

Perspective

Cystamine and cysteamine as inhibitors of transglutaminase activity *in vivo*

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Cystamine is commonly used as a transglutaminase inhibitor. This disulphide undergoes reduction *in vivo* to the aminothiols compound, cysteamine. Thus, the mechanism by which cystamine inhibits transglutaminase activity *in vivo* could be due to either cystamine or cysteamine, which depends on the local redox environment. Cystamine inactivates transglutaminases by promoting the oxidation of two vicinal cysteine residues on the enzyme to an allosteric disulphide, whereas cysteamine acts as a competitive inhibitor for transamidation reactions catalyzed by this enzyme. The latter mechanism is likely to result in the formation of a unique biomarker, *N*-(γ -glutamyl)cysteamine that could serve to indicate how cyst(e)amine acts to inhibit transglutaminases inside cells and the body.

Introduction

Cystamine is a symmetric organodisulphide commonly used as an inhibitor of transglutaminases. This disulphide is also reduced to cysteamine within the body. Cystamine and cysteamine both inhibit transglutaminases but by different mechanisms. Therefore, the purpose of this discussion is to highlight the redox behavior of cystamine and cysteamine *in vivo* and the mechanisms by which cystamine and cysteamine inhibit the activity of transglutaminases inside the body.

Transglutaminases and the formation of cross-linked proteins in disease

Transglutaminases catalyze nucleophilic substitutions of the carboxamide group of glutamyl residues [1,2]. The attacking nucleophiles are typically the amines of various compounds, but can include hydroxyl moieties and H₂O depending on the transglutaminase isozyme or conditions. Thus, subject to the nucleophile, transglutaminases catalyze transamidation, esterification, or deamidation of glutamyl residues. Transamidation involving the ϵ amine of lysyl residues is the reaction most often catalyzed by transglutaminases and results in the formation of *N* ^{ϵ} -(γ -glutamyl)lysine isodipeptide linkages between polypeptide chains (Figure 1A). A number of important pathologies exhibit both aberrant transglutaminase activity and increased production of *N* ^{ϵ} -(γ -glutamyl)lysine cross-linked proteins (*e.g.*, neurodegenerative disorders [3-12] and cardiovascular disease [13-20]). The involvement of increased transglutaminase activity in neurodegenerative or cardiovascular diseases is supported by the observation that genetic inactivation of various transglutaminases in animal models slows progression of these diseases [21-26]. The preceding observation and others prompted a search for medicinal transglutaminase inhibitors [27-29], as well as testing of cystamine in disease models and patients [30-45]. These tests indicate that cystamine might be of benefit in the treatment of selected diseases.

