

Antibody Tracking Demonstrates Cell Type-Specific and Ligand-Independent Internalization of Guanylyl Cyclase-A and Natriuretic Peptide Receptor-C

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Abstract

Atrial natriuretic peptide (ANP) binds guanylyl cyclase-A (GC-A) and natriuretic peptide receptor-C (NPR-C). Internalization of GC-A and NPR-C is poorly understood, in part, because previous studies used ^{125}I -ANP binding to track these receptors, which are expressed in the same cell. Here, we evaluated GC-A and NPR-C internalization using traditional and novel approaches. Although HeLa cells endogenously express GC-A, ^{125}I -ANP binding and cross-linking studies only detected NPR-C, raising the possibility that past studies ascribed NPR-C-mediated processes to GC-A. To specifically measure internalization of a single receptor, we developed an ^{125}I IgG-binding assay that tracks extracellular FLAG-tagged versions of GC-A and NPR-C independently of each other and ligand for the first time. FLAG-GC-A bound ANP identically to wild type GC-A and was internalized slowly (0.5%/min) whereas FLAG-NPR-C was internalized rapidly (2.5%/min) in HeLa cells. In 293 cells, ^{125}I -ANP and ^{125}I IgG uptake curves were superimposable because these cells only express a single ANP receptor. Basal internalization of both receptors was 8-fold higher in 293 compared to HeLa cells and ANP did not increase internalization of FLAG-GC-A. For FLAG-NPR-C, neither ANP, BNP nor CNP increased its internalization in either cell line. Prolonged ANP exposure concomitantly reduced surface and total GC-A levels, consistent with rapid exchange of extracellular and intracellular receptor pools. We conclude that ligand binding does not stimulate natriuretic peptide receptor internalization and that cellular environment determines the rate of this process. We further deduce that NPR-C is internalized faster than GC-A and that increased internalization is not required for GC-A downregulation.

Introduction

Atrial natriuretic peptide (ANP) and B-type natriuretic peptide (BNP) are endogenous cardiac hormones that regulate blood pressure, extracellular volume and cardiac load (Potter et al., 2009). ANP and BNP bind two distinct, single membrane-spanning, cell surface receptors: guanylyl cyclase-A (GC-A) and natriuretic peptide receptor-C (NPR-C). GC-A mediates the signaling functions of ANP and BNP by catalyzing the synthesis of cGMP in response to peptide binding (Potter, 2011). NPR-C controls natriuretic peptide concentrations via receptor mediated endocytosis and lysosomal degradation (Nussenzveig et al., 1990). The extracellular domains of NPR-C and GC-A are similar; but unlike GC-A, NPR-C has a short intracellular domain with no known enzymatic activity. Mice lacking GC-A are hypertensive with large hearts while mice lacking NPR-C are hypotensive with dilute urine, consistent with a signaling role for GC-A and a clearance role for NPR-C (Jaubert et al., 1999; Lopez et al., 1995; Matsukawa et al., 1999; Oliver et al., 1997).

¹²⁵I-ANP binding studies have led to conflicting conclusions regarding natriuretic peptide processing and receptor trafficking due to uncertainty regarding which receptor, GC-A or NPR-C, binds the peptide and changing affinities of GC-A for ANP (Abe et al., 1995; Vieira et al., 2001). Some reports indicate that GC-A internalizes ANP and is rapidly degraded in response to ANP binding (Pandey, 2001; Rathinavelu and Isom, 1991). Other reports indicate that GC-A does not internalize ANP and is not degraded in response to ANP binding (Koh et al., 1992; Vieira et al., 2001). We found that GC-A is downregulated in "regular" 293 cells but is downregulated at much slower rates in 293T cells (Fan et al., 2005; Flora and Potter, 2010; Potter and Hunter, 1999). Recently, we reported that GC-A is downregulated when endogenously expressed in primary cells, in transfected Chinese hamster cells and in tissues from mice with congestive heart failure (Bryan et al., 2007; Dickey et al., 2007; Flora and Potter, 2010). Our current model is that GC-A is downregulated under biologic conditions where ANP is elevated for extended periods of time. The mechanistic details of GC-A internalization, however, are unknown.

Ligand-dependent increases in receptor internalization have been suggested to account for the downregulation of GC-A, but this issue is controversial due to the lack of specificity of the assays used to measure this process. Similarly, the effect of ANP binding on the internalization rate of NPR-C is disputed. Two groups reported that ANP stimulates NPR-C downregulation while another group reported that NPR-C is constitutively internalized (Nussenzveig et al., 1990; Pandey, 1992; Rathinavelu and Isom, 1991).

For the first time, we investigated the effect of ANP binding on the internalization rates of GC-A and NPR-C in HeLa and 293 cells using a newly developed ^{125}I -IgG binding assay that tracks FLAG-tagged versions of each receptor independently of the other receptor or the presence of ligand. We found that FLAG-NPR-C is rapidly internalized regardless of the presence of ligand or cellular environment. Surprisingly, the initial internalization rate of FLAG-GC-A was not increased by ANP in HeLa cells and was internalized by an eight-fold faster, ANP-independent process in 293 cells. Importantly, despite the differences in internalization, GC-A was downregulated at similar rates in both cell lines, indicating that accelerated internalization is not required for GC-A degradation.

Materials and Methods

Materials. ^{125}I -anti-mouse IgG (goat), ^{125}I -ANP (rat) and ^{125}I -transferrin (human) were purchased from Perkin Elmer (Waltham, MA). ^{32}P - α GTP was from Perkin Elmer (Waltham, MA). Unlabeled ANP, cycloheximide, FLAG peptide and the anti-FLAG M2 antibody were from Sigma-Aldrich (St. Louis, MO).

Cell Culture. HeLa and stably transformed tetracycline transactivator (tTA) HeLa cells were cultured as described (Sever et al., 2000). Regular HeLa cells were acquired from Dr. Do-Hyung Kim (University of Minnesota) and propagated in DMEM plus 10% fetal bovine serum (FBS). tTA-HeLa cells were from Dr. Sean Conner (University of Minnesota) and grown in the presence of 200 $\mu\text{g}/\text{ml}$ G418. 293PMA-FLAG-GCA cells were prepared by stably expressing pCMV1-FLAG-GC-A (Flora and Potter, 2010) in 293 cells as described (Fan et al., 2005; Potter and Hunter, 1999).

Plasmids and Transfections. pCMV1-FLAG-NPR-C was made by adding HindIII and EcoRI restriction sites to the N- and C-terminal ends, respectively, of the human NPR-C cDNA. The N-terminal restriction site was added immediately after the signal peptide sequence of NPR-C and the cDNA was amplified by PCR, digested with HindIII and EcoRI and subcloned in-frame into the pCMV1-FLAG construct (Sigma-Aldrich; St. Louis, MO) digested with the same restriction enzymes. HeLa or tTA HeLa cells were transfected with GFP, FLAG-GC-A or FLAG-NPR-C using Lipofectamine 2000 (Invitrogen; Carlsbad, CA) according to manufacturer's instructions 24 - 48 h prior to analysis. 293 cells were transfected with FLAG-NPR-C using the standard calcium phosphate transfection protocol (Potthast et al., 2004).

Intracellular Accumulation Assays. Cells were removed from plates with PBS containing 5 mM EDTA. Suspended cells were cooled to 4°C and washed in 1 ml DMEM containing 10% FBS. Cells were incubated with the anti-FLAG M2 antibody (1:10,000; Sigma-Aldrich) for 30 min at 4°C, washed in DMEM containing 0.5% bovine serum albumin (BSA), and incubated with ^{125}I -anti-mouse IgG for 30

min. The cells were washed twice with DMEM containing 0.5% BSA and resuspended in DMEM containing 10% FBS. Fifty μ l of cells were dispensed into tubes and incubated in a 37°C water bath for the indicated times. All tubes except those designated “total counts” were transferred to 4°C and stripped with 0.2 M acetic acid and 0.5 M NaCl for 5 min at 4°C to remove surface bound radioactivity. Cells were pelleted, the supernatant was removed, and the amount of radioactivity in the pellets was determined. Nonspecific counts, obtained from mock-transfected cells, were subtracted from the counts generated from each time point and the resulting values were graphed as a percentage of the “total counts”. Initial rates of intracellular accumulation were determined by linear regression and a paired t-test was used to determine statistical significance.

