Fast, Cell-Compatible Click Chemistry with Copper-Chelating Azides for Biomolecular Labeling

The MIT Faculty has made this article openly available. Please share how this access benefits you. Your story matters.

<table>
<thead>
<tr>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>As Published</td>
<td><a href="http://dx.doi.org/10.1002/anie.201108181">http://dx.doi.org/10.1002/anie.201108181</a></td>
</tr>
<tr>
<td>Publisher</td>
<td>Wiley Blackwell</td>
</tr>
<tr>
<td>Version</td>
<td>Author's final manuscript</td>
</tr>
<tr>
<td>Accessed</td>
<td>Wed Jan 02 20:48:39 EST 2019</td>
</tr>
<tr>
<td>Citable Link</td>
<td><a href="http://hdl.handle.net/1721.1/74563">http://hdl.handle.net/1721.1/74563</a></td>
</tr>
<tr>
<td>Terms of Use</td>
<td>Creative Commons Attribution-Noncommercial-Share Alike 3.0</td>
</tr>
<tr>
<td>Detailed Terms</td>
<td><a href="http://creativecommons.org/licenses/by-nc-sa/3.0/">http://creativecommons.org/licenses/by-nc-sa/3.0/</a></td>
</tr>
</tbody>
</table>
Fast, Cell-Compatible Click Chemistry with Copper-Chelating Azides for Biomolecular Labeling**

Chayasith Uttamapinant, Anupong Tangpeerachaikul, Scott Grecian, Scott Clarke, Upinder Singh, Peter Slade, Kyle R. Gee, and Alice Y. Ting*

The copper-catalyzed azide–alkyne cycloaddition, or CuAAC, has been used extensively for the conjugation, immobilization, and purification of biomolecules.[1] Despite excellent reaction kinetics, high specificity, and bioorthogonality, CuAAC has been used to a far lesser extent in the cellular context because of toxicity caused by the CuI-mediated generation of reactive oxygen species (ROS) from O2. One way to address this problem is to remove the CuI requirement, by using alkynes activated by ring strain.[3,4] However, even the fastest of the strained cyclooctynes[5] react with azides more than tenfold slower than terminal alkynes in the presence of CuI (kobs ≈ 1 m−1 s−1) for (aza)dibenzocyclooctyne[6] compared to kobs ≈ 10−100 m−1 s−1 per 10–100 μM CuII/CuI for CuAAC.[7] A second approach to improve cell compatibility is to use water-soluble ligands such as tris(hydroxypropyltriazolylmethyl)amine (THPTA),[8] bis[(tert-butyltriazolyl)methyl][(2-carboxymethyltriazolyl)methyl]amine (BTTAA),[9] or bis([2-histidine][10] for CuI. These ligands both accelerate the cycloaddition reaction and act as sacrificial reductants, helping to protect cells and biomolecules from ROS.[9]

Herein we explore a third approach to improve the cell compatibility and performance of CuAAC. In general, decreasing the copper concentration lowers the toxicity of CuAAC to cells, but this is accompanied by a large decrease in reaction kinetics.[9] We reasoned that it might be possible to compensate for this decrease by using an azide reaction partner that contains an internal copper-chelating moiety (Figure 1A), which would raise the effective copper concentration at the reaction site. This concept has been explored for azide–alkyne reactions in organic solvents, with CuII rather than CuI species, and at very high copper (10 mM) and reactant (200–400 mM) concentrations,[11,12] but never before under conditions relevant to biomolecular labeling. The goal of our study was to examine the effect of substrate chelation assistance on CuAAC kinetics and biocompatibility.

The rate-determining step of CuAAC is postulated to be the formation of the metallocycle from the CuI acetylide and the organic azide.[13] We decided to test whether an organic azide containing an internal CuI ligand could accelerate formation of the metallocycle and hence the overall rate of the CuAAC reaction. We prepared two azides with proximal pyridine nitrogen atoms to chelate the CuI ion (picolyl azides 2 and 4), as well as their nonchelating carbocyclic analogues, 1 and 3 (Figure 2).

CuAAC reaction timecourses were measured using 7-ethynylcoumarin, a fluorogenic alkyne whose quantum yield (QY) increases from 1% to 25% upon reaction with azides[4] (Figure 2A). Assays were first performed with 10 μM CuSO4 in the absence of CuI ligands. Reaction timecourses are shown in Figure S1 (see Supporting Information) and values for percent conversion into product after 10 and 30 minutes are given in Figure 2B. Whereas the conventional azides 1 and 3 give no detectable product after 30 minutes under these conditions, the picolyl azides 2 and 4 give 81% and 38% product yields, respectively, after 30 minutes. We examined a few other picolyl azide derivatives as well. The methyl ester 5 gives results similar to the acid 4. Substitution of the aromatic ring with an electron-donating methoxy group (azide 6) further accelerates the CuAAC reaction, while an electron-withdrawing chloride substituent (azide 7) reacts slower than the other picolyl azide derivatives. These observations are consistent with a mechanism in which rate acceleration is caused by coordination of the pyridyl nitrogen atom to CuI or CuII acetylide, since an electron-donating group will increase the electron density on this nitrogen atom, improving coordination.

