Morpholinecarbonyl-Rhodamine 110 Based Substrates for the Determination of Protease Activity with Accurate Kinetic Parameters

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Supporting Information

ABSTRACT: Commonly used fluorogenic substrate analogues for the detection of protease activity contain two enzyme-cleavable bonds conjugated to the fluorophore. Enzymatic cleavage follows a two-step reaction with a monoamide intermediate. This intermediate shows fluorescence at the same wavelength as the final product complicating the kinetic analysis of fluorescence-based assays. Fluorogenic substrate analogues for α-chymotrypsin with one cleavable peptide bond have been prepared from morpholinecarbonyl-Rhodamine 110 (MC-Rh110). A comparison of their kinetic properties with the corresponding (peptide)2-Rh110 derivatives revealed that these frequently used double-substituted substrate analogues yield only apparent $K_{cat}$ and $V_{max}$ values that are quite different from the kinetic parameters obtained from the monosubstituted MC-Rh110 based substrate analogues. Although both the monoamide intermediate and MC-Rh110 are monosubstituted Rhodamine 110 derivatives, they show different spectroscopic properties. The data from the spectroscopic analysis clearly show that these properties are directly related to the electron structure of the fluorophore and not to the previously proposed equilibrium between the lactone form and the open ionic form of the fluorophore. This knowledge about the determinants of the spectroscopic properties of monosubstituted Rhodamine 110 introduces a way for a more systematic development of new fluorogenic protease substrate analogues.

INTRODUCTION

Proteases and peptidases (EC 3.4) are enzymes that catalyze the hydrolysis of peptide bonds. They constitute approximately 2% of the human genome and are involved in many physiological processes such as cell-cycle progression, tissue remodeling, coagulation, wound healing, cell proliferation, and cell death, as well as the immune response.1 Their involvement in these biological processes makes proteases very important drug targets. Furthermore, proteases are important biocatalysts for a wide range of industrial applications. Understanding the enzymatic mechanism and the factors determining their substrate specificity is therefore of crucial importance for the characterization of their medical relevance as well as for obtaining optimized biocatalysts.

To assay enzyme activity and substrate specificity, fluorogenic probes are commonly used.2–4 The chemical modification of a fluorophore with one or two enzyme-cleavable bonds alters its photophysical properties and results in a nonfluorescent derivative. The fluorescence is recovered upon enzymatic cleavage. Peptide-based substrate analogues can further be designed based on photoinduced electron transfer5 or fluorescence resonance energy transfer.6,7 Fluorescence is often chosen as a detectable signal as it provides high sensitivity in vitro. Moreover, fluorescent probes also find widespread application in living cells and tissues where they provide high spatial and temporal resolution.

The choice of fluorophore is critical for the design of a good enzyme substrate analogue, and favorable fluorescent molecules have to meet several requirements: (i) high brightness to obtain high sensitivity, (ii) fluorescence excitation above 450 nm to reduce photodamage in biological molecules and to avoid interference with autofluorescence of biological samples, and (iii) no interference with the enzymatic reaction so that the kinetic parameters remain unaltered.8 Although frequently used, Coumarin-based substrate analogues have a low brightness and are excited below 450 nm. Common fluorophores which possess the aforementioned properties and are often used for introducing an enzyme-cleavable bond are fluorescein, resorufin, and 7-hydroxy-9H-(1,3-dichloro-9,9-dimethylacridin-2-one) (DDAO) for esterases, phosphoesterases, and glycosidases. Fluorophores used for proteases are Rhodamine 110 and cresyl violet. The latter, however, yields only substrate analogues with insufficient stability to autohydrolysis in aqueous solutions.9 Except for resorufin and DDAO, these substrate analogues contain two sites for conjugating the enzyme-cleavable group.10–12 Using the double-substituted pro-fluorescent derivatives for kinetic measurements complicates a
quantitative analysis, since full fluorescence manifestation requires the cleavage of two bonds involving an intermediate with a different fluorescence intensity.