For the ^{125}I -ANP internalization assay, suspended cells were incubated with ^{125}I -ANP for 1 h at 4°C then washed with DMEM containing 0.5 % BSA before resuspension in DMEM containing 10% FBS. The assay was initiated by elevating the temperature of the cells to 37°C. After increasing periods of time, the cells were acid washed at 4°C to separate surface from internalized ^{125}I -ANP and intracellular radioactivity was plotted as a function of time at 37°C.

For the ^{125}I -transferrin internalization assay, cells were resuspended in 1 ml of a phosphate buffered saline solution containing 1 mM MgCl_2 , 1 mM CaCl_2 , 5 mM glucose, and 0.2% BSA. Suspended cells were incubated with ^{125}I -transferrin for 30 min at 4°C. Cells were then pelleted, washed in DMEM/BSA, and resuspended in DMEM containing 10% FBS. Fifty μ l aliquots were incubated in a 37°C water bath for the times indicated. All tubes except those designated “total counts” were washed with 0.2 M acetic acid and 0.5 M NaCl for 5 min at 4°C. The percentage of internalized counts was then determined as described above.

Whole cell cGMP elevation assays. The assays were performed as previously described (Dickey et al., 2009). Briefly, cells were plated on poly-D-lysine-coated 48-well plates and then incubated 4-12 h in serum-free media upon reaching 75-90% confluency. For the assay, the medium was aspirated and replaced with 0.15 ml DMEM containing 1 mM 1-methyl-3-isobutylxanthine (IBMX) and 25 mM Hepes

pH 7.4 for 10 min at 37°C. Following pretreatment, the medium was aspirated and cells were treated with DMEM containing 1 mM IBMX and 25 mM Hepes pH 7.4 with or without natriuretic peptide for 3 min. Treatment medium was then aspirated and the reaction was stopped with 0.2 ml ice-cold 80% ethanol. An aliquot of the resulting supernatant was dried in a centrifugal vacuum concentrator and analyzed for cGMP content by radioimmunoassay.

Whole cell ANP binding. Whole cell ^{125}I -ANP binding assays were performed as previously described (Dickey et al., 2009). Briefly, cells were added to 24-well plates precoated with poly-D-lysine. When 75-90% confluent, the cells were washed with DMEM and then incubated with DMEM containing 0.2% BSA at 37°C for 1-2 hours. Medium was aspirated and 0.2 ml of binding medium containing 75 pM ^{125}I -ANP and 1% BSA, alone or with increasing concentrations of unlabeled ligand was added to the cells. The plates were incubated at 4° C for 1 h before the binding medium was aspirated and the cells washed twice with 0.5 ml ice-cold PBS. The cells were solubilized in 0.5 ml of 1 N NaOH, transferred to glass tubes and bound radioactivity was measured in a Beckman 5500 gamma counter.

Crosslinking of ^{125}I -ANP-HeLa. Cells from three plates (10 cm) were resuspended in 3 ml Hank's buffered salt solution (HBSS) containing 10 mM HEPES, pH 7.4 and divided into 3 tubes. ^{125}I -ANP (0.28 nM) in the absence or presence of 1 μM unlabeled ANP or CNP was added for 2 hr at 4°C. 0.25 ml of a 2.17 mM solution of freshly prepared disuccinimidyl suberate (DSS) in HBSS was added to the cells at room temperature for 1 h for a final concentration of 0.5 mM to crosslink the bound radioligand. Cells were washed to remove unbound ligand and resuspended in 0.1 ml of 2X reducing SDS sample buffer. An aliquot was removed and lysed by passing through a 21-gauge needle 6-10 times. The cell extract was then fractionated by SDS-PAGE. The gel was dried and cross-linked proteins were visualized by autoradiography.

ANP-dependent downregulation- Cells on 10-cm plates were incubated with DMEM in the presence or absence of 200 nM ANP and 10 $\mu\text{g/ml}$ cycloheximide for the indicated times. The cells were washed at 4°C with phosphate buffered saline before preparation of crude membranes as previously

described (Dickey et al., 2009). For surface receptor measurements, cells were removed from the plate with PBS containing 5 mM EDTA and labeled with anti-FLAG/¹²⁵I-IgG as described for the internalization assay. Fifty microliters of labeled cells were then aliquoted into tubes and pelleted before counting in a gamma counter.

Guanylyl cyclase assays. Guanylyl cyclase assays were performed on crude membranes at 37°C for 5 min using ³²P-GTP as previously described (Dickey et al., 2009). Reactions were started by the addition of 0.080 μ l of the above reagents to 0.05 to 0.20 μ g of crude membrane protein suspended in 0.020 μ l of phosphatase inhibitor buffer (Bryan and Potter, 2002).

Quantification and Statistical Analysis. GraphPad Prism software was used for graphing and statistical analysis of the data. The specific statistical tests performed are indicated in the text and figure legends.

Results

Different ^{125}I -ANP Uptake Profiles For Mock and GC-A Transfected HeLa Cells. Since previous photoaffinity ^{125}I -ANP labeling studies indicated that HeLa cells express GC-A but not NPR-C (Watt and Yip, 1989), we investigated GC-A internalization in HeLa cells by measuring intracellular ^{125}I -ANP accumulation (Fig. 1). Intracellular radioactivity accumulated rapidly in control cells transfected with green fluorescent protein (GFP) and was maximal by 5 min. After 10 min, intracellular radioactivity had diminished and by 1 h intracellular radioactivity was less than half of maximum. In contrast, cellular uptake of ^{125}I -ANP was slower in cells transfected with FLAG-GC-A and did not decline with time. The slow internalization rate of FLAG-GC-A was not explained by differences in the ability of ANP to bind FLAG-GC-A versus wild type GC-A because similar EC_{50} and Kd values were obtained for each receptor (Fig. 1B and 1C).

NPR-C, Not GC-A, Is the Major ANP Receptor in HeLa Cells. Because the ^{125}I -ANP uptake curve in the GFP transfected cells was similar to that reported for NPR-C (Nussenzveig et al., 1990) and different from that observed in cells transfected with GC-A (Fig. 1A), we asked whether HeLa cells also express NPR-C. ^{125}I -ANP was chemically cross-linked to two independent HeLa cell lines. Reducing SDS-PAGE fractionated membranes from cross-linked cells and labeled receptors were visualized by autoradiography (Fig. 2). In both cell lines, the major ^{125}I -ANP binding protein migrated at the molecular weight of NPR-C (~60 kDa) in the absence of unlabeled natriuretic peptides. In the presence of saturating concentrations of cold ANP, no specific binding was observed, consistent with ANP blocking binding to both NPR-C and GC-A. Addition of excess unlabeled CNP reduced ^{125}I -ANP binding to NPR-C and increased binding to GC-A. These data indicate that HeLa cells express much higher concentrations of NPR-C than GC-A and that ^{125}I -ANP preferentially binds NPR-C, not GC-A. Thus, the vast majority of the internalization observed in the GFP-transfected HeLa cells in Fig. 1A was due to internalization of NPR-C, not GC-A.

Development of ^{125}I -IgG-based Intracellular Receptor Accumulation Assay. Because most cells, like HeLa cells, express higher concentrations of NPR-C than GC-A, acid-resistant ^{125}I -ANP uptake primarily measures NPR-C internalization. Therefore, we developed a new assay that measures the uptake of a single class of receptors in the presence or absence of ligand. HeLa cells were transfected with plasmids expressing extracellular, amino-terminal FLAG-tagged versions of GC-A or NPR-C. Transfected cells were successively incubated with mouse anti-FLAG M2 and ^{125}I -conjugated anti-mouse IgG antibodies at 4°C to radioactively label surface receptors. Elevating the temperature of the cells to 37°C initiated the internalization assay and acid washing at 4°C separated internalized receptors from surface receptors.

