A Monomeric Variant of Insulin Degrading Enzyme (IDE) Loses Its Regulatory Properties

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A Monomeric Variant of Insulin Degrading Enzyme (IDE) Loses Its Regulatory Properties

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Abstract

**Background:** Insulin degrading enzyme (IDE) is a key enzyme in the metabolism of both insulin and amyloid beta peptides. IDE is unique in that it is subject to allosteric activation which is hypothesized to occur through an oligomeric structure.

**Methodology/Principal Findings:** IDE is known to exist as an equilibrium mixture of monomers, dimers, and higher oligomers, with the dimer being the predominant form. Based on the crystal structure of IDE we deleted the putative dimer interface in the C-terminal region, which resulted in a monomeric variant. Monomeric IDE retained enzymatic activity, however instead of the allosteric behavior seen with wild type enzyme it displayed Michaelis-Menten kinetic behavior. With the substrate Abz-GGFLRKHGQ-EDDnp, monomeric IDE retained ~25% of the wild type activity. In contrast with the larger peptide substrates [β-endorphin and amyloid β peptide 1-40], monomeric IDE retained only 1 to 0.25% of wild type activity. Unlike wild type IDE neither bradykinin nor dynorphin B-9 activated the monomeric variant of the enzyme. Similarly, monomeric IDE was not activated by polyphosphates under conditions in which the activity of wild type enzyme was increased more than 50 fold.

**Conclusions/Significance:** These findings serve to establish the dimer interface in IDE and demonstrate the requirement for an oligomeric form of the enzyme for its regulatory properties. The data support a mechanism where the binding of activators to oligomeric IDE induces a conformational change that cannot occur in the monomeric variant. Since a conformational change from a closed to a more open structure is likely the rate-determining step in the IDE reaction, the subunit induced conformational change likely shifts the structure of the oligomeric enzyme to a more open conformation.

Introduction

Insulin-degrading enzyme (IDE) also known as insulinysin, is a zinc metalloprotease first described based on its ability to cleave insulin [1–3]. Mutations in IDE are linked to a type II diabetic phenotype in the GK rat [4]. In addition IDE has been shown to play a key role in Alzheimer’s disease in that it is one of the major enzymes responsible for amyloid β peptide (Aβ) clearance in the brain. Studies from this [5] and other laboratories [6] have shown that mice lacking IDE activity through gene disruption accumulate Aβ in the brain in a gene dose dependent manner. A number of studies have linked the IDE gene to both type 2 diabetes [7,8] and AD [9,10] although in the latter case a genetic association has yet to be firmly established.

We first reported that IDE is unique among the zinc metalloproteases in that it exhibits allosteric kinetic behavior [11]. The reaction of IDE with the internally quenched fluorogenic substrate 2-aminobenzyl-glycyl-glycyl-phenylalanyl-leucyl-arginyl-lysyl-histidyl-glycyl-asparaginyl-ethylenediamine-2,4-dinitrophenol (Abz-GGFLRKHGQ-EDDnp) was shown to exhibit both substrate induced (homoitrophic) activation as well as activation produced by small peptides (heterotrophic activation). In addition we reported that polyphosphates such as ATP and triphosphate act as non-substrate heterotrophic activators, binding at a site distinct from the active site and distinct from the peptide activation site [12].

Recently the structures of IDE both liganded and unliganded were determined by Tang and co-workers [13–15]. These structures show that larger peptides make extended binding interactions at both the active site and at a distal site. We have recently determined the structure of rat IDE and found that this distal binding site serves as the site in which small peptide activators bind (Nicholas Noinaj, Sonia K. Bhasin, Eun Suk Song, Kirsten Scoggin, Louis B. Hersh, and David W. Rodgers, manuscript in preparation).

IDE exists as a mixture of monomers, dimers, and tetramers with the dimer the predominant species [11]. From the IDE structure of Shen et al [16] and confirmed in our IDE structure an interface in the C-terminal region, which resulted in a monomeric variant. Monomeric IDE retained enzymatic activity, however instead of the allosteric behavior seen with wild type enzyme it displayed Michaelis-Menten kinetic behavior. With the substrate Abz-GGFLRKHGQ-EDDnp, monomeric IDE retained ~25% of the wild type activity. In contrast with the larger peptide substrates [β-endorphin and amyloid β peptide 1-40], monomeric IDE retained only 1 to 0.25% of wild type activity. Unlike wild type IDE neither bradykinin nor dynorphin B-9 activated the monomeric variant of the enzyme. Similarly, monomeric IDE was not activated by polyphosphates under conditions in which the activity of wild type enzyme was increased more than 50 fold.

