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Martin Eiblmaier
Washington University School of Medicine in St. Louis

Laura A. Meyer
Washington University School of Medicine in St. Louis

Carolyn J. Anderson
Washington University School of Medicine in St. Louis

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Research Paper

The role of p53 in the trafficking of copper-64 to tumor cell nuclei

Martin Eiblmaier, Laura A. Meyer and Carolyn J. Anderson*

Mallinckrodt Institute of Radiology; Washington University School of Medicine; Saint Louis, Missouri USA

Abbreviations: BSA, bovine serum albumin; CB-TE2A, 4,11-bis(carboxymethyl)-1,4,8,11-tetraazabicyclo[6,6,2]hexadecane; DOTA, 1,4,7,10-tetraazacyclododecane-1,4,7,10-tetraacetic acid; DTPA, diethylenetriaminepentaacetic acid; EDTA, ethylene diamine tetraacetic acid; EGFR, epidermal growth factor receptor; FITC, fluorescein isothiocyanate; mAb, monoclonal antibody; PET, positron emission tomography; SPECT, single photon emitted computed tomography; SSTr2, somatostatin receptor subtype 2; TETA, 1,4,8,11-tetraazacyclotetradecane-1,4,8,11-tetraacetic acid; TLC, thin-layer chromatography; Y3-TATE, tyrosine-3 octreotate; WT, wild type

Key words: copper-64, nuclear localization, targeted radiotherapy, tumor cell nuclei, p53, copper chaperone

Copper-64 (T1/2 = 12.7 h; β1: 17.8%, β2: 41%) has applications in both positron emission tomography (PET) imaging and targeted radiotherapy of cancer. Copper-64 radiopharmaceuticals have shown tumor growth inhibition with a relatively low radiation dose in animal models; however, the mechanism of cytotoxicity has not been fully elucidated. Here, we report an investigation on the potential role of the tumor suppressor protein p53 in trafficking of Cu to tumor cell nuclei. Two EGFR expressing human colorectal cell lines (HCT 116 +/+ and HCT 116 −/−) that are positive or negative for p53 expression respectively, were used to compare internalization and nuclear localization of [64Cu]copper acetate and of [64Cu]-DOTA-cetuximab, a monoclonal anti-EGFR antibody. [64Cu]copper acetate uptake into cells was similar between the two cell lines during a 24 h time course. In contrast, the uptake of [64Cu]copper acetate in the nuclei of HCT 116 +/+ cells was significantly higher than in HCT 116 −/− cells (p < 0.0001) at 24 h. There was no difference in receptor binding, receptor-mediated internalization, and efflux of [64Cu]-DOTA-cetuximab between the two HCT 116 cells lines. However, nuclear localization of [64Cu]-DOTA-cetuximab showed increased uptake in the nuclei of HCT 116 +/+ cells as early as 4 h. These data demonstrate that [64Cu]Cu is delivered to tumor cell nuclei in a p53 positive cell line in significantly greater amounts than in p53 negative cells by both non-specific and receptor-mediated uptake mechanisms.

Introduction

There has been increasing interest in the use of copper radiopharmaceuticals for PET imaging and/or targeted radiotherapy of cancer. Copper-64 (T1/2 = 12.7 h; β1: 0.655 MeV; 17.8%; β2: 0.573 MeV; 41%) emits both β+ and β- radiation for PET and therapy applications, while 67Cu (T1/2 = 62 h; 100% β: 0.576 MeV max) is a β+ emitter that has shown success in radioimmunotherapy of non-Hodgkin’s lymphoma in tumor-bearing mice1-3 and in humans.5,5 We previously observed that 64Cu-labeled tumor-targeting agents showed enhanced therapeutic efficacy of an internalizing 64Cu-labeled anti-colorectal carcinoma mAb, 64Cu-labeled 1A3, in a tumor-bearing hamster model compared to 90Y- or 131I-labeled mAbs in the same animal model.6,7 We also evaluated the 64Cu-labeled somatostatin analogs octreotide and Y3-TATE as therapeutic agents, and although we did not observe complete tumor remissions, we did see tumor growth inhibition at relatively low radiation doses to the tumors (465-600 cGy).8,9