With this technique, ^{125}I -IgG binding was dependent on expression of FLAG-GC-A as total counts were more than ten-fold higher in cells transfected with FLAG-GC-A compared to cells transfected with GFP (Fig. 3A). Binding was specific to the extracellular FLAG epitope because acid stripping removed the vast majority of bound counts and inclusion of the FLAG peptide in the medium reduced total counts from $10,525 \text{ cpm} \pm 1,576$ to $715 \text{ cpm} \pm 39$ (data not shown). Various primary and secondary antibody concentrations were tested to optimize the assay. The final conditions chosen (labeled as 1X in Fig. 3A) gave the highest signal to noise ratio while using the least amount of ^{125}I -IgG. These conditions do not saturate all secondary-binding sites because this would have been cost prohibitive.

To rule out the possibility that receptor overexpression artificially reduced the rate or magnitude of FLAG-GC-A internalization, 293 cells were transfected with increasing amounts of FLAG-GC-A plasmid and receptor uptake rates were measured. Western blot analysis indicated that FLAG-GC-A expression increased in proportion to the level of the transfected DNA. However, neither the rate nor magnitude of FLAG-GC-A internalization was reduced in cells expressing higher levels of receptor (Fig. 3B). Thus, at all conditions tested, the same ratio of internalized to surface receptors was observed, which indicates that the ^{125}I -IgG uptake assay accurately measured the fate of the average cell surface receptor.

FLAG-GC-A Is Slowly Internalized in HeLa Cells. ^{125}I -ANP uptake was much faster than ^{125}I -IgG uptake in FLAG-GC-A transfected tTA-HeLa cells, which is consistent with NPR-C, not GC-A, mediating the majority of the ^{125}I -ANP internalization in these cells (Fig. 4A). ^{125}I -IgG uptake indicated that basal FLAG-GC-A internalization was linear for 10-20 min with approximately 4% of the surface receptors being internalized during this period of time (Fig. 4B). Multiple experiments determined that the initial internalization rate was slow ($0.2\%/min \pm 0.006$, $N = 4$). Maximum receptor accumulation was achieved between 10 and 20 min. Inclusion of $1 \mu\text{M}$ ANP in the assay had no effect on initial internalization rates but increased accumulation after 1 h by 1.6-fold. To verify that the basal clathrin-dependent internalization pathway in these cells was functional, ^{125}I -transferrin uptake was measured and found to be robust, rapid and saturable (Fig. 4C).

GC-A Internalization Is Rapid and ANP-Independent in 293 Cells. To measure internalization in cells where GC-A is the only measurable ^{125}I -ANP binding protein, FLAG-GC-A was stably expressed in 293 cells that do not endogenously express detectable levels of GC-A or NPR-C (Potter and Hunter, 1999). In contrast to the HeLa cells, the uptake curves for ^{125}I -ANP and ^{125}I -IgG were virtually indistinguishable in 293 cells (Fig. 5A). Internalization was clearly mediated by GC-A because cells lacking FLAG-GC-A failed to accumulate ^{125}I -ANP or ^{125}I -IgG (Fig. 5B and C, untransfected). Thus, ^{125}I -IgG uptake faithfully mirrors ^{125}I -ANP internalization in these cells. Surprisingly, basal FLAG-GC-A internalization was eight-fold higher and more robust in the 293 cells compared to the HeLa cells. Eighteen percent of the total cell surface receptor population was internalized by 3 minutes at a rate of $4.9 \%/min \pm 0.27$. As in the HeLa cells, ANP did not increase the initial rate of FLAG-GC-A internalization in the 293 cells, and unlike the HeLa cells, had no effect on accumulation after 1 h (Fig. 5C).

NPR-C Internalization Is Rapid and Ligand-Independent in HeLa and 293 Cells. NPR-C internalization was also examined using the antibody-based assay. ^{125}I -IgG was internalized at an initial

rate of $2.4\%/min \pm 0.01$ in tTA-HeLa cells transfected with FLAG-NPR-C (Fig. 6A), which is similar to the rate of internalization of ^{125}I -ANP in GFP transfected cells (Fig. 1A). In 293 cells transiently transfected with FLAG-NPR-C, receptor and initial ligand uptake were coincident with time. After 1 min, the rate of ^{125}I -ANP and ^{125}I -IgG accumulation were $18.8\%/min \pm 0.09$ and $19.7\%/min \pm 0.11$, respectively, and the percentage of surface receptor internalized as measured by ^{125}I -IgG was increased to 25 to 40% depending on the assay (Fig. 6B). Neither ANP, BNP nor CNP increased NPR-C internalization as measured by ^{125}I -IgG uptake (Fig. 6C). Thus, the internalization of GC-A and NPR-C is ligand-independent.

GC-A Downregulation Does Not Require Increased Internalization. We recently reported that GC-A is downregulated in HeLa cells (Flora and Potter, 2010), but those experiments measured total receptor levels in cell lysates. To specifically measure surface levels of receptor, HeLa cells were transiently transfected with FLAG-GC-A and then incubated in the presence or absence of ANP for 8 h prior to labeling with anti-FLAG/ ^{125}I -IgG to measure surface receptor concentrations. Total counts (representing surface labeled receptors) were reduced by 53% in cells exposed to ANP (data not shown), which is consistent with previous studies showing that 8 h ANP exposure reduced total cellular GC-A concentrations by nearly 60% in HeLa cells (Flora and Potter, 2010).

We also examined the downregulation of FLAG-GCA in stably expressing 293 cells. 293PMA-FLAG-GCA cells were incubated at 37°C with ANP for 0, 2, 4 and 8 h to stimulate GC-A downregulation (Fig. 7). In one experiment, crude membranes were prepared and assayed for detergent-dependent guanylyl cyclase activity to measure the effect of prior ANP exposure on total cellular receptor concentrations. In a separate experiment, ^{125}I -IgG binding was used to specifically measure receptors at the cell surface. Prior ANP exposure significantly reduced both activities after 4 and 8 hours of exposure, and the reductions in surface and total receptors were temporally correlated. These data indicate that GC-A downregulation does not require increased receptor internalization, since ANP clearly stimulates downregulation but not

internalization in 293 cells. Furthermore, it indicates that either the vast majority of receptors are at the cell surface or that intracellular and extracellular pools of receptor rapidly exchange.

Discussion

In this report, an antibody-based trafficking assay was developed that allowed the independent evaluation of GC-A and NPR-C internalization for the first time. The validity of the ^{125}I -IgG assay was established by demonstrating identical uptake rates for ^{125}I -IgG and ^{125}I -ANP in cells expressing a single ANP-binding receptor. All previous uptake studies followed receptors with ^{125}I -ANP, which clearly measures NPR-C, not GC-A, trafficking in HeLa cells. A major advantage of the ^{125}I -IgG assay is that it measures a single receptor class without complicating contributions from related receptors. Another advantage is that it measures internalization rates of unbound receptors (basal rates), which was not possible using the ^{125}I -ANP binding approach. Although we demonstrated that ^{125}I -ANP binding accurately measured GC-A and NPR-C uptake in transfected 293 cells, ^{125}I -ANP binding is unlikely to accurately measure GC-A uptake in biologic systems because most, if not all, cells express higher levels of NPR-C than GC-A. Leitman and colleagues studied eight cell lines and found that cells expressing GC-A also express higher concentrations of NPR-C (Leitman et al., 1986). In contrast, Watt and Yip reported that HeLa cells only express GC-A (Watt and Yip, 1989). However, our ^{125}I -ANP chemical cross-linking studies indicated that NPR-C, not GC-A, is the major ANP receptor in the two HeLa cell lines that we examined. We suggest that past and future ^{125}I -ANP uptake studies should be carefully interpreted so that NPR-C uptake is not erroneously ascribed to GC-A.