The difficulty of quantifying the kinetic constants of such a two-step reaction has been addressed in several studies, and solutions have been proposed to obtain the kinetic constants. These approaches, however, always require the detection of the intermediate concentration, which is often not possible in a fluorescence measurement due to the overlap of the excitation and emission spectra of the intermediate and the final product. Other assays to determine the intermediate concentration such as HPLC might not be considered feasible especially in high-throughput assays or measurements in cellular systems. As a consequence, efforts are being made to synthesize monosubstituted substrate analogues, and a number of examples exist utilizing Rhodamine 110 (Rh110).

The most obvious solution might be to attach only one peptide to the Rh110 core. Although this yields a stable molecule, the applicability of such a monoamide Rh110 derivative is limited by its fluorescence, which is approximately still 10% relative to Rh110. Hence, it is desirable to develop Rh110-based substrate analogues that have no intrinsic blocking group while attaching a peptide to the second amino group. Initially designed to increase cell permeability, a range of different blocking groups have been investigated, but they mostly yield dye molecules with a relative fluorescence intensity of only 5–15% compared to Rh110. The best blocking group known to date, which preserves much of the high fluorescence of Rh110, introduces a urea functionality into Rh110. Originally designed by Wang et al., morpholinecarbonyl-Rh110 (MC-Rh110) is a promising candidate for developing sensitive monoamide substrate analogues.

Although Rh110 has been used for many years to synthesize substrate analogues for proteases, the properties of the monosubstituted derivatives have never been investigated systematically. Double-substitution of Rh110 yields a nonfluorescent lactone. Consequently, it has been proposed in several reports that the fluorescence of monosubstituted Rh110 is determined by an equilibrium between a nonfluorescent monosubstituted lactone form and an open zwitterionic fluorescent form of the molecule. It was further suggested that the electron-withdrawing character of the substituent in the molecule. It was further suggested that the electron-withdrawing character of the substituent influences this equilibrium and therefore the fluorescence intensity of the respective derivative.

Using α-chymotrypsin as the model system, we determined the enzyme kinetic parameters for different MC-Rh110 based substrate analogues and compared them with conventional bisamide Rh110 substrate analogues. Furthermore, we performed a systematic analysis of the photophysical properties of MC-Rh110 and monoamide Rh110 in order to understand why different substituents on one of the amino-groups of Rh110 yield derivatives with different fluorescence intensity.

### EXPERIMENTAL PROCEDURES

**Synthetic Approaches.** Unless stated otherwise, reagents were obtained from Sigma-Aldrich or Acros. The substrate analogues were purified on a Waters 996 HPLC with a Waters 600 controller. Reversed-phase C18 columns (Alltech Previa or Phenomenex Luna, both 15 cm long with 2.1 mm diameter and 5 μm particle size) were used. MPLC chromatography was performed using a Büchi Sepacore Flash apparatus. Mass spectra were run using Thermo Finnigan LCQ Advantage apparatus (ESI). NMR spectra were acquired on commercial instruments (Brucker Avance 300 MHz, Bruker AMX 400 MHz or Bruker Avance II+ 600 MHz with TXI probe or TCI CryoProbe) and chemical shifts (δ) are reported in parts per million (ppm) referenced to tetramethylsilane (H) or the internal (NMR) solvent signals (13C). Rhodamine 110 (99% pure, laser grade, Acros) was used for the synthesis of the substrate analogues.

(suc-AlaAlaProPhe)2-Rh110; (sucAAPP)2-Rh110. The synthesis of (sucAAPP)2-Rh110 was performed as described in the Supporting Information of De Cremer et al. and verified by ESI and NMR spectrometry.