Particularly in the area of receptor-targeted therapy agents,10,11 the intracellular fate of the radiopharmaceuticals following binding to cell surface receptors has been a topic of interest.12,13 It was previously demonstrated that 111In from 111In-DTPA-octreotide (Octreoscan®), an imaging agent clinically approved for somatostatin receptor positive tumors in the United States and Europe, showed uptake in tumor cell nuclei.12 This suggests a possible mechanism for the therapeutic efficacy of this Auger electron-emitting radiopharmaceutical. We demonstrated that 64Cu from 64Cu-TETA-octreotide was significantly localized in the nuclei of AR42J rat pancreatic tumor cells in cell culture, whereas 111In from 111In-DTPA-octreotide was localized to tumor cell nuclei in much smaller amounts.14 Although 64Cu only emits 2 Auger electrons per decay, it has been reported that the recoil energy from the transmutation of this radionuclide in the vicinity of DNA can cause lethal damage to the cell.15 These data suggested that delivery of 64Cu to the cell nuclei may enhance the therapeutic effect of beta-emitting, tumor targeting copper radiopharmaceuticals.

Because copper can readily form oxygen radicals, free copper essentially does not exist in vivo.16 Several copper chaperones have been identified that transport copper to various organelles in mammalian cells (for a review on this subject, see ref. 17). Copper is transported into the cell via hCtr1 (human copper transporter). Several copper chaperones serve to traffic copper between cellular compartments. Cox17 carries copper to the mitochondria for incorporation into...
cytochrome c. Copper can also be incorporated into nascent Cu/Zn SOD via the copper chaperone CCS. The Wilson disease P-type ATPase receives copper from HAH1 in the trans-golgi-network, where copper binds to ceruloplasmin during synthesis. Metallothionein is thought to play a role as a copper storage pool within the cell. 18 To date, no chaperones have been identified that traffic copper to the cell nucleus. There are proteins common in tumors and other tissues that may play a role in the transport of copper to the nucleus. The tumor suppressor protein p53 is a critical cellular mediator of the response to oxidative stress and genotoxic damage. Upon activation, p53 accumulates in the nucleus where it transcriptionally activates the expression of a number of proteins. There is in vitro evidence that copper may displace zinc in the p53 structure. 19 

In addition to the possibility that 64Cu might bind to p53 itself, there is also evidence that p53 facilitates the transport of other copper-based proteins to the nuclei of tumor cells. Azurin is a cupredoxin protein secreted by Pseudomonas aeruginosa. It has been shown to have cytotoxic effects on J774 macrophages and human breast cancer cells. 20,21 The induction of apoptosis by azurin is independent of its redox activity and involves complex formation with p53 and translocation to the nucleus. 22-24

Here we report on the transport of 64Cu to the nuclei of HCT116 cells lines that are either p53 WT or p53 negative (herein referred to as HCT 116 +/+ and HCT 116 −/−). We evaluated [64Cu]copper acetate, which will bind to proteins in serum and be taken up by cells via the hCtrl1 transporter, as well as the EGFR antibody 64Cu-DOTA-cetuximab, which will be delivered to the EGFR-positive HCT 116 cell lines by a receptor-mediated pathway. Cetuximab was the first monoclonal antibody targeted against the ligand-binding site of EGFR to be approved by the FDA for treatment of EGFR-positive metastatic colorectal cancer and advanced head-and-neck cancer. DOTA is a well-characterized chelator for copper, and it is known that 64Cu can dissociate from the Cu-DOTA complex in vivo. 32 64Cu-DOTA-cetuximab was produced with a specific activity of 10–15 μCi/μg [0.37–0.56 MBq/μg; 1.5–2.3 nCi/fmol (560–860 Bq/fmol)]. Initial radiochemical purity ranged from 75–100%. For yields < 95%, 64Cu-DOTA-cetuximab was challenged with 5 μl of 10 mM EDTA to complex free 64Cu. 64Cu-DOTA-cetuximab was then isolated with a miniature size exclusion column, resulting in final radiochemical purities ranging from 98 - 100%. Saturation receptor binding experiments with 64Cu-DOTA-cetuximab and isolated HCT 116 +/+ and HCT 116 −/− cell membranes showed that there was no significant difference in the binding characteristics between the two cell lines (Fig. 2). The dissociation constant (Kd) was 0.95 ± 0.26 nM for HCT 116 −/− cells and 1.13 ± 0.22 nM for HCT 116 +/+ cells. These values are comparable to dissociation constants reported for unmodified cetuximab, which range from 0.15–1.2 nM. 33,34 Maximum EGF receptor densities (Bmax) were very similar as well: 1,950 ± 180 fmol/mg for HCT 116 +/+ cells, and 2,180 ± 150 fmol/mg for HCT 116 −/− cells. It was important to demonstrate that EGFR receptor numbers were comparable for both cell lines and were not dependent on their p53 status in order to exclude the possibility that a difference in receptor numbers would confound the results of internalization, nuclear uptake, and efflux studies with 64Cu-DOTA-cetuximab.