Another clear conclusion from these studies is that cellular environment is a major determinant of receptor uptake. In HeLa cells, GC-A internalization was very slow, whereas in 293 cells internalization was eight times faster for both GC-A and NPR-C. The rapid internalization of ^{125}I -ANP and ^{125}I -transferrin indicated that the meager FLAG-GC-A uptake in the HeLa cells was not due to a global internalization defect caused by transfection but was due to a difference in the GC-A internalization machinery. Likewise, the similar internalization rates of GC-A and NPR-C with either ^{125}I -ANP or the FLAG-based assay in the 293 cells suggest that the slow FLAG-GC-A internalization rate was not an

artifact of the FLAG-tagged receptor and is representative of GC-A uptake in these cells. Additionally, similar uptake rates in cells expressing various levels of receptors suggest that FLAG-GC-A uptake is representative of the internalization of endogenous GC-A.

Another conclusion that can be drawn from these studies is that FLAG-NPR-C internalization was several times faster than GC-A internalization regardless of cell line, which is consistent with unique trafficking pathways mediating uptake of each receptor. Future work will focus on the identification of these pathways. Surprisingly, ANP did not increase the internalization of either receptor in either cell line, although it did increase total GC-A uptake at later times in the HeLa cells. The fact that ANP increased uptake at later but not earlier time points is consistent with inhibition of recycling, not increased internalization and is inconsistent with ANP binding increasing the ability of GC-A or NPR-C to attach to cellular transport systems as occurs for other receptors.

As described in the introduction, many previous investigators have studied the trafficking of GC-A and/or NPR-C. However, an important question pertaining to all previous studies is which receptor is being measured. Our data suggest that previous internalization studies conducted on cells expressing both GC-A and NPR-C, most likely measured NPR-C uptake. Nonetheless, regarding the debate over whether GC-A internalizes ^{125}I -ANP, it clearly does in the two cell lines that we tested. We do not know why our data differ from a previous study showing that intracellular ^{125}I -ANP radioactivity decreased rapidly in 293 cells transfected with GC-A (Pandey et al., 2002), but perhaps it is a function of the unique trafficking properties of the individual cell lines.

Downregulation proceeds by three sequential processes: receptor internalization, endosomal sorting, and receptor proteolysis (Katzmann et al., 2002). Downregulation of canonical G-protein coupled or tyrosine kinase receptors is associated with receptor internalization rates that are increased several fold in response to ligand binding (Vieira et al., 1996). However, since GC-A or NPR-C initial internalization rates were

unchanged in the presence of ligand, we can conclude that increased uptake rates do not contribute to GC-
A downregulation in 293 cells. Furthermore, the similar loss of total and surface receptors indicates the
intracellular and extracellular pools of receptor are closely linked and rapidly exchange.

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Authorship Contribution

Participated in research design: Dickey, Flora, and Potter.

Conducted experiments: Dickey and Flora.

Performed data analysis: Dickey and Flora.

Wrote or contributed to the writing of the manuscript: Dickey, Flora, and Potter.

Other: Flora and Potter acquired funding for the research.

References

- Abe T, Arakawa Y, Rajasekaran AK, Yu TH and Wada O (1995) Interaction of atrial natriuretic peptide with its receptors in bovine lung membranes. *J Biol Chem* **270**(13):7672-7678.
- Bryan PM and Potter LR (2002) The atrial natriuretic peptide receptor (NPR-A/GC-A) is dephosphorylated by distinct microcystin-sensitive and magnesium-dependent protein phosphatases. *J Biol Chem* **277**(18):16041-16047.
- Bryan PM, Xu X, Dickey DM, Chen Y and Potter LR (2007) Renal hyporesponsiveness to atrial natriuretic peptide in congestive heart failure results from reduced atrial natriuretic peptide receptor concentrations. *Am J Physiol Renal Physiol* **292**(5):F1636-1644.
- Dickey DM, Flora DR, Bryan PM, Xu X, Chen Y and Potter LR (2007) Differential regulation of membrane guanylyl cyclases in congestive heart failure: natriuretic peptide receptor (NPR)-B, Not NPR-A, is the predominant natriuretic peptide receptor in the failing heart. *Endocrinology* **148**(7):3518-3522.
- Dickey DM, Yoder AR and Potter LR (2009) A familial mutation renders atrial natriuretic Peptide resistant to proteolytic degradation. *J Biol Chem* **284**(29):19196-19202.
- Fan D, Bryan PM, Antos LK, Potthast RJ and Potter LR (2005) Down-Regulation Does Not Mediate Natriuretic Peptide-Dependent Desensitization of Natriuretic Peptide Receptor (NPR)-A or NPR-B: Guanylyl Cyclase-Linked Natriuretic Peptide Receptors Do Not Internalize. *Mol Pharmacol* **67**(1):174-183.
- Flora DR and Potter LR (2010) Prolonged atrial natriuretic peptide exposure stimulates guanylyl cyclase-A degradation. *Endocrinology* **151**(6):2769-2776.
- Jaubert J, Jaubert F, Martin N, Washburn LL, Lee BK, Eicher EM and Guenet JL (1999) Three new allelic mouse mutations that cause skeletal overgrowth involve the natriuretic peptide receptor C gene (Npr3). *Proc Natl Acad Sci U S A* **96**(18):10278-10283.

- Katzmann DJ, Odorizzi G and Emr SD (2002) Receptor downregulation and multivesicular-body sorting. *Nat Rev Mol Cell Biol* **3**(12):893-905.
- Koh GY, Nussenzveig DR, Okolicany J, Price DA and Maack T (1992) Dynamics of atrial natriuretic factor-guanylate cyclase receptors and receptor-ligand complexes in cultured glomerular mesangial and renomedullary interstitial cells. *J Biol Chem* **267**(17):11987-11994.
- Leitman DC, Andresen JW, Kuno T, Kamisaki Y, Chang JK and Murad F (1986) Identification of multiple binding sites for atrial natriuretic factor by affinity cross-linking in cultured endothelial cells. *J Biol Chem* **261**(25):11650-11655.
- Lopez MJ, Wong SK, Kishimoto I, Dubois S, Mach V, Friesen J, Garbers DL and Beuve A (1995) Salt-resistant hypertension in mice lacking the guanylyl cyclase-A receptor for atrial natriuretic peptide. *Nature* **378**(6552):65-68.
- Matsukawa N, Grzesik WJ, Takahashi N, Pandey KN, Pang S, Yamauchi M and Smithies O (1999) The natriuretic peptide clearance receptor locally modulates the physiological effects of the natriuretic peptide system. *Proc Natl Acad Sci U S A* **96**(13):7403-7408.
- Nussenzveig DR, Lewicki JA and Maack T (1990) Cellular mechanisms of the clearance function of type C receptors of atrial natriuretic factor. *J Biol Chem* **265**(34):20952-20958.
- Oliver PM, Fox JE, Kim R, Rockman HA, Kim HS, Reddick RL, Pandey KN, Milgram SL, Smithies O and Maeda N (1997) Hypertension, cardiac hypertrophy, and sudden death in mice lacking natriuretic peptide receptor A. *Proc Natl Acad Sci U S A* **94**(26):14730-14735.

