the serum stability of cFΦR₄, Tat, R₉, and Antp. (B) Cytotoxicity of cFΦR₄. The indicated cell lines were treated with DMSO (control) or 5 or 50 μM cFΦR₄ for 24 h, and the percentage of live cells was determined by the MTT assay.

greatly increases their proteolytic stabilities.⁷⁹ The potential cytotoxicity of cFΦR₄ was assessed by MTT assays with five different human cell lines (HEK293, MCF-7, A549, H1650, and H1299). After incubation for 24 or 48 h with up to 50 μM cFΦR₄, there was no significant growth inhibition for any of the cell lines (Figure 9B and Figure S8 of the Supporting Information). After 72 h, a slight growth inhibition (up to 20%) was observed at 50 μM (Figure S8 of the Supporting Information). Thus, cFΦR₄ is relatively nontoxic to mammalian cells.

CONCLUSION

In this study, we demonstrate that cFΦR₄ is effective for the exocyclic delivery of small-molecule, peptide, and protein cargos into the cytoplasm and nucleus of mammalian cells. By using a pCAP-containing peptide as the cargo or reporter, we show that cFΦR₄ is 3.7–12-fold more efficient than R₉, Tat, and Antp for cytoplasmic cargo delivery, making cFΦR₄ one of the most active CPPs known to date. Although modification of polybasic CPPs such as addition of hydrophobic acyl groups has previously been reported to enhance cellular uptake by a similar magnitude,²⁷ to the best of our knowledge, these previous studies have not established whether the enhanced uptake translates into a similar increase in the cytoplasmic CPP concentration (our attempt to directly compare cFΦR₄ and the acylated CPPs was not successful, because the latter caused extensive cell death during our experiments). The pCAP-based reporter system described in this work should provide a simple, robust method for quantitatively assessing the cytoplasmic delivery efficiency of other CPPs. Several lines of evidence indicate that cFΦR₄ enters cells through multiple endocytic mechanisms, including its failure to enter cells at 4 °C or in the presence of sodium azide, partial overlap between the

fluorescence puncta of cFΦR₄^{Rho} and the fluid-phase endocytic marker dextran^{Fluorescein}, colocalization of cFΦR₄^{Rho} and endosomal proteins Rab5 and Rab7, and a decreased level of cFΦR₄^{Dex} uptake upon administration of endocytic inhibitors. The minimal effect of the PI3K inhibitor wortmannin and the Rab5 Q79L mutation on the cytoplasmic delivery of cFΦR₄, in addition to the strong colocalization observed between cFΦR₄ and Rab5⁺ endosomes, suggest that cFΦR₄ escapes from early endosomes (Figure 10). In comparison, Tat has been

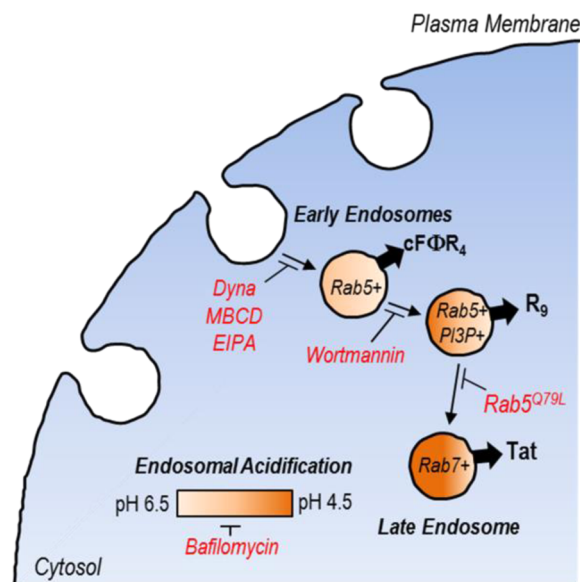


Figure 10. Diagram showing the points along the endocytic pathway where cFΦR₄, R₉, and Tat escape into the cytoplasm and where specific inhibitors are proposed to function.

demonstrated to enter cells through endocytosis and be released from late endosomes, while R₉ escapes endosomes prior to Rab7 recruitment.⁴² Early endosomal release offers significant advantages, especially for peptide and protein cargos, because it minimizes cargo degradation by late endosomal and lysosomal proteases and denaturation caused by acidification during endosomal maturation. Indeed, both GFP and PTP1B delivered into the cytoplasm by cFΦR₄ were in their folded, active forms, as evidenced by the green fluorescence and the ability to dephosphorylate intracellular pY proteins, respectively. Additionally, because of its more rigid structure, cFΦR₄ is significantly more stable against proteolytic degradation than linear peptides, and because of its smaller size, cFΦR₄ is less expensive to synthesize and potentially less likely to interfere with the cargo function. These properties make cFΦR₄ a useful transporter for cytosolic delivery of small molecules to protein cargos. Direct protein delivery provides a useful research tool, e.g., for studying the cellular function of a protein, as it offers improved temporal control over DNA transfection and allows delivery of chemically modified proteins and proteins whose overexpression causes toxicity. The ability of cFΦR₄ to escape from early endosomes and its simple structure may also provide an excellent system for elucidating the mechanism of endosomal escape and the factors that influence the escape efficiency.

■ ASSOCIATED CONTENT

■ Supporting Information

Additional materials and methods for peptide synthesis, SUV preparation, FP assay, preparation of cF Φ R₄-PTP1B, image analysis, flow cytometry analysis, the serum stability assay, and the cytotoxicity assay. This material is available free of charge via the Internet at <http://pubs.acs.org>.

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Notes

The authors declare no competing financial interest.

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