**Results**

Internalization and nuclear uptake of [64Cu]copper acetate. HCT 116 +/+ and HCT 116 −/− cells were incubated with [64Cu]copper acetate over a 24 h time course to measure internalization. 64Cu accumulated in both lines over time and reached approximately 20% ID/mg at 24 h. Minimal difference was observed between the two cell lines (Fig. 1A). p53 status thus had no apparent influence on transport of 64Cu via the hCtrl1 transporter. The difference in nuclear uptake of 64Cu, however, was quite significant (Fig. 1B). At the end of the 24 h time course, 64Cu accumulation in the nuclei was two-fold higher in HCT 116 +/+ cells compared HCT 116 −/− cells (8.26 ± 0.13 vs. 4.05 ± 0.07% ID/mg cellular protein, n = 3, p < 0.0001). Even though uptake of 64Cu from [64Cu]copper acetate was not influenced by p53 status, transport of this radiometal to the nucleus was significantly higher in the p53 expressing cell line.

To test for the integrity of the HCT 116 cell lines utilized in this study, which have been passaged for several decades, and to ensure the absence of clonal artifacts, HCT 116 +/+ cells were treated with p53 siRNA (short interfering RNA, silencing RNA) to downregulate p53 mRNA and p53 protein. After three days, these cells were exposed to 25 μCi of [64Cu]copper acetate, and cell nuclei were isolated and measured for 64Cu activity. Nuclear uptake was significantly lower in HCT 116 −/− cells treated with p53 siRNA (0.126 ± 0.008% ID/mg, n = 3) compared to untreated HCT 116 +/+ cells (0.252 ± 0.003% ID/mg, n = 2, p < 0.01). There was no statistical significance between down-regulated HCT 116 +/+ cells and HCT 116 −/− cells (0.165 ± 0.033% ID/mg, n = 2, p = 0.23). Thus, downregulation of p53 mRNA and protein in HCT 116 +/+ cells led to nuclear localization of 64Cu more similar in quantity to HCT 116 −/− cells than to HCT 116 +/+ cells. This control experiment reduces the probability that clonal artifacts were responsible for the 64Cu nuclear uptake patterns observed in the two HCT 116 clones.

**Synthesis and receptor binding of 64Cu-DOTA-cetuximab.** Next, experiments were performed to determine whether this difference would be observed when 64Cu enters the cells via a receptor-mediated pathway. HCT 116 cells express EGFR, and we chose 64Cu-DOTA-cetuximab as a vector for bringing 64Cu into HCT 116 cells. Cetuximab is a humanized anti-EGFR monoclonal antibody and has been approved by the FDA for treatment of EGFR-positive metastatic colorectal cancer and advanced head-and-neck cancer. DOTA is a well-characterized chelator for copper, and it is known that 64Cu can dissociate from the 64Cu-DOTA complex in vivo. 32 64Cu-DOTA-cetuximab was produced with a specific activity of 10–15 μCi/μg [0.37–0.56 MBq/μg; 1.5–2.3 nCi/fmol (560–860 Bq/fmol)]. Initial radiochemical purity ranged from 75–100%. For yields < 95%, 64Cu-DOTA-cetuximab was challenged with 5 μl of 10 mM EDTA to complex free 64Cu. 64Cu-DOTA-cetuximab was then isolated with a miniature size exclusion column, resulting in final radiochemical purities ranging from 98 - 100%. Saturation receptor binding experiments with 64Cu-DOTA-cetuximab and isolated HCT 116 +/+ and HCT 116 −/− cell membranes showed that there was no significant difference in the binding characteristics between the two cell lines (Fig. 2). The dissociation constant (Kd) was 0.95 ± 0.26 nM for HCT 116 −/− cells and 1.13 ± 0.22 nM for HCT 116 +/+ cells. These values are comparable to dissociation constants reported for unmodified cetuximab, which range from 0.15–1.2 nM. 33,34 Maximum EGF receptor densities (Bmax) were very similar as well: 1,950 ± 180 fmol/mg for HCT 116 +/+ cells, and 2,180 ± 150 fmol/mg for HCT 116 −/− cells. It was important to demonstrate that EGFR receptor numbers were comparable for both cell lines and were not dependent on their p53 status in order to exclude the possibility that a difference in receptor numbers would confound the results of internalization, nuclear uptake, and efflux studies with 64Cu-DOTA-cetuximab.