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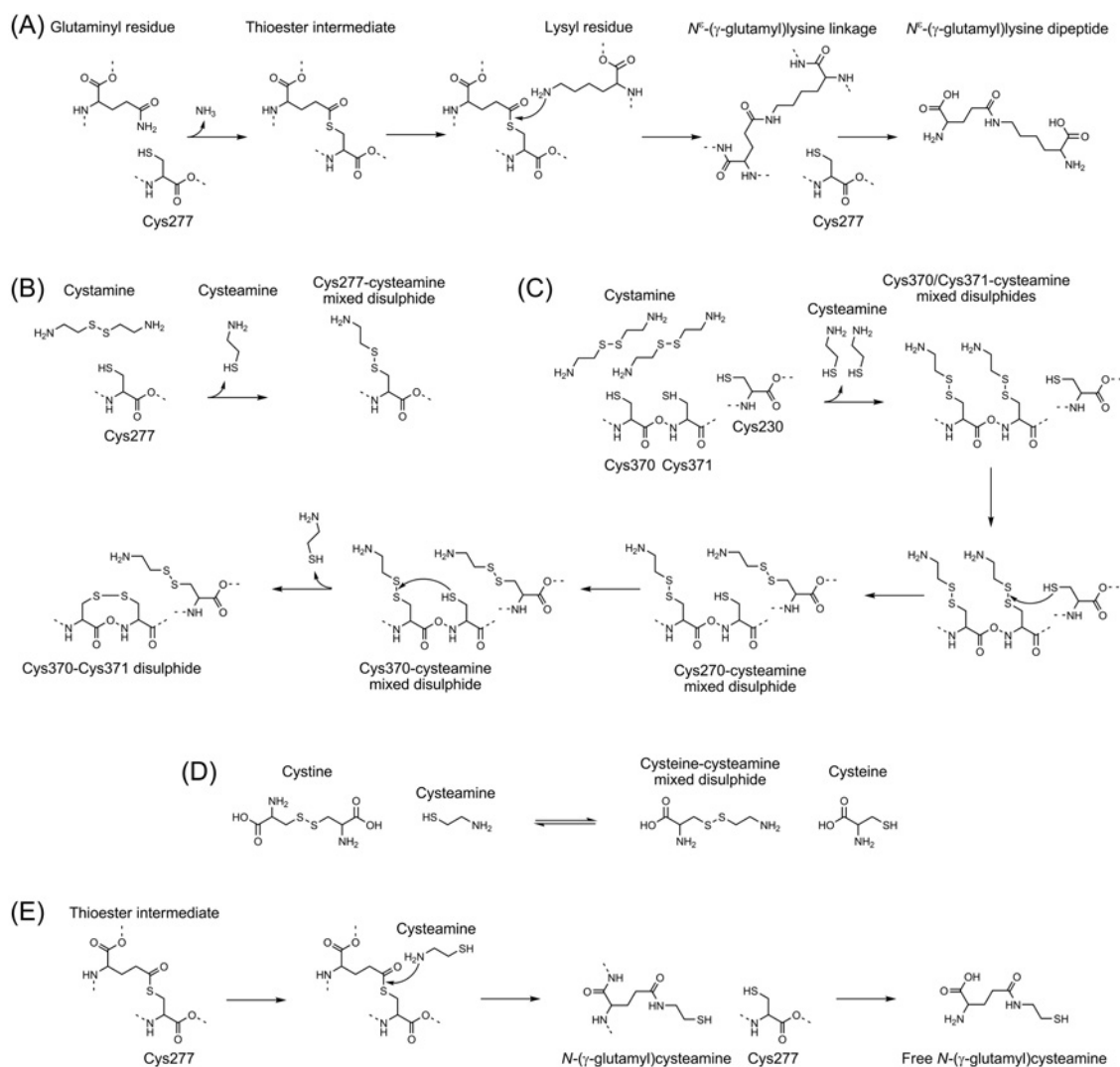