We further investigated picolyl azide 4, because it is the synthetic precursor of the ligase substrate and fluorophore conjugates, described later in this work. We repeated the CuAAC reaction, but this time at three different copper concentrations (10, 40, and 100 μM), either in the absence or the presence of CuI ligand THPTA (4 molar equivalents relative to copper). Figure 2C shows the timecourses of these six reactions, as well as control reactions using the nonchelating analogue of 4, azide 3.

As has previously been observed, the addition of THPTA increases the CuAAC reaction rate. For the conventional azide 3, product is undetectable after 30 minutes in the absence of THPTA (consistent with Figure 2B), whereas the reactions at 100 and 40 μM copper proceed to completion.

Department of Chemistry, Massachusetts Institute of Technology
77 Massachusetts Avenue, Room 18-496, Cambridge, MA 02139
(USA)
E-mail: ating@mit.edu
Dr. S. Grecian, Dr. S. Clarke, Dr. U. Singh, Dr. P. Slade, Dr. K. R. Gee
Life Technologies, Eugene, OR 97402 (USA)

[**] We thank Carolyn Kwa, Daniel Liu, and Ken Loh for assistance with protein production. Jennifer Yao for help with LPLA enzymes, and Peng Zou for critical reading of the manuscript. Prof. M. G. Finn (Scripps) provided the initial batch of THPTA ligand. Funding was provided by the NIH (R01 GM072670), the Dreyfus Foundation, and the American Chemical Society. C.U. was supported by the C.P. Chu and the NIH (R01 GM072670), the Dreyfus Foundation, and the American Chemical Society. C.U. was supported by the C.P. Chu and the NIH (R01 GM072670), the Dreyfus Foundation, and the American Chemical Society.

Supporting information for this article (experimental details) is available on the WWW under http://dx.doi.org/10.1002/anie.201108181.
within 30 minutes when THPTA is added. As expected, lowering the copper concentration lowers the reaction rate. Dramatic rate enhancements are seen for all six conditions when azide 3 is substituted by the chelation-competent azide 4 (Figure 2C). Without THPTA, reactions proceed to completion within 30 minutes for the two higher Cu concentrations (100 and 40 μM), in striking contrast to azide 3. When THPTA is added, azide 4 reacts to completion within 5 minutes at all three copper concentrations. In other words, the use of chelating azide 4 far offsets the decrease in the CuAAC reaction rate caused by lowering the Cu concentration. The effect is so strong that the reaction rate of chelating azide 4 at all three Cu concentrations in the absence of THPTA are at least as high as the reaction rates of conventional azide 3 in the presence of THPTA.

Based on the dramatic effects observed in vitro, we tested the utility of copper-chelating azides to fluorescently label proteins in a cellular setting. To target the picoyl azide moiety to specific cellular proteins, we turned to our PRIME (probe incorporation mediated by enzymes[17]) protein-labeling method. A panel of E. coli lipoic acid ligase (LplA) mutants was prepared, each with a mutation at the gatekeeper residue Trp37.[17–19]

We synthesized a picoyl azide derivative that matches the substrate requirements for LplA, i.e., with a carboxylic acid joined by four methylene groups to the picoyl azide moiety (picoyl azide 8; structure in Figure 1B; synthesis in Figure S2 of the Supporting Information).

In vitro screening by HPLC of six LplA mutants (W37G, A, V, I, L, S) showed that the valine mutant (W37VLplA) was most efficient at recognizing picoyl azide 8 and catalyzing its covalent, ATP-dependent ligation to the 13 amino acid recognition sequence of LplA, namely LAP (LplA acceptor peptide; Supporting Information Figure S3).[20]

To test LplA-catalyzed picoyl azide targeting on cells, we prepared human embryonic kidney (HEK) cells expressing LAP-tagged cyan fluorescent protein (CFP) targeted to the cell surface. Picoyl azide 8, W37VLplA, and ATP were added for 20 minutes to these transfected cells. LAP-conjugated picoyl azide was then detected by CuAAC with Alexa Fluor 647-alkyne. Figure 3 and Figure S4 show that labeling was easily detectable and specific to transfected cells.
workers to be superior to THPTA and to give the fastest and most cell-compatible CuAAC labeling to date.\[9,21\]

As a control, we compared LAP-expressing cells labeled with LplA and 8-azidooctanoic acid, an alkyl azide that is incapable of chelation assistance.\[22\] Since this enzymatic ligation may have different kinetics than picolyl azide 8 ligation catalyzed by W37VLplA, we compared their labeling yields on cells after 20 minutes (Supporting Information, Figure S5). Although picolyl azide 8 ligation is faster, the difference in yield after 20 min of labeling is at most 1.5-fold over that of 8-azidooctanoic acid ligation. This correction factor can therefore be applied to the multivariate comparison performed in Figure S4 (cell images) and Figure 3 (quantitation of these cell images).