Internalization and nuclear uptake of 64Cu-DOTA-cetuximab. These experiments were performed in the same manner as described for [64Cu]copper acetate. Figure 3A shows the uptake of 64Cu-DOTA-cetuximab into both HCT 116 cell lines. As was the case with [64Cu]copper acetate, internalization was similar in both lines. However, uptake did not increase between the 4 h and 24 h time point. It is possible that the receptor-mediated uptake of 64Cu-DOTA-cetuximab was saturated at 4 h, whereas non-specific uptake of [64Cu]copper acetate increased over the 24 h time course. At 24 h the total amount of internalized 64Cu-DOTA-cetuximab was 43.7 ± 1.3% ID for HCT 116 +/+ cells vs. 42.2 ± 3.3% ID for HCT 116 −/− cells (P = 0.68, N = 6, data not shown). As expected from similar Kd and Bmax values for the interaction of 64Cu-DOTA-cetuximab and the EGF receptor on the two HCT 116 cell lines, a difference in receptor-mediated endocytosis of 64Cu-DOTA-cetuximab could not be observed.
Copper is one of the most important trace metals in humans, being surpassed in abundance only by iron and zinc. Therefore, mechanisms for copper uptake, transport, and excretion exist within all living cells. Molecular imaging and targeted radiotherapy can take advantage of these mechanisms, e.g., by developing strategies to deliver radioactive isotopes like $^{64}$Cu or $^{67}$Zn to target cells. Due to its cytotoxicity, however, copper exists in biological systems only in specific complexes, such as the ubiquitous copper transporter hCtr1, or the metallochaperone CCS, to deliver radioactive isotopes like $^{64}$Cu or $^{67}$Zn.

When isolated nuclei were measured for $^{64}$Cu activity after incubation with $^{64}$Cu-DOTA-cetuximab (Fig. 3B), numbers were higher in HCT 116$^{+/+}$ cells compared to HCT 116$^{-/-}$ cells ($0.56 \pm 0.05\%$ vs. $0.36 \pm 0.03\%$ of internalized activity/mg cellular protein at 24 h, $P < 0.001$, $N = 6$). Those values correspond to $10.3 \pm 1.0\%$ and $7.0 \pm 0.5\%$ of internalized $^{64}$Cu-DOTA-cetuximab ($P = 0.01$, $N = 6$, data not shown). In contrast to the analogous experiment with $[^{64}$Cu]copper acetate, when a significant difference had not been seen at early time points, more $^{64}$Cu from $^{64}$Cu-DOTA-cetuximab appeared in the nuclei of HCT 116$^{+/+}$ cells as early as 1 h, with the difference being statistically significant at 4 h ($0.75 \pm 0.09\%$ vs. $0.47 \pm 0.05\%$ of internalized activity/mg, $p = 0.02$, $n = 6$).

Efflux of $^{64}$Cu-DOTA-cetuximab. We hypothesize that $^{64}$Cu dissociates from $^{64}$Cu-DOTA-cetuximab and is complexed by a different protein before entering the cell nucleus. To rule out that the observed difference in nuclear uptake between the two HCT 116 cell lines resulted from a variation in release of $^{64}$Cu into the medium, $^{64}$Cu efflux was monitored for 20 h after an uptake period of 4 h. Figure 4 shows the efflux profiles of both cell lines. Both cell lines retained comparable amounts of $^{64}$Cu from internalized $^{64}$Cu-DOTA-cetuximab throughout the time course, with the exception of increased efflux of $^{64}$Cu from HCT 116$^{-/-}$ cells at 4 h. This time point may be an outlier, and the overall profiles suggest that the difference in $^{64}$Cu efflux between HCT 116 cell lines is minimal.