- Pandey KN (1992) Kinetic analysis of internalization, recycling and redistribution of atrial natriuretic factor-receptor complex in cultured vascular smooth-muscle cells. Ligand-dependent receptor down-regulation. *Biochem J* **288**(Pt 1):55-61.
- Pandey KN (2001) Dynamics of internalization and sequestration of guanylyl cyclase/atrial natriuretic peptide receptor-A. *Can J Physiol Pharmacol* **79**(8):631-639.
- Pandey KN, Nguyen HT, Sharma GD, Shi SJ and Kriegel AM (2002) Ligand-regulated internalization, trafficking, and down-regulation of guanylyl cyclase/atrial natriuretic peptide receptor-A in human embryonic kidney 293 cells. *J Biol Chem* **277**(7):4618-4627.
- Potter LR (2011) Regulation and therapeutic targeting of peptide-activated receptor guanylyl cyclases. *Pharmacology & therapeutics* **130**(1):71-82.
- Potter LR and Hunter T (1999) A constitutively "Phosphorylated" guanylyl cyclase-linked atrial natriuretic peptide receptor mutant is resistant to desensitization. *Mol Biol Cell* **10**(6):1811-1820.
- Potter LR, Yoder AR, Flora DR, Antos LK and Dickey DM (2009) Natriuretic peptides: their structures, receptors, physiologic functions and therapeutic applications. *Handb Exp Pharmacol*(191):341-366.
- Potthast R, Abbey-Hosch SE, Antos LK, Marchant JS, Kuhn M and Potter LR (2004) Calcium-dependent Dephosphorylation Mediates the Hyperosmotic and Lysophosphatidic Acid-dependent Inhibition of Natriuretic Peptide Receptor-B/Guanylyl Cyclase-B. *J Biol Chem* **279**(47):48513-48519.
- Rathinavelu A and Isom GE (1991) Differential internalization and processing of atrial-natriuretic-factor B and C receptor in PC12 cells. *Biochem J* **276**(Pt 2):493-497.

- Sever S, Damke H and Schmid SL (2000) Dynamin:GTP controls the formation of constricted coated pits, the rate limiting step in clathrin-mediated endocytosis. *J Cell Biol* **150**(5):1137-1148.
- Vieira AV, Lamaze C and Schmid SL (1996) Control of EGF receptor signaling by clathrin-mediated endocytosis. *Science* **274**(5295):2086-2089.
- Vieira MA, Gao M, Nikonova LN and Maack T (2001) Molecular and cellular physiology of the dissociation of atrial natriuretic peptide from guanylyl cyclase a receptors. *J Biol Chem* **276**(39):36438-36445.
- Watt VM and Yip CC (1989) HeLa cells contain the atrial natriuretic peptide receptor with guanylate cyclase activity. *Biochem Biophys Res Commun* **164**(2):671-677.

Footnotes

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Legends for figures

Fig 1. (A) ^{125}I -ANP uptake in tTA-HeLa cells transiently transfected with GFP or FLAG-GC-A. Cells were labeled with subsaturating concentrations of ^{125}I -ANP at 4°C. Aliquots of labeled cells were incubated at 37°C for the times indicated before acid washing and counting. Values represent average \pm the range of the determinations where N = 2. The graph is representative of multiple experiments. (B) FLAG-GC-A and wild type GC-A bind and are activated by ANP similarly. 293 cells were transiently transfected with wild-type GC-A or FLAG-GC-A and incubated with increasing concentrations of ANP for 1 min. Cellular cGMP concentrations were measured and plotted as a function of peptide concentration. The data points represent the mean \pm the SEM assayed in triplicate. (C) FLAG-GC-A has similar affinity for ANP as wild-type GC-A. Transiently transfected 293 cells were incubated for 1 hr at 4°C with ^{125}I -ANP in the presence or absence of increasing concentrations of unlabeled ligand. Specifically bound ^{125}I -ANP was plotted as a function of competing peptide concentration. The data points represent the mean \pm the SEM assayed in triplicate.

Fig 2. HeLa cells endogenously express high and low levels of NPR-C and GC-A, respectively. HeLa and tTA-HeLa cells were incubated with ^{125}I -ANP in the absence or presence of 1 μM ANP or CNP for 2 hr at 4°C before cross-linking ^{125}I -ANP to the receptors with disuccinimidyl suberate. Membrane fractions were separated by SDS-PAGE and ^{125}I -ANP-receptor complexes were visualized by autoradiography.

Fig 3. The ^{125}I -IgG uptake assay specifically measures FLAG-GC-A internalization. (A) tTA-Hela cells were transiently transfected with GFP or FLAG-GCA. The cells were dispensed into tubes and incubated with 0.05 μl (1X primary) or 0.1 μl (20X primary) anti-FLAG-M2 antibody. Excess antibody was removed before addition of 5 (1X), 50 (10X secondary) or 100 μl ^{125}I -IgG. Cellular radioactivity was measured directly or after acid stripping to remove surface ^{125}I -IgG. Values represent the range of

determinations where $N = 2$. The graph is representative of more than 3 experiments. (B) 293 cells were transiently transfected with 10 μg (1x), 1 μg or 5 μg of FLAG-GC-A plasmid DNA. Internalization assays were performed 48 h later. An equal number of cells from each transfection were separated by SDS-PAGE, blotted to an Immobilon membrane and GC-A expression was detected by Western blot using an anti-GC-A antibody (inset). Values represent average \pm SEM where $N = 6$.

Fig 4. GC-A is slowly internalized in HeLa cells. (A) tTA-HeLa cells transiently transfected with FLAG-GC-A were labeled with ^{125}I -ANP or anti-FLAG-M2 antibody followed by ^{125}I -anti-mouse-IgG at 4°C . Values represent average \pm SEM where $N = 4$ (B) ANP increases GC-A uptake at longer but not shorter periods of time. Cells transfected with FLAG-GC-A were labeled with anti-FLAG-M2 antibody and ^{125}I -anti-mouse-IgG before incubation at 37°C in the absence or presence of 1 μM ANP for the periods of time shown. Samples were then acid-washed and counted. Values represent average \pm SEM where $N = 6$ (C) ^{125}I -transferrin is rapidly internalized in tTA-HeLa cells. Aliquots of the tTA-HeLa cells transfected with FLAG-GC-A were labeled with ^{125}I -transferrin at 4°C . Internalized ^{125}I -transferrin was determined after the indicated periods of time at 37°C . Values represent the average \pm SEM where $N = 8$.

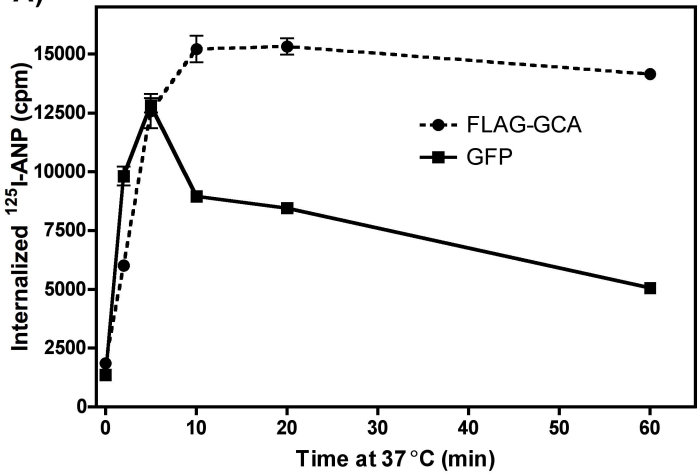
Fig 5. GC-A is rapidly internalized in 293 PMA cells. (A) 293 cells stably expressing FLAG-GC-A were incubated at 4°C with either ^{125}I -ANP or anti-FLAG antibody followed by ^{125}I -anti-mouse IgG. Cells were incubated at 37°C for the indicated times before acid-washing and counting. Values represent average \pm SEM where $N = 14$ (B) Untransfected 293 cells or 293 cells stably expressing FLAG-GC-A were labeled at 4°C with ^{125}I -ANP. Internalized radioactivity as a function of time at 37°C is shown. Values represent average \pm the range of two determinations (C) Untransfected or 293 cells stably expressing FLAG-GC-A were labeled at 4°C with anti-FLAG antibody followed by ^{125}I -IgG secondary antibody. The cells were incubated at 37°C in the presence or absence of 1 μM ANP for the indicated periods of time. Values represent the average \pm the range determinations where $N = 2$.