MC-Rh110. The synthesis of MC-Rh110 was based on the method described in the patent application by Diwu et al. Since the described purification procedure using a silica gel column did not yield pure product, the dye was purified with MPLC using a mixture of EtOAc/CHCl3/MeOH (50:47.5:2.5). Yield: 25%. MS (ESI+): 444 (MH+). 1H NMR (600 MHz, CDCl3): δ (ppm) 7.99 (d, J = 7.9 Hz, 1H; H-6′), 7.65 (t, J = 7.5 Hz, 1H; H-5′), 7.59 (t, J = 7.5 Hz, 1H; H-4′), 7.50 (s, 1H; H-5), 7.15 (d, J = 7.6 Hz, 1H; H-1′), 6.83 (d, J = 6.8 Hz, 1H; H-7′), 6.63 (d, J = 8.6 Hz, 1H; H-8′), 6.53 (d, J = 8.3 Hz, 1H; H-1), 6.51 (s, 2H; H-4), 6.34 (d, J = 6.8 Hz, 1H; H-2), 3.90 (s, 2H; NH2), 3.74 (t, J = 4.7 Hz, 4H; H-2a, 6a), 3.49 (t, J = 4.7 Hz, 4H; H-3a, 5a). 13C NMR (125 MHz, CDCl3): δ (ppm) 169.8 (C; COO), 154.7 (C; CO), 153.4 (C; C-6), 152.8 (C; C-11), 152.1 (C; C-14), 149.0 (C; C-3), 141.0 (C; C-2′), 135.1 (CH; C-4′), 129.7 (CH; C-1′), 129.2 (CH; C-5′), 124.8 (CH; C-7′), 115.2 (C; C-13), 111.7 (CH; C-2), 108.6 (C; C-12), 107.6 (CH; C-5), 101.6 (CH; C-4), 84.1 (C; C-9), 66.6 (CH2; C-2a, 6a), 44.4 (CH2; C-3a, 5a).

**Chart 1**

Fluorescent open form (polar environment)

Non-fluorescent lactone form (polar environment)
suc-AlaAlaProPhe-Rh110-MC; sucAAPF-Rh110-MC. TBTU (N,N,N',N'-tetramethyl-1,4-phenylenediamine) was obtained from Novabiochem and Boc-L-AlaPro-OH from Bachem. A mixture of TBTU (215 mg, 0.7 mmol) and DIPEA (350 μL, 2 mmol) was dissolved in 1 mL of dry DMF and added to Boc-L-Phe-OH (180 mg, 0.7 mmol) dissolved in 2 mL of dry CH2Cl2 under Ar. Phe-Rh110 MC (50 mg, 0.1 mmol) was dissolved in 1 mL of dry CH2Cl2 and slowly added to the reaction. After 17 h of stirring, the solvents were evaporated and the crude mixture was directly purified by HPLC using an acetonitrile/water gradient (12–100% ACN). Yield: 67% (14 mg, 0.04 mmol) Boc-Phe-Rh110-MC. MS (ESI+): 592 (M+H+). Deprotection of Phe was achieved by slow addition of 50/50 (v/v) TFA/CH2Cl2 (3 mL) to Boc-Phe-Rh110-MC (30 mg, 0.04 mmol) in CH2Cl2 (1.5 mL). After 3 h, the reaction was stopped and concentrated under vacuum. MS (ESI+): 579 (M+H+). NMR: 1H NMR (400 MHz, DMSO): δ (ppm) 9.99 (d, J = 7.5 Hz, 1H), 7.68–7.56 (m, 3H), 7.30 (d, J = 6.8 Hz, 1H), 7.29–7.21 (m, 3H), 7.14 (d, J = 6.8 Hz, 1H), 6.79 (s, 1H), 6.65 (d, J = 8.3 Hz, 1H), 6.55–6.51 (m, 2H), 6.34 (d, J = 7.9 Hz, 1H), 5.10 (s, 1H), 4.44 (s, 1H), 3.90 (s, 2H), 3.15 (s, 2H), 1.42 (s, 9H).13C NMR (125 MHz, CDCl3): δ (ppm) 177.6 (C), 169.8 (C), 153.4 (C), 152.6 (C), 152.0 (C), 149.0 (C), 139.2 (C), 135.0 (C), 129.7 (CH), 129.4 (CH), 129.3 (CH), 128.7 (CH), 127.4 (CH), 127.0 (C), 125.1 (CH), 124.1 (CH), 115.2 (CH), 111.8 (CH), 108.6 (C), 108.0 (CH), 101.6 (CH), 100.1 (C), 83.5 (C), 56.8 (CH), 38.1 (CH2), 28.4 (CH2).