Figure 1. Reactions of cyst(e)amine with transglutaminases and cystine

(A) Transglutaminase-catalyzed *N*^ε-(γ-glutamyl)lysine isodiipeptide formation: transglutaminases catalyze an acyl transfer reaction that proceeds by a Bi-Molecular or Ping-Pong mechanism. Activated transglutaminases first act to form a thioester bond between the active site Cys²⁷⁷ and the carboxamide moiety of glutamyl residues. Formation of this intermediate involves the release of the amide nitrogen as ammonia, which powers the subsequent catalysis. The thioester bond then undergoes a nucleophilic attack by the ε amine of lysine to complete the acyl transfer and produce *N*^ε-(γ-glutamyl)lysine isodiipeptide linkage. These dipeptides can then be released from the protein by hydrolysis of the peptide linkages. **(B)** Oxidative inactivation of transglutaminase 2 by cystamine by the mechanism of Lorand and Conrad [46]: in this model, the thiol moiety of Cys²⁷⁷ participates in thiol-disulphide interchange with cystamine to produce cystamine–Cys²⁷⁷ mixed disulphide. **(C)** Oxidative inactivation of transglutaminase 2 by cystamine by our interpretation of the mechanism of Palanski and Khosla [48]: in this model, cystamine first forms mixed disulphides with Cys³⁷⁰ and Cys³⁷¹. Cys²³⁰ then undergoes thiol-disulphide interchange with cystamine–Cys²³⁰ mixed disulphide. The newly reduced Cys³⁷¹ then reduces the mixed disulphide of cystamine–Cys³⁷⁰ while being oxidized to the Cys³⁷⁰–Cys³⁷¹ disulphide. It is also possible that the Cys²³⁰ undergoes thiol-disulphide interchange with the cystamine–Cys³⁷⁰ mixed disulphide rather than the cystamine–Cys³⁷¹ mixed disulphide. In either case, the Cys³⁷⁰–Cys³⁷¹ disulphide would form and allosterically regulate the enzyme. **(D)** Thiol-disulphide interchange of cystamine and cystine: cystamine interacts with cystine by thiol-disulphide interchange to form the cystamine–cystine mixed disulphide. Note that the latter resembles the lysyl residue depicted in (A). **(E)** Transglutaminase-catalyzed *N*-(γ-glutamyl)cystamine formation: a mechanism for the competitive inhibition of transglutaminase by cystamine. This mechanism is analogous to that shown in (A) and for the sake of brevity begins with thioester bound intermediate. The thio-ester bond is attacked by the amine nitrogen of cystamine to complete the acyl transfer and produce *N*-(γ-glutamyl)cystamine. We propose that *N*-(γ-glutamyl)cystamine is released from the protein by proteolysis, as is the case for other *N*-(γ-glutamyl)amines.

Oxidative mechanisms for the inhibition of transglutaminases by cystamine

Cystamine was first reported to be an inhibitor of transglutaminase 2 by Lorand and Conrad in 1984 [46]. They hypothesized that cystamine and the active site Cys²⁷⁷ undergo a thiol-disulphide interchange to produce a mixed disulphide that prevents catalysis (Figure 1B). Cystamine is the disulphide form of cysteamine. Thus, the proposed thiol-disulphide interchange (thiolation) produces free cysteamine and a mixed disulphide of cysteamine and Cys²⁷⁷. An 'oxidative mechanism' for the inhibition of transglutaminase 2 is supported by subsequent investigations by Jeon *et al.* [47], and also by Palanski and Khosla [48]. The latter researchers, however, proposed a modified hypothesis, which states that cystamine forms mixed disulphides with a triad of cysteinyl residues on the surface of transglutaminase 2 that regulates the activation of the extracellular pool of this enzyme. According to Palanski and Khosla [48], cystamine reacts with Cys²³⁰, Cys³⁷⁰, or Cys³⁷¹ to promote the eventual formation of an allosteric disulphide bond between Cys³⁷⁰ and Cys³⁷¹ as shown in Figure 1C. These mechanisms, however, presume that cystamine is not metabolized *en route* to the targetted transglutaminases; a presumption that is not supported by pharmacokinetic studies.

Conversion of cystamine into cysteamine within the body

Cystamine is rapidly reduced to cysteamine by serum, as well as by the liver and kidneys [49]. By contrast, cysteamine is relatively stable in plasma and rapidly absorbed from blood into tissues [49-53]. Prior to cellular uptake, cysteamine undergoes thiol-disulphide interchange with extracellular cystine to form cysteamine-cysteine mixed disulphide (Figure 1D), which resembles lysine [54,55]. Consequently, the cysteamine-cysteine mixed disulphide enters cells through amino acid transporters and is then reduced to cysteamine and cysteine. Thus, the major form in which cystamine inhibits intracellular transglutaminases is cysteamine and not cystamine.