Fig 6. NPR-C is rapidly and constitutively internalized in HeLa and 293 cells. (A) tTA-HeLa cells were transiently transfected with FLAG-NPR-C. Cells were then labeled with anti-FLAG antibody followed by ^{125}I -anti-mouse-IgG at 4°C. Cells were incubated at 37°C for the indicated times before acid washing. Values represent the average \pm SEM where N = 14. (B) 293 cells were transfected with FLAG-NPR-C and labeled with either ^{125}I -ANP or ^{125}I -IgG at 4°C. Aliquots were incubated at 37°C for the times shown and before acid washing. Values represent the average \pm SEM where N = 6 (C) 293 cells transiently transfected with FLAG-NPR-C were labeled with anti-FLAG antibody and ^{125}I -IgG secondary antibody at 4°C. Aliquots were incubated at 37°C in the presence or absence of 1 μM ANP, BNP or CNP for the times indicated where N = 4.

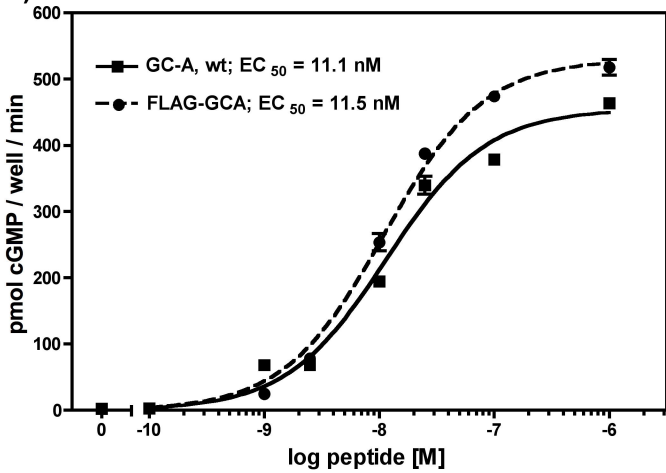
Fig 7. Concomitant downregulation of extracellular and intracellular FLAG-GC-A in 293 cells. 293 cells stably expressing FLAG-GC-A were incubated with 10 $\mu\text{g}/\text{ml}$ cycloheximide in the absence or presence of 200 nM ANP for the period of times indicated. In one experiment, crude membranes were prepared and then assayed for guanylyl cyclase activity in the presence of 1 % Triton X-100 and Mn^{2+} GTP. In a second experiment, cells were incubated with ANP as described above and then labeled with anti-FLAG antibody followed by ^{125}I -IgG at 4°C. Total ^{125}I -IgG radioactivity and guanylyl cyclase activities were normalized to activities obtained from cells not incubated with ANP (control) and plotted as a function of time of ANP exposure.

Figure 1

A)



B)



C)

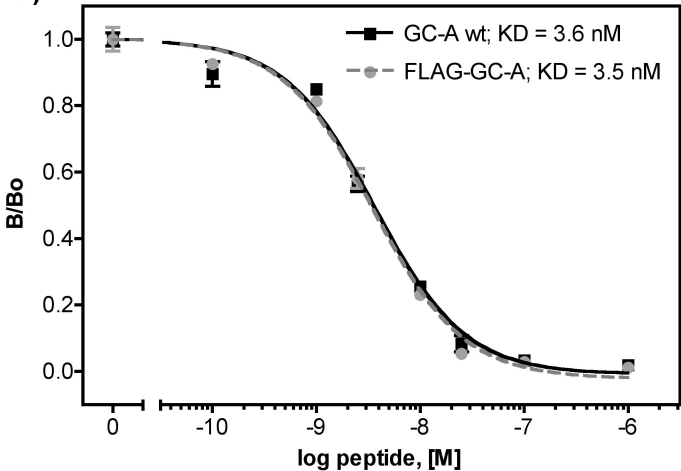


Figure 2

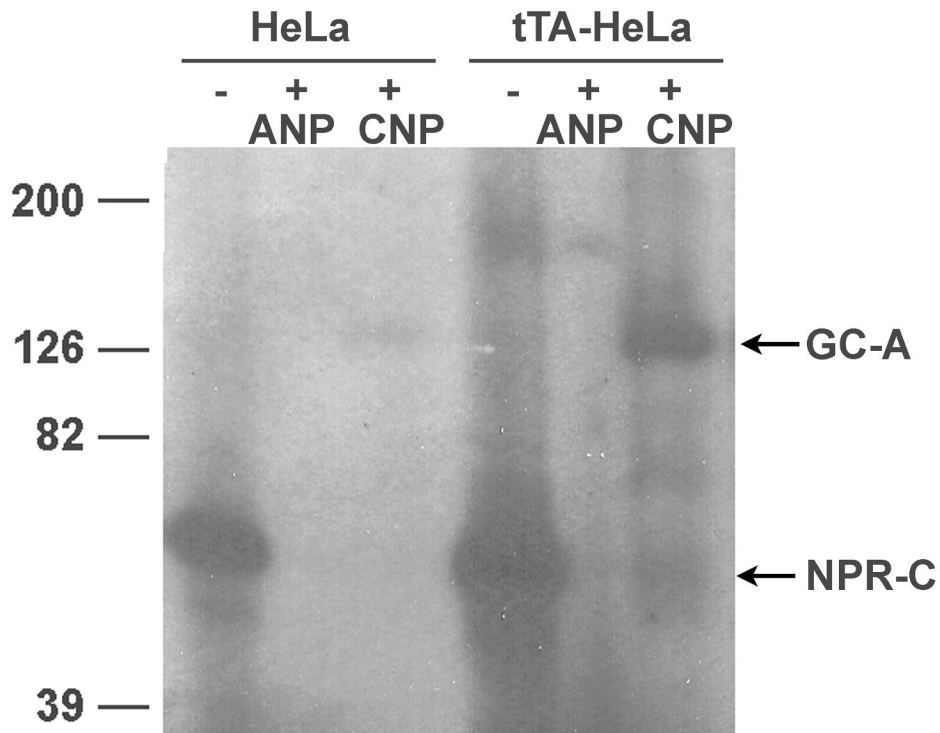
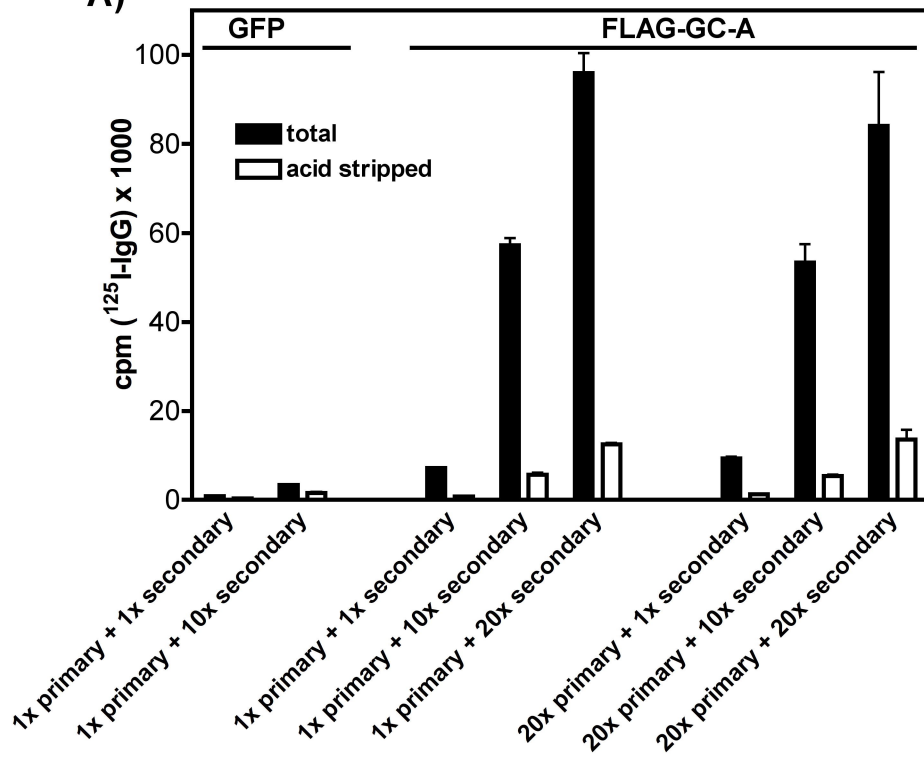