**Conclusions/Significance:** These findings serve to establish the dimer interface in IDE and demonstrate the requirement for an oligomeric form of the enzyme for its regulatory properties. The data support a mechanism where the binding of activators to oligomeric IDE induces a conformational change that cannot occur in the monomeric variant. Since a conformational change from a closed to a more open structure is likely the rate-determining step in the IDE reaction, the subunit induced conformational change likely shifts the structure of the oligomeric enzyme to a more open conformation.

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support our previous hypothesis [11] that an oligomeric form of IDE is required for allosteric activation.

**Results**

IDE is known to exist in a monomer-dimer-tetramer equilibrium with the dimer being the predominant form [11]. We examined our crystal structure of rIDE for a possible dimerization domain and found that molecular packing within the rIDE crystal lattice consistent with the presence of a dimer interface at the C-terminal region of the enzyme. This possibility is supported by the conservation of this interface in the crystals of hIDE [13] even though the human enzyme crystallizes in a different form. The proposed dimer interface buries about 1,400 Å² of accessible

![Images showing the proposed dimer of IDE.](A) Two orthogonal views of rIDE monomers from the crystal lattice are shown with elements making up the dimer interface highlighted in red for the top subunit. IDE is composed of four structurally related domains. Those domains are numbered in the top subunit in the left panel, and the N and C termini are indicated for the top subunit in the right panel. The C terminal region of IDE deleted in the rIDE_C construct intended to destabilize the dimer interface is highlighted in blue for the lower monomers in both panels. (B) Close up of the dimer interface showing the region deleted in the rIDE_C construct. Deleted residues 1002–1014 are shown in a stick representation with sheet-like hydrogen bonds across the interface at Leu1004 indicated by dashed lines.

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Figure 1. Proposed dimer of IDE.
surface area and involves elements from domains 3 and 4 of the four structurally related domains that make up the enzyme, Figure 1. A key set of contacts occurs between regions near the C-terminus of each monomer, residues 1002–1006, which make non-polar and hydrogen bond interactions across the interface.

rIDE has only 13 residues C terminal to this interaction region, and only eight (to residue 1014) are seen in the crystal structure, which makes that C-terminal region of IDE could be removed without greatly compromising the stability of the enzyme. Such a deletion should destabilize the dimer interface sufficiently to make monomeric IDE the predominant form in solution. To test this hypothesis and to study the properties of monomeric IDE we generated a mutant in which residues 1002 to 1019 were deleted yielding rIDE<sup>DC</sup>. This mutant, as well as wild type rIDE, were expressed in insect cells as hexahistidine fusion proteins and purified by nickel affinity chromatography.

We demonstrated that rIDE<sup>DC</sup> is monomeric by molecular sieve chromatography. As shown in Figure 2, chromatography of wild type rIDE on a Superdex S200 column revealed the presence of tetrameric, dimeric, and monomeric species, with the dimer being the predominant form as expected. In contrast chromatography of rIDE<sup>DC</sup> on the same column at the same protein concentration showed a single monomeric species.

The kinetics of the rIDE<sup>DC</sup> reaction was compared to wild type rIDE using the fluorogenic substrate Abz-GGFLRKHGQ-EDDnp. rIDE<sup>DC</sup> retained enzymatic activity, however it no longer exhibited the sigmoidal kinetics seen with wild type rIDE, Figure 3. The kinetic constants, summarized in Table 1, show that rIDE<sup>DC</sup> exhibits about 25% of the k<sub>cat</sub> of wild type rIDE, but has a lower substrate K<sub>M</sub>. In contrast to wild type rIDE, where the reaction is cooperative with a Hill coefficient of 2, rIDE<sup>DC</sup> exhibits classical Michaelis-Menten kinetics with a Hill coefficient of ~1.