Cysteamine as an inhibitor of intracellular transglutaminases

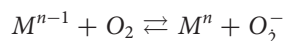
In earlier studies, we demonstrated that cysteamine acts as a substrate for transglutaminase 2 to link this compound to glutamyl residues by way of an isopeptide linkage forming *N*-(γ -glutamyl)cysteamine (Figure 1E) [56]. In other words, cysteamine by virtue of being a transglutaminase 2 substrate, acts as a competitive inhibitor of the other amine substrates of this enzyme. Cystamine has not been shown to be an amine substrate of transglutaminase 2, an assertion erroneously attributed to us elsewhere [48]. Formation of *N*-(γ -glutamyl)cysteamine by transglutaminases could account for two puzzling observations pertaining to the metabolism of exogenously supplied cysteamine. The first of these observations is that a significant portion of the administered cysteamine is unaccounted for following analysis of established routes of metabolism. Cysteamine generated endogenously by the catabolism of pantetheine is oxidized to hypotaurine and then taurine [57]. The administration of cysteamine to rodents, however, does not result in significant accumulation of hypotaurine or taurine in brain or plasma [49], and indicates that the metabolism of exogenous cysteamine bypasses oxidation to taurine. A small portion of cysteamine administered *per os* is metabolized to thialysine and then *S*-(2-aminoethyl)-cysteine ketimine decarboxylated dimer [50]. Based on the levels of cysteine that accompany cysteamine into cells as a mixed disulphide, significant quantities of cysteamine must enter cells [38,49-51,54,55] but it is then rapidly metabolized. The cellular fate of the majority of exogenous cysteamine remains unaccounted for.

A role for transglutaminases in the metabolism of cysteamine

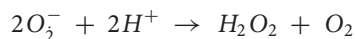
A novel hypothesis for the metabolism of cysteamine is that it is covalently attached to proteins by intracellular transglutaminases. This hypothesis is supported by the observation that a significant portion of radiolabeled cysteamine administered to animals or cells is covalently bound to proteins, but not by disulphide bonds [58,59]. This hypothesis requires that the intracellular transglutaminases be activated while cysteamine is being absorbed by cells. Transglutaminases are activated by calcium. Exogenous cysteamine may stimulate calcium release from intracellular stores and thereby promote transglutaminase activity. This mechanism depends on the production of hydrogen peroxide (H_2O_2), by micromolar amounts of cysteamine. At these concentrations, thiols (*RSH*) such as cysteamine reduce transition metals ($M^n \rightarrow M^{n-1}$, where *n* is the oxidation number), while being oxidized to the corresponding disulphide (*RSSR*):



The reduced metals, in turn, reduce oxygen (O_2) to superoxide (O_2^-):



Dismutation of superoxide yields hydrogen peroxide (H_2O_2), which is a mild oxidant at physiological pH values (7.2–7.4):



Thiols, such as cysteamine, react slowly with hydrogen peroxide under these conditions [60]. Effective scavenging of the peroxide by thiols does not occur until the thiols are present at millimolar concentrations [54]. Thus, at the micromolar concentrations that it attains outside of cells, cysteamine promotes hydrogen peroxide production by the reactions shown above [54]. Hydrogen peroxide readily enters cells and causes a peroxidative stress that is exacerbated by the inhibition of cellular glutathione peroxidases by cysteamine [54].

Hydrogen peroxide promotes the release of calcium from intracellular stores [61,62] and should therefore stimulate transglutaminase activity. In support of this notion, the addition of hydrogen peroxide to cells in culture stimulates their *in situ* transglutaminase activity [63,64].

The above conjecture could be readily tested by investigating the plasma of cysteamine-treated animals or medium of cells in culture treated with cysteamine for the presence of free *N*-(γ -glutamyl)cysteamine. Isopeptide linkages are resistant to proteolysis and consequently transglutaminase-made *N*-(γ -glutamyl)amines are excised as free *N*-(γ -glutamyl)amines during proteolysis of proteins bearing these species [65]. Free *N*-(γ -glutamyl)amines are present in various body fluids and reflect the levels of active transglutaminases in tissues [3,66,67]. If our hypothesis is correct, then the simultaneous measurements of taurine, *S*-(2-aminoethyl)l-cysteine ketimine decarboxylated dimer, as well as protein-bound and free *N*-(γ -glutamyl)cysteamine should provide a comprehensive accounting of the metabolism of exogenous cyst(e)amine, in addition to indicating the mechanism by which cysteamine inhibits intracellular transglutaminases.