Figure 3

A)



B)

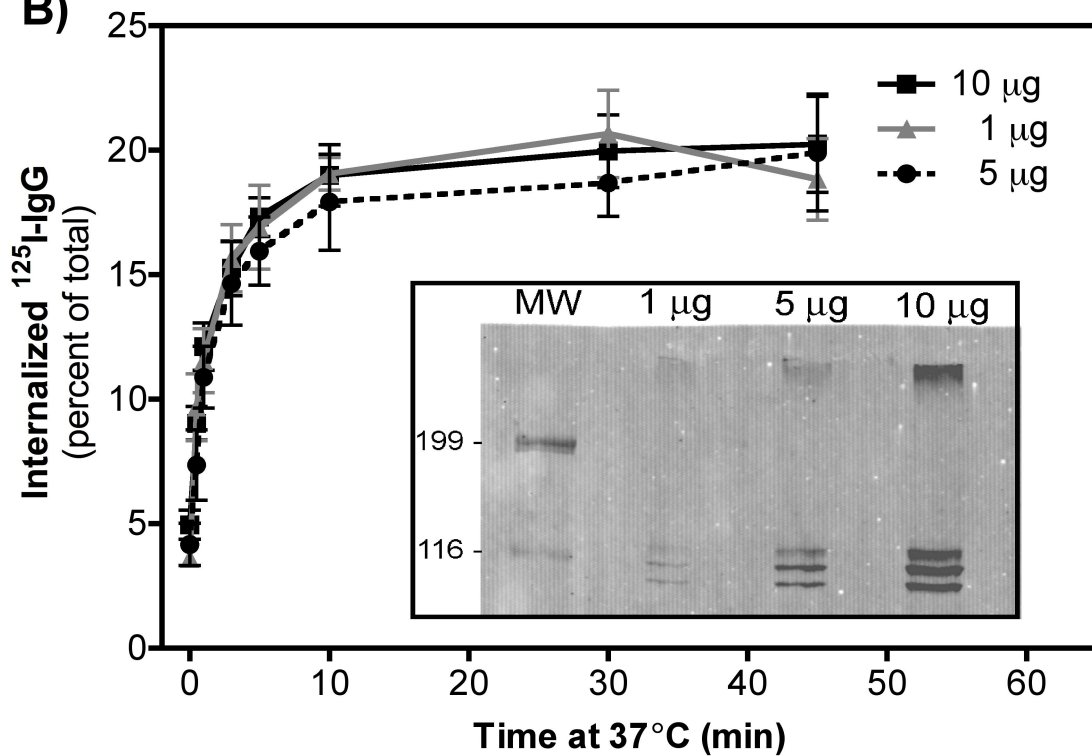
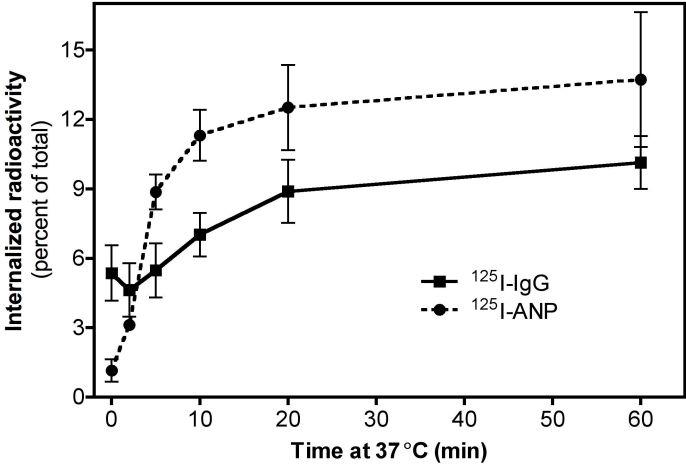
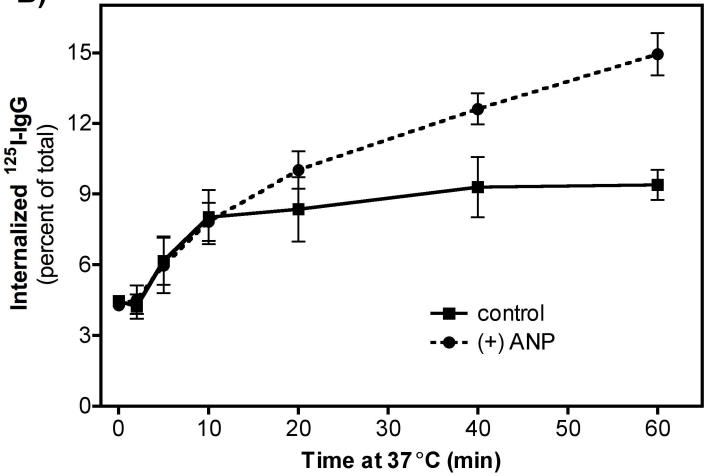


Figure 4

A)



B)



C)