Discussion

Copper is one of the most important trace metals in humans, being surpassed in abundance only by iron and zinc. Therefore, mechanisms for copper uptake, transport, and excretion exist within all living cells. Molecular imaging and targeted radiotherapy can take advantage of these mechanisms, e.g., by developing strategies to deliver radioactive isotopes like $^{64}$Cu or $^{67}$Zn to target cells. Due to its cytotoxicity, however, copper exists in biological systems only in specific complexes, such as the ubiquitous copper transporter hCtr1, or the metallochaperone CCS, which delivers the metal to the copper redox enzyme superoxide dismutase. Copper also exists in the cell nucleus and can interact with DNA; however, it is not known how copper enters the nucleus or which proteins may assist in its transport.

In the case of $^{64}$Cu, nuclear localization may have an additional effect on targeted radiotherapy of cancer. If transported to the nucleus, $^{64}$Cu from radiopharmaceuticals may have improved tumor cell killing properties in tumors, in part due to the delivery of a higher radiation dose to nuclear DNA. This extra dose comes from two Auger electrons with energies of 6.5 keV (22.5%) and 840 eV (57.7%), which are emitted by $^{64}$Cu. According to the MIRD database, the range for the 6.5 keV electron is less than 1.5 μm in soft tissues, while the range for the 840 eV electron is only 0.05 μm. The diameter of HCT 116 tumor cell nuclei was determined to be 12–13 μm; therefore, nuclear localization is clearly necessary to bring tumor cell DNA in range of these Auger electrons. Another potential mode of cell killing is caused by the recoil energy associated with the transmutation of $^{64}$Cu nuclei to stable $^{67}$Ni ($β^+$ decay) or $^{65}$Zn ($β^+$ decay). Apelget and colleagues proposed that this mode of cell killing may be important if the decays occur within the DNA molecule itself, as DNA is highly sensitive to changes in its structure.

We previously demonstrated that $^{64}$Cu localized to the nuclei from $^{64}$Cu-TETA-ocotreotide in AR42J rat pancreatic tumor cells, and from $^{64}$Cu-TETA-Y3-TATE in A427-7 human non-small cell lung carcinoma cells. $^{64}$Cu-CB-TE2A-Y3-TATE is a very stable copper complex, and no nuclear accumulation has been observed with this somatostatin analogue over 24 h. This finding supports the hypothesis that $^{64}$Cu must dissociate from its chelator before entering the nucleus. Given the lack of free copper ions in living systems, a yet unidentified binding partner involved in copper trafficking to the nucleus almost certainly exists.

We present research indicating that the tumor suppressor protein p53 is directly or indirectly involved in the process of copper transport to tumor cell nuclei. $^{64}$Cu administered as $[^{64}$Cu]copper acetate and $^{64}$Cu-DOTA-cetuximab entered the nuclei of HCT 116$^{+/+}$ cells, which express p53, in significantly greater amounts than was the case with HCT 116$^{-/-}$ cells (Figs. 1B and 3B), which lack both p53 alleles. In the case of $[^{64}$Cu]copper acetate, the metal is transported into the tumor cells via the hCtr1 transporter. $^{64}$Cu-DOTA-cetuximab, a monoclonal chimeric antibody against the EGF receptor, enters the cell by receptor-mediated endocytosis. Different uptake mechanisms may account for the observation that the uptake of $^{64}$Cu-DOTA-cetuximab into HCT 116$^{+/+}$ nuclei was significantly increased after 4 h of exposure to the radiopharmaceutical (Fig. 3B), whereas a significant increase of $[^{64}$Cu]copper acetate uptake occurred only at 24 h (Fig. 1B). Control experiments showed that uptake of $[^{64}$Cu]copper acetate (Fig. 1A) and $^{64}$Cu-DOTA-cetuximab (Fig. 3A), as well as receptor binding (Fig. 2) and efflux of $^{64}$Cu-DOTA-cetuximab (Fig. 4) are not significantly different between p53 positive and negative cell lines. Thus, increased trafficking of $^{64}$Cu into HCT 116$^{+/+}$ cell lines is not confounded by increased uptake or reduced efflux.