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Rho dimers were started by adding 190 μL of chymotrypsin in PBS to 10 μL of a substrate solution in the cuvette. The final enzyme solution was 10 mM phosphate pH 7.4, 138 mM NaCl, 2.7 mM KCl, Sigma). Substrates were prepared as stock solutions in DMSO. Reactions were started by adding 190 μL of chymotrypsin in PBS to 10 μL of a substrate solution in the cuvette.
concentration was 3 nM for \((\text{suc-AAPF})_2 \text{-Rh110}\) and \(\text{suc-AAPF-Rh110-MC}\) or 900 nM for \((\text{suc-F})_2 \text{-Rh110}\) and \(\text{suc-F-Rh110-MC}\). The substrate concentrations varied between 0.4 and 50 μM. Product formation was followed by recording fluorescence \((\lambda_{\text{ex}} = 488 \text{ nm}; \lambda_{\text{em}} = 520 \text{ nm})\) with a Photon Technology International fluorescence spectrometer. The emission intensity was converted into product concentrations using calibration curves of Rh110 or MC-Rh110, respectively. 

**RESULTS AND DISCUSSION**

For the enzyme activity measurements, the following substrate analogues were synthesized: \((\text{suc-AAPF})_2 \text{-Rh110}\), \(\text{suc-AAPF-Rh110-MC}\), \((\text{suc-F})_2 \text{-Rh110}\), and \(\text{suc-F-Rh110-MC}\). These molecules were nonfluorescent and stable in aqueous solution. No autohydrolysis could be detected. The bis-amide substrate analogues \((\text{suc-AAPF})_2 \text{-Rh110}\) and \((\text{suc-F})_2 \text{-Rh110}\) are hydrolyzed by the enzyme following the two-step reaction shown in Scheme 1. The hydrolysis of the monoamide substrate analogues \(\text{suc-AAPF-Rh110-MC}\) and \(\text{suc-F-Rh110-MC}\) follows the reaction of Scheme 2.

Enzymatic activity was measured over a range of substrate concentrations (at least 12 data points) in order to determine the kinetic constants. At least one reaction in each series was followed to completion. In this way, the final product concentration could be determined, which corresponds directly to the initial substrate concentration. This approach yields an accurate value of the substrate concentration even if the respective compound contains noncleavable components such as molecules with D-amino acids that have not been completely removed during purification.

The results (Table 1) clearly show that the activity of α-chymotrypsin is higher for the substrate analogues containing the AAPF sequence instead of phenylalanine only. It has been observed before that the activity of α-chymotrypsin increases with increasing length of the peptide. More interesting are, however, the differences between the peptide-Rh110-MC and the bis-amide Rh110 substrate analogues. For both the 4 amino-acid-long and the 1 amino-acid-long peptides, the \(k_{\text{cat}}\) values for the peptide-Rh110-MC base substrate analogue are higher than for the \((\text{peptide})_2 \text{-Rh110}\) substrate analogue. This is expected when considering that the cleavage of the bis-amide substrate analogue (Scheme 1) involves the less fluorescent intermediate. When using the fluorescence of the product as the calibration, the actual number of cleaved bonds is underestimated due to the presence of the intermediate leading to a lower measured reaction velocity and \(k_{\text{cat}}\) value. The lower \(K_{\text{m app}}\) values for the \((\text{peptide})_2 \text{-Rh110}\) substrate analogues can potentially result from a higher effective molarity of the cleavable products.
bonds or rebinding of the intermediate after hydrolysis of the first bond. Although we cannot exclude that the MC-moiety influences the binding of the substrate analogues to the enzyme, it appears likely that the kinetic parameters obtained from the hydrolysis of the monoamide peptide-Rh110-MC substrate analogue represent the true kinetic constants related to peptide-bond cleavage. The result that the determined $k_{\text{cat/app}}$ and $K_m$ values for the double-substituted substrate analogue do not resemble the real kinetic constants is further supported by the observation that the two cleavage steps are characterized by different kinetic constants as has been shown for other fluorogenic substrate analogues before.13

Making several assumptions, we have also made an attempt to calculate the individual kinetic constants of the two-step hydrolysis reaction (see Supporting Information). While the calculated $k_{\text{cat}}/K_m$ values for the individual reaction steps have a large error, they are clearly different from each other and from the apparent values. This further emphasizes the problem associated with obtaining kinetic constants for double-substituted substrate analogues. In summary, these results show that the apparent $K_m$ and $k_{\text{cat/app}}$ values determined for the double-substituted Rh110 substrate analogues are not the true rate constants characterizing the enzymatic reaction. Clearly, there is no accurate way to determine these from an assay purely based on fluorescence. Monosubstituted substrate analogues such as peptide-Rh110-MC are required for an accurate determination of $K_m$ and $k_{\text{cat}}$.