Sites for the oxidative inactivation of transglutaminases by cystamine

Transglutaminases are fully activated by the binding of three calcium ions per enzyme and reducing conditions that maintain the active site cysteine in a fully reduced state [1,2,47]. The cytosol is highly reducing and therefore the activation of intracellular transglutaminases is regulated by the availability of cytosolic calcium. The extracellular environment is different; calcium is readily available whereas reductants are not. Khosla et al. discovered that the activity of extracellular transglutaminase 2 is regulated by the redox status of two vicinal cysteinyl residues on the surface of this enzyme [68]. Under the oxidizing conditions of interstitial fluids [69], these residues: Cys³⁷⁰ or Cys³⁷¹ form a disulphide in a manner that involves a third cysteinyl residue, Cys²³⁰, and ERp57 [70]. Reduction in the Cys³⁷⁰–Cys³⁷¹ disulphide linkage by thioredoxin activates extracellular transglutaminase 2 [71,72]. The activation of extracellular transglutaminase by this mechanism is blocked by cystamine forming mixed disulphides with Cys³⁷⁰ and Cys³⁷¹ (Figure 1C). As noted earlier, cystamine is converted into cysteamine in the body [49]. It is possible that a portion of the plasma-derived cysteamine is oxidized to cystamine within the interstitial spaces and in this form inactivates extracellular transglutaminases. The amount of cystamine available to inhibit the extracellular transglutaminases by this mechanism will depend on the amounts of cysteamine and cysteamine–cysteine mixed disulphide; the amounts of the latter are expected to be significant after the administration of cyst(e)amine. It should be noted that cysteamine–cysteine mixed disulphide could also inhibit transglutaminase in an oxidative manner, as shown in Figure 1C with cysteamine–cysteine mixed disulphide replacing cystamine. The lumen of the gut is also likely to be an oxidizing environment because the administration of cysteamine by gavage results in the appearance of cystamine in the plasma [50]; the most likely site for oxidation of cysteamine to cystamine, in this case, is the gut. Thus, cystamine is most likely to inhibit transglutaminases by an oxidative mechanism in the gut. This observation is important since aberrant transglutaminase activities contribute to etiology of several intestinal diseases, in particular, celiac disease. In this disease, transglutaminases act to deamidate glutamyl residues in the wheat protein gliadin increasing the autoantigenicity of the modified protein in the context of HLA-DQ2 or HLA-DQ8 [73]. Cystamine inhibits the generation of the relevant epitopes *in vitro*, but only at millimolar concentrations [74]. Given the relatively safe use of cysteamine in humans [75–77] and the potential to assess the mechanism by which this compound inhibits transglutaminases (*i.e.*, by measurement of *N*-(γ -glutamyl)cysteamine), cysteamine may be of use in the treatment of celiac disease and other diseases involving transglutaminases.

Conclusion

The activities of intracellular and extracellular transglutaminases contribute to a number of important pathologies. Agents that safely inhibit the *in situ* activities of these transglutaminase pools are therefore of interest as possible therapeutics. The evidence presented here indicates that cystamine inhibits extracellular transglutaminases, while its reduced congener – cysteamine – inhibits intracellular transglutaminases. This distinction is important for the design of other transglutaminase inhibitors based on the mechanisms by which cysteamine or cystamine inhibit these enzymes (e.g., disulphiram [48]). It may also guide the form in which cystamine is administered: as either cystamine or cysteamine. Finally, the measurement of *N*-(γ -glutamyl)cysteamine may provide a means of determining the mechanism by which intracellular transglutaminases are inhibited following the administration of cystamine or cysteamine.

Competing interests

The authors declare that there are no competing interests associated with the manuscript.

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