p53 protein is maintained at very low levels in the absence of cellular stress. It can be activated by many conditions such as...
DNA damage, hypoxia, chromosomal aberrations, telomere shortening and others, whereupon it accumulates in the nucleus, acting as a sequence-specific transcriptional regulator. Copper toxicity is correlated with apoptotic cell death, and translocation of p53 from the cytosol into the nucleus has been shown to occur in cells treated with 200 µM copper supplied as cupric sulfate. Our study shows that presence of p53 in turn increases the amount of $^{64}$Cu that is transported to the nucleus of HCT 116 cells. Copper is capable of displacing zinc from metal-binding sites in proteins and has been shown to bind to p53 in vitro. Thus one possibility is that p53 itself is responsible for the increased transport of $^{64}$Cu into the nuclei of HCT 116 cells.

A third potential mechanism involves proteins from genes whose expression is upregulated by p53 after exposure to the radiocopper. This increased localization of p53 compared to p53 null or p53 mutant expressing tumor cells. This increased localization of $^{64}$Cu in the nuclei may cause increased DNA damage to cells, and therefore improved tumor cell killing. In addition, we have identified a role for p53 in the transport of copper into the cell nucleus.

**Materials and Methods**

**Materials.** 1,4,7,10-Tetraazacyclododecane-1,4,7-tris(t-butyl acetic acid mono (N-hydroxysuccinimide ester) [DOTA-mono-NHS-tris(tBu) ester] was purchased from Macrocycles (Dallas, TX). Centricon 100 concentrators were purchased from Amicon Inc. (Beverly, MA). All chemicals used were purchased from Aldrich Chemical Co. (Milwaukee, WI). All solutions were made using distilled deionized water (Milli-Q, 18 MΩ resistivity). Monoclonal antibody cetuximab (C225) was kindly provided by ImClone Systems (New York, NY). HCT 116 +/- and HCT 116 -/- cell lines were kindly provided by Dr. Bert Vogelstein (Johns Hopkins University). A Branson Sonifier cell disrupter, and a Sorvall RC2-B centrifuge were used in the receptor binding experiments. Size-exclusion HPLC used in conjugation and purification of radio-labeled conjugate was accomplished on a Superose 12 HR 10/300 column (Amersham Biosciences, Uppsala, Sweden) with a Waters (Milford, MA) 2487 dual λ absorbance detector and an Ortec Model 661 (EG&G Instruments, Oak Ridge, TN) radioactive detector. The mobile phase was 20 mM HEPES, 150 mM NaCl, pH 7.3 eluted at a flow rate of 0.5 ml/min. Millenium 32 software (Waters, Milford, MA) was used to quantify chromatograms by integration. A Beckman 8000 automated well-typed gamma counter (Fullerton, CA) was used to measure internalization and nuclear uptake samples. Copper-64 was produced as previously reported on a biomedical cyclotron CS-15 at Washington University School of Medicine.

**Preparation of $^{64}$Cu-DOTA-cetuximab.** DOTA was conjugated to cetuximab in 0.1 M Na$_2$HPO$_4$ (pH 7.5) using an adaptation of the method described by Lewis et al. Cetuximab (2 mg/ml) was washed with 0.1 M Na$_2$HPO$_4$ (pH 7.5) and concentrated using a Centricon 100. DOTA-mono-NHS-tris(tBu) ester was dissolved in 0.1 M Na$_2$HPO$_4$ (pH 7.4) and pH was adjusted to 7.4 by adding 0.1 M NaOH. An aliquot of this solution was added to the concentrated cetuximab in a molar ratio of DOTA-mono-NHS-tris(tBu) ester : cetuximab = 90 : 1, followed by incubation at 4°C overnight with end-over-end rotation. The conjugate was then transferred to a Centricon 100, diluted to 2.0 ml with 0.1 M ammonium citrate (pH 5.5), and centrifuged. This procedure was repeated to remove small molecule reactants and the conjugate was collected from the membrane. Purity and concentration of the resulting conjugate were determined by size-exclusion HPLC, and DOTA-cetuximab was stored at 4°C until needed.