In order to obtain a more detailed picture of the molecular mechanism determining the fluorescence of MC-Rh110, we also synthesized the monosubstituted peptide-Rh110 derivatives. We expected that a comparison of MC-Rh110 with Boc-F-Rh110 and Boc-AAPF-Rh110 as well as with Rh110 would give insight into the properties determining the high fluorescence intensity of MC-Rh110. The Boc-protected analogues were used instead of the succinylated peptides, because they are easier to obtain in high purity, which is essential for spectroscopic measurements. The Boc-group is not expected to affect the structural and photophysical properties as it has been shown before that only the amino acid closest to the fluorophore determines its properties.26 The latter is confirmed by our measurements that show similar photophysical properties for Boc-F-Rh110 and Boc-AAPF-Rh110 (see Supporting Information).

For both MC-Rh110 and Boc-F-Rh110, we have observed that their solutions in chloroform do not absorb visible light. This suggests their presence in the nonfluorescent lactone form, which is confirmed by NMR spectra. The $^1$H signals for protons 1, 2, 7, and 8 of the xanthene moiety are shielded, and the carbon $^{13}$C signal at 84 ppm corresponds to carbon 9 (see Supporting Information). Combining the $^{13}$C and DEPT spectra indicates that the number of carbons is compatible with the presence of a single molecular species. When these molecules are dissolved in water, however, they absorb in the blue region with a maximum absorption coefficient of 24 600 and 52 000 M$^{-1}$ cm$^{-1}$ for Boc-F-Rh110 and MC-Rh110, respectively. NMR measurements of MC-Rh110 in D$_2$O/DMSO (5%) confirm the formation of the open zwitterionic form and do not indicate the presence of more than one species. The carbon signals of the benzene ring and C-2, 3 of the xanthene moiety show very similar ppm values as for unsubstituted Rh110 (see Supporting Information).27 X-ray diffraction analysis of MC-Rh110 single-crystals, obtained from the slow evaporation of a methanol solution, also revealed the open ionic conformation. Methanol as a medium corresponds to a polar environment just as in an aqueous solution. In conclusion, we suggest that the previously proposed conformational equilibrium of monosubstituted Rh110 molecules is completely shifted to the lactone form in a nonpolar solution. In contrast, all molecules adopt the open ionic form in a water solution. This result is further supported by the photophysical properties of Boc-F-Rh110 and MC-Rh110 that obviously suggest a different reason for the decrease in fluorescence intensity from Rh110 to MC-Rh110 and Boc-F-Rh110.

The data presented in Figure 1 and Table 2 show that the attachment of a substituent to one of the amino groups of Rh110 leads to a blue shift of the absorption maximum, a red shift of the emission maximum, an increased bandwidth, and vibrational progression in the absorption and emission spectra. This is accompanied by a decrease of the fluorescence quantum yield. This effect is more pronounced for Boc-F-Rh110 than for MC-Rh110. These results can be rationalized by considering the

### Table 1. Kinetic Parameters for the α-Chymotrypsin Catalyzed Hydrolysis of the Substrate Analogues with One and Two Cleavable Peptide Bonds

<table>
<thead>
<tr>
<th>Substrate Analogue</th>
<th>$k_{\text{cat}}$ [s$^{-1}$]</th>
<th>$K_m$ [μM]</th>
<th>$k_{\text{cat}}/K_m$ [M$^{-1}$ s$^{-1}$]</th>
</tr>
</thead>
<tbody>
<tr>
<td>(suc-AAPF)$_2$-Rh110</td>
<td>0.43 ± 0.03</td>
<td>8.7 ± 1.6</td>
<td>(5.0 ± 1) × 10$^4$</td>
</tr>
<tr>
<td>Apparent</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Suc-AAPF-Rh110-MC</td>
<td>11 ± 1</td>
<td>68 ± 7</td>
<td>(16 ± 2) × 10$^4$</td>
</tr>
<tr>
<td>Suc-(suc-F)$_2$-Rh110</td>
<td>0.0035 ± 0.0003</td>
<td>31 ± 4</td>
<td>(1.1 ± 0.2) × 10$^3$</td>
</tr>
<tr>
<td>Apparent</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Suc-F-Rh110-MC</td>
<td>0.054 ± 0.006</td>
<td>182 ± 23</td>
<td>(3.0 ± 0.5) × 10$^2$</td>
</tr>
</tbody>
</table>