Several trends are apparent from Figure 3. First, for the conventional azide, 8-azidooctanoic acid, decreasing the copper concentration reduces the cell-labeling signal, as expected. Second, BTTAA does indeed give higher signals than THPTA, but not as much as previously reported\[9\] and not at the lowest copper concentration of 10 \(\mu\)M. Third, replacement of 8-azidooctanoic acid on LAP with the chelation-competent picolyl azide 8 boosts cell signal at all Cu concentrations 4- to 38-fold. When differences in picolyl azide versus alkyl azide enzymatic ligation efficiencies are taken into account, the difference is 2.7- to 25-fold (Supporting Information, Figure S5). The signal enhancements are greatest at the higher Cu concentrations of 40 and 100 \(\mu\)M.

Similar to the in vitro data shown in Figure 2C, the signal enhancement caused by picolyl azide more than offsets the decrease in the CuAAC rate caused by lowering the Cu concentration. For example, the signal with picolyl azide at 10 \(\mu\)M Cu (+ THPTA) is still 1.6-fold (corrected value) greater than the signal with alkyl azide at 100 \(\mu\)M Cu (+ THPTA).

Comparisons in the presence of BTTAA ligand show that picolyl azide at 40 \(\mu\)M Cu gives a 3.9-fold (corrected value) greater signal than alkyl azide at 100 \(\mu\)M Cu. This experiment also shows that the rate enhancement caused by picolyl azide (compared to the nonchelating alkyl azide) is much greater than the rate enhancement due to switching from a previous-generation ligand (THPTA) to the newest-generation ligand (BTTAA). Overall, the best cell-labeling results are obtained using picolyl azide 8 in combination with BTTAA ligand and either 40 or 100 \(\mu\)M CuSO\(_4\).

Figure 3. Comparison of protein labeling signals on live cells using PRIME and CuAAC, with and without chelating azide. Two-step, site-specific protein labeling was performed as depicted in Figure 1B on HEK cells expressing LAP-tagged cyan fluorescent protein fused to the transmembrane domain of the PDGFR receptor (LAP-CFP-TM). In the first step, either \(t^{37}V\)LplA was used to target picolyl azide 8 to LAP, or wild-type LplA was used to target nonchelating 8-azidooctanoic acid. In the second step, CuAAC was performed for 5 min with Alexa Fluor 647/alkyne and CuSO\(_4\) (10, 40, or 100 \(\mu\)M), with either THPTA or BTTAA ligand (in fivefold excess over CuSO\(_4\)). Live cells were imaged immediately and representative images are shown in Figure S4. To quantify labeling signals, the mean Alexa Fluor 647 and mean CFP intensities were calculated for >90 cells for each condition, ratioed and averaged. Error bars, ± standard error of the mean (s.e.m.).
Using these optimized labeling conditions, we tested the site specificity of cell-surface protein labeling using LplA and CuAAC. In Figure 4, HEK cells expressing the transmembrane construct LAP-neurexin-1β (LAP is extracellular) were labeled first with W37VLplA and picolyl azide 8, then with Alexa Fluor 647-alkyne in the presence of 40 μM CuSO4 and 200 μM BTTA ligand. Transfected cells (expressing a nuclear yellow fluorescent protein (YFP) marker) were strongly yellow fluorescent protein (YFP) marker) were strongly labeled with a ring of Alexa Fluor 647 fluorescence, whereas neighboring untransfected cells were unlabeled. Negative controls with ATP omitted, wild-type ligase and (Lys→Ala) LAP were not efficiently labeled, showing a significant increase in background signal.

In summary, the use of copper-chelating azides dramatically accelerates the CuAAC reaction under conditions relevant to biomolecular labeling. We see this advance as complementary to advances in ligand design, which have also led to CuAAC rate acceleration and reduced cell toxicity. [2,9] Our in vitro data show that the picoly azide effect is so strong for maximal versatility, we also developed a similar but reverse-order site-specific protein labeling scheme based on LplA ligation of an alkyne, followed by CuAAC derivatization with picoly azide-fluorophore conjugates (Supporting Information, Figure S6). The alkyne substrate for LplA is 10-undecynoic acid, and it is best ligated by W37VLplA. Figure S7 compares the original labeling scheme to this reverse-order scheme. Picoly azide ligation, followed by CuAAC with fluorophore-alkyne, gives an approximately 2.4-fold greater signal on average than alkyl azide ligation followed by CuAAC with fluorophore-picoly azide. This may reflect higher efficiency for the enzymatic ligation of picoly azide 8 compared to 10-undecynoic acid.