Radiolabeling of DOTA-cetuximab with $^{64}$Cu was carried out by adding approximately 100 µg of the conjugate to 0.5–2 mCi (19–74 MBq) $^{64}$CuCl$_2$ in 0.1 M ammonium citrate buffer, pH 5.5, followed by a 1 h incubation at 40°C. The radiochemical purity of the resulting $^{64}$Cu-DOTA-cetuximab was determined by size-exclusion HPLC and radio-TLC. If necessary, $^{64}$Cu-DOTA-cetuximab was challenged with 5 µl of 10 mM EDTA to complex free $^{64}$Cu. $^{64}$Cu-DOTA-cetuximab was then isolated with a Zea™ Desalt Spin column (0.5 ml, Pierce, Rockford, IL) to obtain radiochemical purities > 95%.
For isolation of HCT 116 cell
64
2
max
‑
‑/‑
2
p
7
14
64
‑
2
2
67
+/+
were added to membranes to measure total binding, and non‑specific
www.landesbioscience.com (PerkinElmer, Boston, MA) (25
were washed twice with 200
medium was removed with a vacuum manifold and the membranes
an excess (2
binding was determined by conducting the assay in the presence of
concentrations (0.05 nM–6 nM) of
A), and 10
mM PIPES, pH 6.8) and incubated
of 1, 4 and 24 h. At each time
point, the media was removed and the cells were washed twice with
wash without incubation, which was pooled with the first rinse. The
cellular fraction was solubilized in 0.1% SDS. All of the fractions
were counted for radioactivity with a gamma counter. The
percentage internalized was the amount of activity in the final cell
pellet, corrected for activity in the blocked fractions and background
activity, and normalized to protein content.

For efflux experiments, cells were seeded in 6‑well plates and
allowed to adhere overnight. Cells were fed 3 ml fresh growth media
on the morning of the experiment, 64Cu‑DOTA‑cetuximab was
added to each well, and cells were incubated at 37°C, 5% CO2 for
10 min followed by a second 20 mM sodium acetate in PBS (pH 3.0)
wash without incubation, which was pooled with the first rinse. The
cellular fraction was solubilized in 0.1% SDS. All of the fractions
were counted for radioactivity with a gamma counter. The
percentage internalized was the amount of activity in the final cell
pellet, corrected for activity in the blocked fractions and background
activity, and normalized to protein content.

Internalization and efflux of [64Cu]copper acetate and
64Cu‑DOTA‑cetuximab in HCT 116 cell lines.
HCT 116 +/+ or HCT 116 ‑/‑ cells were seeded in 6‑well plates containing growth medium (McCoy's 5a medium with 1.5 mM L‑glutamine adjusted to contain
2.2 g/l sodium bicarbonate, 90%; fetal bovine serum, 10%) and were incubated at 37°C, 5% CO2 until 80% confluent. On the day of the assay, the medium was
aspirated and 3 ml fresh growth medium was placed in each well. For determination of nonspecific internalization in the cetuximab experiments, one set of wells
was incubated with unlabeled cetuximab (375 µg/100 µl) at 37°C, 5% CO2 for 10 min to block EGF receptors. [64Cu]copper acetate (25 µCi/10 µl) or 64Cu‑DOTA‑cetuximab (3.6 µCi, 0.38 µg/15 µl)
were added to all of the wells and incubated at 37°C, 5% CO2 for 1, 4 or 24 h. At each time point, radioactive medium was aspirated, and the plate was washed twice with 2 ml PBS. To collect the surface‑bound fraction, each well was treated with 20 mM sodium acetate in PBS (pH 3.0) and was incubated at 4°C for 10 min followed by a second 20 mM sodium acetate in PBS (pH 3.0) wash without incubation, which was pooled with the first rinse. The

Figure 3. (A) %ID/mg of 64Cu‑DOTA‑cetuximab internalized in HCT 116 cell lines positive (□) and negative (▲) for p53. (B) Percentage of internalized activity localized to the nuclear
fraction of HCT 116 cells per mg (N = 6 with two independent 64Cu productions).

Figure 4. Efflux of 64Cu‑DOTA‑cetuximab from HCT 116 cell lines positive (□) and negative (▲) for p53. Efflux is expressed as the percentage of
retained activity, where the activity at t = 0 (when the radioactive media is
removed) is 100%.