**Figure 1.** (A) Absorption and (B) emission spectra of Rhodamine 110, morpholinecarbonyl-Rh110, and Boc-F-Rh110; (C) normalized emission spectra of Rhodamine 110 and its monosubstituted peptide derivative.
resonance forms of the dyes. For Rh110, two equivalent and iso-enertic resonance forms exist with the positive charge on the left and right amino groups, respectively. For MC-Rh110, the attachment of an electron withdrawing amide moiety to one of the amino groups destabilizes the resonance form with the positive charge on the corresponding amino group. For Boc-F-Rh110, this resonance form is even more destabilized as the electron withdrawing character of the carbonyl is no longer attenuated by the electron donating morpholino moiety. As both resonance forms are no longer iso-enertic, there is an alternation of single and double bonds in the xanthene cation leading to a blue shift of the absorption. Furthermore, the alternation of single and double bonds increases upon excitation which leads to increased electron phonon coupling and hence increased vibrational progression. The asymmetry furthermore leads to a dipole moment along the long axis of the molecule that is different in the excited state and the ground state. This difference in dipole moment leads to an increased Stokes shift and hence a red shift of the fluorescence. Furthermore, the increased asymmetry of the π-cloud results in a reduced transition dipole moment between the S0 and S1 states that is reflected in the fluorescent rate constant. The molar extinction coefficient at the maximum shows an even stronger decrease resulting from the combination of an increased electron phonon coupling and a decreased transition dipole moment. Finally, the increased electron phonon coupling also leads to an increase of the nonradiative decay rate from 7.5 × 10^8 s⁻¹ in Rh110 over 1.1 × 10^9 s⁻¹ in MC-Rh110 and 2.5 × 10^9 s⁻¹ in Boc-F-Rh110. Finally, it should be noted that the fluorescence lifetimes measured at both maxima of Boc-F-Rh110 are the same, indicating that they must be attributed to the same emitting species. Overall, our results clearly suggest that the differences in fluorescence intensity do not originate from the proposed equilibrium between a lactone form and a zwitterionic form but result from differences in the electron structure of the monosubstituted Rh110 derivatives.

The absence of this equilibrium is important information for single molecule experiments, where it is essential that the fluorophore population studied is homogeneous. Thus, the chemical properties of MC-Rh110 in principle make it an ideal fluorophore for preparing substrate analogues with 1:1 stoichiometry for the analysis of enzyme kinetics at the single molecule level. However, not only the chemical properties ensure that each generated product molecule can be detected individually as a fluorescent signal.21,28 MC-Rh110 further shows sufficient brightness to be detected at the single molecule level. It is therefore our next goal to investigate if (suc-AAPF)2-Rh110 also yield different kinetic parameters in single molecule experiments where the intermediate is probably not detected due to its low brightness.

In conclusion, we have synthesized a series of fluorogenic substrate analogues for α-chymotrypsin. We have shown that only substrate analogues with one cleavable bond give access to the real kinetic constants of the enzymatic reaction. The origin of the relatively high fluorescence of the morpholine-carbonyl monosubstituted Rh110 was established. We anticipate that the fluorescence of monosubstituted fluorogenic derivatives is determined by the same mechanism and that in aqueous solution xanthene dyes in general adopt an open ionic form. This information is vital for the development of the next generation of monosubstituted fluorogenic substrate analogues, e.g., with improved solubility or cell permeability, which might ultimately allow the study of single enzyme molecules in living systems.

## ASSOCIATED CONTENT

- **Supporting Information.** Calculation of the individual kinetic constants of the two-step hydrolysis reaction, and comparison of the fluorescent properties of monoamide Rh110 derivatives and NMR data. This material is available free of charge via the Internet at http://pubs.acs.org

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