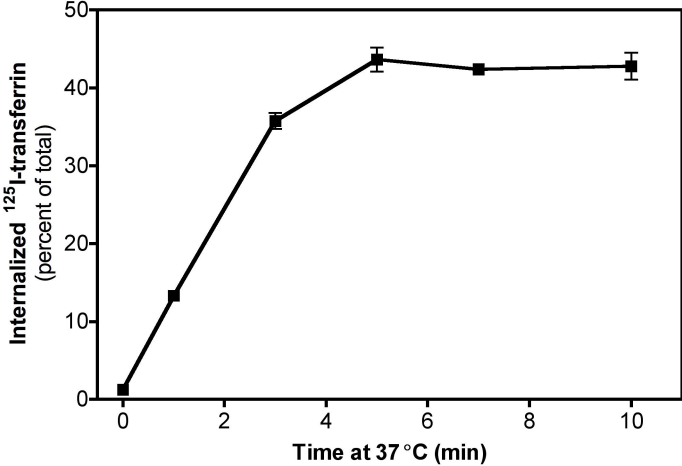


Figure 5

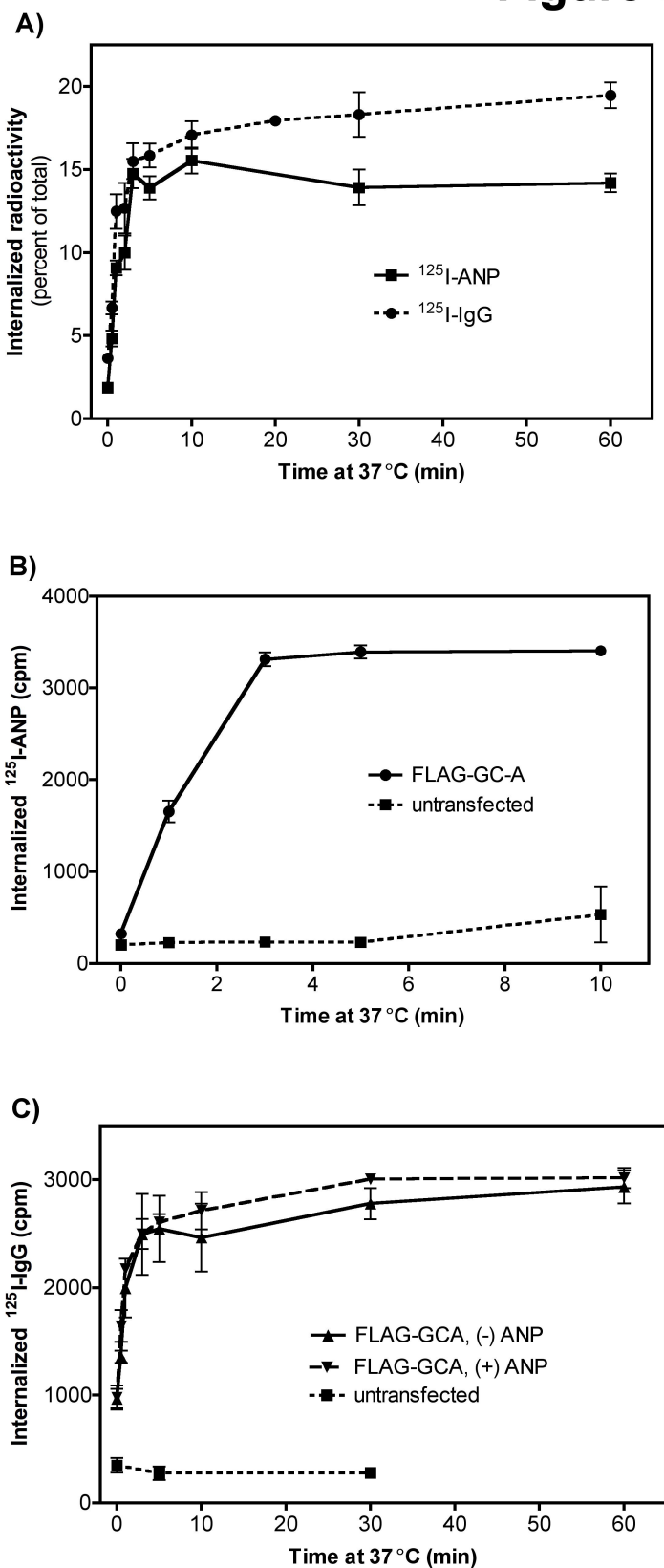
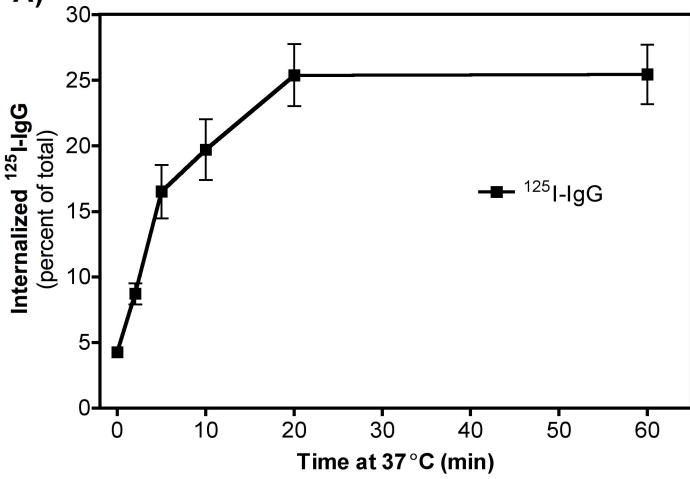
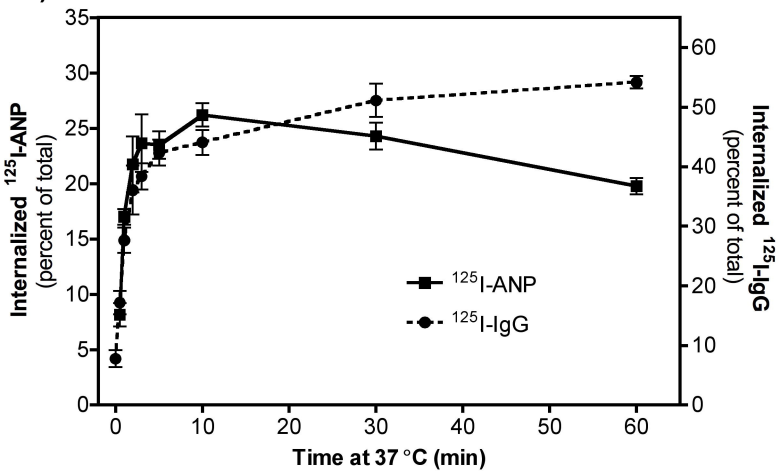


Figure 6

A)



B)



C)

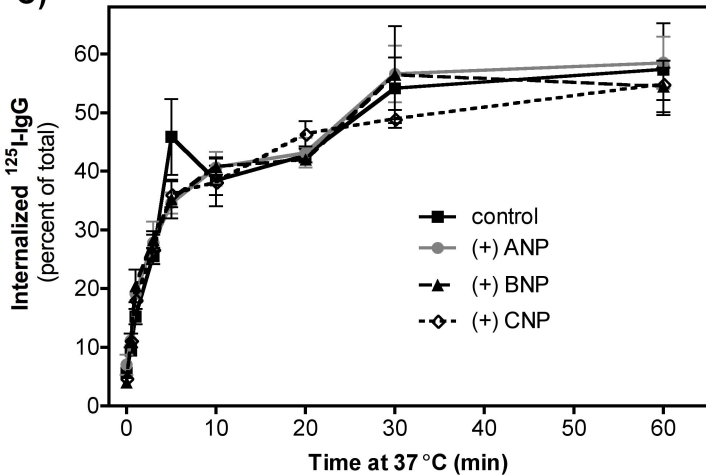
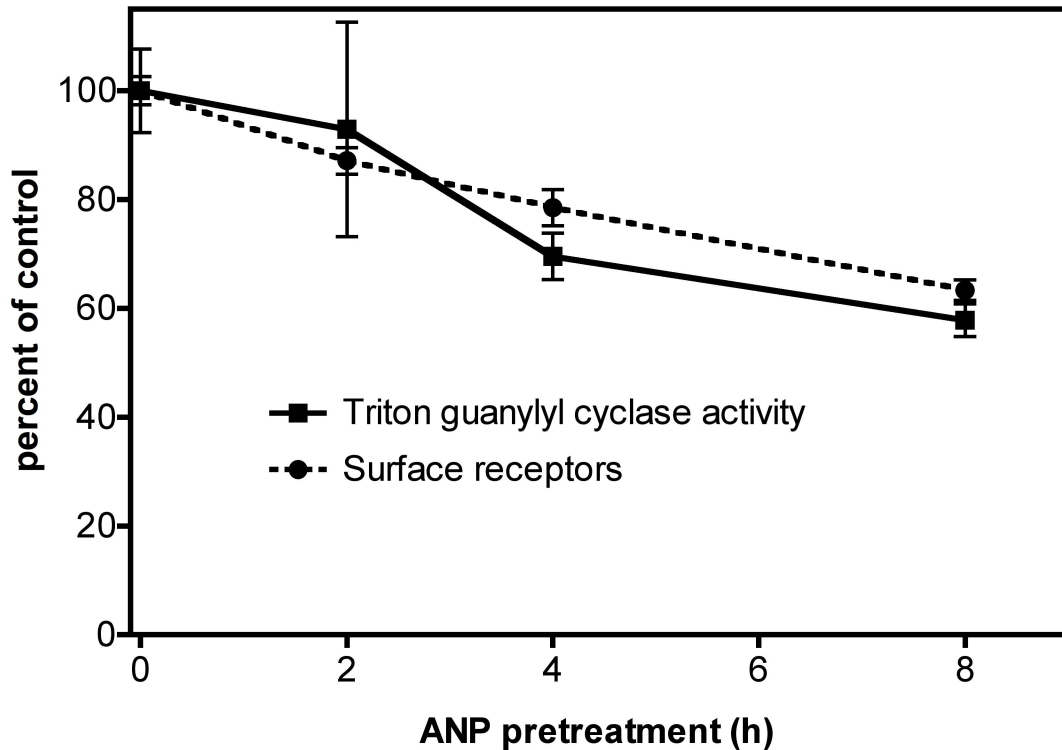


Figure 7



Correction to “Antibody Tracking Demonstrates Cell Type-Specific and Ligand-Independent Internalization of Guanylyl Cyclase A and Natriuretic Peptide Receptor C”

In the above article [Dickey DM, Flora DR, and Potter LR (2011) *Mol Pharmacol* 80: 155–162 DOI: 10.1124/mol.110.070573], the following funding information was omitted:

This article was supported by funding from the National Institutes of Health (Grant R21 HL093402).

The authors regret this error and any inconvenience it may have caused.