Binding affinity of 64Cu‑DOTA‑cetuximab. Cell membranes
from HCT 116 +/+ and HCT 116 ‑/‑ cell lines for binding assays
were prepared as previously described. Assays were performed on a
96‑well Multiscreen® Durapore filtration plate (Millipore, Billerica,
MA) using methods previously described with some modifications. Membranes were diluted in binding buffer (50 mM Tris‑HCl, pH 7.4, 5 mM MgCl2, 6 H2O, 0.1% BSA, 0.5 µg/ml aprotinin, 200 µg/ml bacitracin, 10 µg/ml leupeptin, and 10 µg/ml pepstatin A), and 10 µg of membrane protein were used per well. Increasing concentrations (0.05 nM–6 nM) of 64Cu‑DOTA‑cetuximab were
added to membranes to measure total binding, and non‑specific binding was determined by conducting the assay in the presence of an excess (2 µM) of cetuximab. After incubation at RT for 2 h, the medium was removed with a vacuum manifold and the membranes
were washed twice with 200 µl binding buffer. OptiPhase ‘Super‑Mix’ (PerkinElmer, Boston, MA) (25 µl) was added to each well, and
bound activity was measured with a 1450 Microbeta liquid scintillation and luminescence counter (Perkin Elmer, Boston, MA). Specific binding was obtained by subtraction of non‑specific binding from total binding. Maximum binding capacities (Bmax) were estimated from non‑linear curve fitting of specific binding versus the concentration of 64Cu‑DOTA‑cetuximab using GraphPad Prism (San Diego, CA).

For efflux experiments, cells were seeded in 6‑well plates and
allowed to adhere overnight. Cells were fed 3 ml fresh growth media
on the morning of the experiment, 64Cu‑DOTA‑cetuximab was
added to each well, and cells were incubated at 37°C, 5% CO2 for
4 h. The radioactive medium was removed and the cells were washed twice with ice cold PBS. Fresh growth medium (3 ml) was added to each well, and the cells were incubated for 1, 4 or 20 h. At each time
point, the media was removed and the cells were washed twice with
ice cold PBS. The cells were solubilized in 0.1% SDS, transferred to a microfuge tube, and counted for radioactivity on the gamma
counter.

Nuclear localization of [64Cu]copper acetate and 64Cu‑DOTA‑
cetuximab in HCT 116 cell lines. For isolation of HCT 116 cell
nuclei, the procedure of Wang et al. was used. The experiments
were performed in T‑175 flasks containing approximately 5 x 107
cells at the beginning of the time course. 64Cu‑DOTA‑cetuximab (4.0 µCi, 0.33 µg/20 µl) was added, and after incubation times of 1, 4 and 24 h, the cells were pelleted and resuspended in CSK buffer (0.5% Triton X‑100, 300 mM sucrose, 100 mM NaCl, 1 mM EGTA, 2 mM MgCl2, and 10 mM PIPES, pH 6.8) and incubated on ice for 2 min. Cell lysates were centrifuged at 560 g for 5 min at
4°C, and the supernatant was discarded. The nuclear pellet was resus‑
pended in 1 ml CSK buffer without Triton X‑100, and centrifuged

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at 560 g at 4°C for 5 min. The supernatant was discarded and the nuclear pellet was collected and weighed as a gamma counter. Aliquots of nuclei were assayed qualitatively for purity by fluorescence microscopy after staining with a 1:10 dilution of FITC (3 μg/ml) and propidium iodide (7 μg/ml). Micrographs were obtained at 100, 200 and 1000 magnification. The yield of nuclei was determined by counting the initial cell number and the collected nuclei using a Coulter Counter. The percentage in the cell nucleus was determined by the gamma counts in the pure nucleus divided by gamma counts internalized into whole cells, and was corrected for the yield of nuclei.

As an additional control in the HCT 116 cell lines, nuclear uptake of [64Cu]copper acetate was determined in HCT 116/6+ cells after downregulation of p53 by p53 siRNA, and compared to untreated HCT 116/6- and HCT 116/6- cells. Cells were seeded in T-75 flasks so that they were 30–40% confluent after 24 h. TransPass® R1 Transfection Reagent (200 μl; New England BioLabs, Boston, MA) was mixed with 5 ml serum-free medium and incubated for 15 min at RT and addition of 43 ml medium with serum. This mixture was added to HCT 116 and incubated for 15 min incubation at RT and addition of 43 ml medium with serum. The percentage in the cell nucleus was determined by the gamma counter. As an additional control in the HCT 116 cell lines, nuclear localization of radiolabeled somatostatin analogues: Implications for targeted radiotherapy for cancer. Cancer Res 2003; 63:6846-9.

References