Since strain-promoted cycloaddition is frequently used as an alternative to CuAAC in the cellular context, including by us, [21] we compared it to our newly optimized CuAAC, in terms of both labeling signal and cell toxicity. Figure S8A in the Supporting Information shows that picoly azide ligation to LAP on cells, followed by CuAAC at 50 μM CuSO4, gives far greater signal than alkyl azide ligation to LAP followed by addition of dibenzocyclooctyne. [23] We also compared the toxicity of these labeling conditions using the CellTiter-Glo assay, which measures cellular ATP levels. Figure S8B shows that both our CuAAC and strain-promoted cycloaddition conditions are equally nontoxic.

A demanding test of the biocompatibility of our new CuAAC is to perform it on neuron cultures. These delicate cells show morphological changes in the presence of even low concentrations of toxic substances. We transected five-day-old hippocampal rat neuron cultures with plasmids for Homer1b-GFP (a postsynaptic marker) and LAP-neuroli- gin-1 (a postsynaptic transmembrane adhesion protein with an extracellular LAP tag). On day 11, picoly azide 8 was ligated to LAP for 20 minutes, then CuAAC was performed with THPTA and either 50 μM or 300 μM CuSO4. Figure 4B shows that both conditions produce specific labeling, with Alexa Fluor 647 on neuroli-gin-1 colocalized with Homer1b-GFP marker. However, the high copper concentration causes focal swelling in the neurons (white arrows), which is a sign of toxicity. The use of chelation-assisted CuAAC allows the concentration of Cu to be decreased to levels minimally toxic to neurons, with little sacrifice to the signal intensity.

A faster and more biocompatible CuAAC labeling protocol also benefits the detection of metabolically labeled proteins and RNA. To demonstrate this, we used either conventional CuAAC or chelation-assisted CuAAC to image cellular RNAs and proteins metabolically labeled with 5-ethynyluridine (EU) [13] or L-homopropargylglycine (Hpg), [14] respectively (Figure 1C and Figure 5). Detection of these alkynes on fixed cells was accomplished with a 1.8–2.7-fold improvement in average signal intensity with Alexa Fluor 647-picolyl azide compared to Alexa Fluor 647-alkyl azide.

In summary, the use of copper-chelating azides dramatically accelerates the CuAAC reaction under conditions relevant to biomolecular labeling. We see this advance as complementary to advances in ligand design, which have also led to CuAAC rate acceleration and reduced cell toxicity. [2,9] Our in vitro data show that the picoly azide effect is so strong
that it more than compensates for the effect of omitting THPTA ligand, or decreasing the Cu concentration from 100 µM to 10 µM. Our experiments on living cells show that the use of picolyl azide, instead of a conventional nonchelating azide, increases the specific protein labeling signal by as much as 25-fold.

By engineering a lipoic acid ligase mutant capable of conjugating picolyl azide to LAP fusion proteins, we have made it straightforward to use chelation-assisted CuAAC to tag specific cell-surface proteins with bright and photostable fluorophores, such as the Alexa Fluors. We also demonstrated the utility of picolyl azide for the sensitive detection of metabolically labeled proteins and RNAs in cells. In summary, the CuAAC protocol reported here, in which a copper-chelating organic azide, a newest-generation Cu ligand (BTTAA), and low Cu concentrations (10–100 µM) are utilized, may represent the fastest biocompatible version of CuAAC to date.

Received: November 21, 2011
Revised: February 13, 2012
Published online: ■ ■ ■ ■ ■ ■ ■ ■ ■ ■

Keywords: click chemistry · fluorescent probes · lipoic acid ligase · metabolic labeling · protein engineering

Communications

Bioorthogonal Click Chemistry

C. Uttamapinant, A. Tangpeerachaikul, S. Grecian, S. Clarke, U. Singh, P. Slade, K. R. Gee, A. Y. Ting*

Fast, Cell-Compatible Click Chemistry with Copper-Chelating Azides for Biomolecular Labeling

Bring your own copper: Copper-chelating azides undergo much faster click reactions (CuAAC) than nonchelating azides under a variety of biocompatible conditions. This kinetic enhancement allows site-specific protein labeling to be performed on the surface of living cells with only 10–40 μM CuI/CuII (see scheme). Detection sensitivity was also increased for CuAAC detection of alkyne-modified proteins and RNA.

Bioorthogonale Klick-Chemie

C. Uttamapinant, A. Tangpeerachaikul, S. Grecian, S. Clarke, U. Singh, P. Slade, K. R. Gee, A. Y. Ting*

Fast, Cell-Compatible Click Chemistry with Copper-Chelating Azides for Biomolecular Labeling