We next determined whether rIDE<sup>DC</sup> retained the ability to degrade larger physiological substrates by comparing its reaction with β-endorphin and amyloid β peptide 1–40 (Aβ<sub>1–40</sub>) to the reaction of wild type rIDE. At a fixed concentration of 10 μM substrate rIDE<sup>DC</sup> cleaved these larger peptide substrates at about 1 to 0.25% the rate of wild type rIDE. With Aβ<sub>1–40</sub> we observed...
peptide products that appeared with wild type IDE, but were absent from the rIDE<sup>MC</sup> cleavage, and unique products appeared only in the rIDE<sup>MC</sup> cleavage. As shown in figure 4 (top), those products absent in the rIDE<sup>MC</sup> cleavage of Ab<sub>1-40</sub> were identified as Ab<sub>1-18</sub> (cleavage at a Val-Phe bond) and Ab<sub>1-13</sub> (cleavage at a His-His bond), while products unique to the rIDE<sup>MC</sup> cleavage of Ab<sub>1-40</sub> were Ab<sub>1-17</sub> (unique cleavage at a Leu-Val bond), Ab<sub>14-22</sub> (unique cleavage at a Glu-Asp bond), Ab<sub>19-33</sub> (unique cleavage at a Gly-Leu bond), and Ab<sub>26-40</sub> (unique cleavage at Ser-Asn bond). Similarly we identified two additional cleavage sites in β-endorphin with rIDE<sup>MC</sup>, Figure 4B. IDE normally cleaves β-endorphin at the Leu<sub>17</sub>-Phe<sub>18</sub> and Phe<sub>18</sub>-Lys<sub>19</sub> bonds [16]. The rIDE<sup>MC</sup> mutant cleaved at these sites, but in addition cleaved at Thr<sup>6</sup>-Ser<sup>7</sup> plus Phe<sup>10</sup>-Lys<sup>13</sup> and at Thr<sup>6</sup>-Ser<sup>7</sup> plus Asn<sup>9</sup>-Ala<sup>11</sup> Time course experiments showed that these products could not be detected with wild type IDE throughout the entire time course of its reaction with β-endorphin. Additional cleavage sites in β-endorphin (Met<sup>6</sup>-Thr<sup>7</sup> and Lys<sup>10</sup>-Asn<sup>14</sup>) were previously observed in the reaction of rIDE mutants containing substitutions of the active site glutamate [16].

We previously reported that substrates for IDE such as bradykinin and dynorphin B-9 act as activators of the hydrolysis of Abz-GGFLRKHGQ-EDDnp [11]. Based on our hypothesis that activation of IDE by activators occurs through conformational changes transmitted from one subunit to the other, we would predict that the monomeric rIDE<sup>MC</sup> variant would not exhibit this activation. That this is the case is shown for bradykinin and dynorphin B-9 as the effectors, Figure 5. With wild type rIDE, activation of IDE by activators occurs through conformational changes in the adjacent subunit. Clearly this cannot occur in monomeric IDE, leading to a decrease in k<sub>cat</sub>.

With the larger substrates β-endorphin and amyloid β peptide the extended binding interactions would be expected to make the conformational change needed for product release energetically more difficult than with small substrates. We suggest that one possibility is that hydrolysis of the substrate in the active site of one oligomeric subunit produces the driving force that leads to a conformational change transmitted to the adjacent subunit. This conformational change increases the rate of enzyme opening produced by the binding of substrate to one subunit and transmitting a conformational change to the adjacent subunit. Clearly this cannot occur in monomeric IDE, leading to a decrease in k<sub>cat</sub>.

The crystallographic studies of Tang and coworkers [13] show that IDE totally engulfs the bound peptide in the Michaelis complex, with no room for products to dissociate. Thus the rate-determining step must involve a conformational change that opens the enzyme to permit product dissociation. The increase in k<sub>cat</sub> produced by activators with small synthetic substrates would therefore involve an increase in the rate of enzyme opening produced by the binding of substrate to one subunit and transmitting a conformational change to the adjacent subunit.

Table 1. Comparison of kinetic constants for IDE and monomeric IDE.

|       | IDE  | IDE<sup>MC</sup> |
|-------|------|------------------|
| k<sub>cat</sub> (min<sup>-1</sup>) | 2.62±0.26 | 0.67±0.02 |
| Km<sub>b</sub> or Km<sub>c</sub> (μM) | 21.5±3.7 | 6.6±0.2 |
| Hill coefficient | 2.0±0.3 | 1.1±0.1 |

Kinetic constants were derived by fitting the data from two experiments similar to that shown in figure 3 to a sigmoidal or hyperbolic substrate versus velocity response curve as described in Methods. doi:10.1371/journal.pone.0009719.t001

Discussion

Contacts in crystals of IDE suggest that the dimer interface is formed by elements of the two C-terminal domains, including a sheet-like contact formed by a terminal β strand. Thus by deleting 18 residues from the C terminus, we anticipated that the intermolecular contacts would be sufficiently weakened that only monomers would be stable. This was indeed the case as evidenced by the finding of only monomeric rIDE in the deletion mutant preparation.

The monomeric rIDE variant exhibits 25% of the catalytic activity of wild type rIDE and no longer exhibits substrate induced homotropic activation with Abz-GGFLRKHGQ-EDDnp. Substrate induced cooperativity or homotropic activation, likely results from binding of the substrate at a site distinct from the catalytic site that is part of an extended substrate-binding site (Nicholas Noiíñaj, Sonia K. Bhasin, Eun Suk Song, Kirsten Scoggin, Louis B. Hersh, and David W. Rodgers, manuscript in preparation). Binding at this region of the extended substrate binding site is suggested to produce a conformational change in the adjacent subunit. Thus the absence of substrate induced cooperativity as shown by change from a sigmoidal substrate versus velocity response seen with wild type IDE to a hyperbolic response seen in monomeric IDE can be explained by the loss of subunit-subunit interactions.

In contrast to the relatively small decrease in k<sub>cat</sub> observed with Abz-GGFLRKHGQ-EDDnp as substrate, the monomeric rIDE variant exhibits a 100 to 200-fold decrease in the rate of cleavage of the larger physiological peptides β-endorphin and amyloid β peptide. Larger peptides like β-endorphin and amyloid β peptide traverse the protein and bind both at the active site as well as at a distal site [13]. Since a portion of amyloid β peptide (and likely β-endorphin) occupies the distal site we suggest these substrates “self-activate” producing the same or similar conformational change in the adjacent subunit and are thus insensitive to heterotropic activation.

The crystallographic studies of Tang and coworkers [13] show that IDE totally engulfs the bound peptide in the Michaelis complex, with no room for products to dissociate. Thus the rate-determining step must involve a conformational change that opens the enzyme to permit product dissociation. The increase in k<sub>cat</sub> produced by activators with small synthetic substrates would therefore involve an increase in the rate of enzyme opening produced by the binding of substrate to one subunit and transmitting a conformational change to the adjacent subunit. Clearly this cannot occur in monomeric IDE, leading to a decrease in kcat.
Figure 4. HPLC chromatograms showing the cleavage of Aβ₁₋₄₀ and β-endorphin by IDE and IDE<sup>DC</sup>. (Top) Reaction mixtures containing 10 μM Aβ₁₋₄₀ in 50 mM Tris-HCl, pH 7.4 (curve A) were incubated with 100 ng of IDE for 5 min (curve B) or 2 μg of the monomeric IDE variant for 3 hrs (curve C). The amount of enzyme and time used was chosen so that a similar fraction of substrate would be consumed by both IDE and the monomeric IDE variant permitting a comparison of products formed at the same fraction of substrate consumed. Reaction products were separated by gradient HPLC on a Vydac C4 reverse phase column as previously described (16). Product peaks were collected manually and identified by mass spectrometry. Peak 1 is Aβ₁₋₁₄ (observed mass = 1698.72, calculated mass = 1698.72); peak 2 is Aβ₁₋₁₃ (observed mass = 1561.68, calculated mass = 1561.58); peak 3 is Aβ₁₋₁₈ (observed mass = 2167.32, calculated mass = 2167.32); peak 4 is Aβ₁₋₁₃ (observed mass = 2314.50, calculated mass = 2314.5); peak 5 is Aβ₁₋₂₀ (observed mass = 2461.67, calculated mass = 2461.67); peak 6 is Aβ₅₋₂₈ (observed mass = 1581.78, calculated mass = 1581.78); peak 7 is Aβ₁₋₄₀ (observed mass = 1886.2, calculated mass = 1886.2); peak 8 is Aβ₁₋₂₀ (observed mass = 2033.02, calculated mass = 2033.37); peak 9 is Aβ₁₋₄₀ (observed mass = 2785.5, calculated mass = 2786.29); peak 10 is Aβ₁₋₁₇ (observed mass = 2068.04, calculated mass = 2068.19); peak 11 is Aβ₁₋₁₃ (observed mass = 1413.8, calculated mass = 1413.8); peak 12 is Aβ₁₋₁₃ (observed mass = 1524.69, calculated mass = 1524.69); peak 13 is Aβ₁₋₁₃ (observed mass = 1118.6, calculated mass = 1118.3). Note peaks 3 and 4 are absent in the rIDE<sup>DC</sup> cleavage products, while peaks 10 to 13 are unique to rIDE<sup>DC</sup>. Although not shown the reaction was followed from 15% cleavage to 90% cleavage with similar results. (Bottom) Reaction mixtures containing 10 μM β-endorphin (βEp) in 50 mM Tris-HCl, pH 7.4 (curve A) were incubated with 50 ng of IDE for 15 min (curve B) or 2 μg of the monomeric IDE variant for 3 hrs (curve C). Reaction conditions and product separation and identification were as in (A) above. Peak 1 is β-endorphin 19–31 (observed mass = 1475.84, calculated mass = 1476.74); peak 2 is β-endorphin 18–31 (observed mass = 1623.91, calculated mass = 1623.91); peak 3 is β-endorphin 1–17 with methionine oxidized to its sulfoxide (observed mass = 1874.94, calculated mass = 1875.13); Peak 4 is β-endorphin 1–18 (observed mass = 2005.97, calculated mass = 2006.3); peak 5 is β-endorphin 7–20 (observed mass = 1590.86, calculated mass = 1591.82); peak 6 is β-endorphin 7–18 (observed mass = 1349.78, calculated mass = 1349.54). Note peaks 5 and 6 were only observed in the reaction with IDE<sup>DC</sup>. Although not shown the reaction was followed from ~20% cleavage to ~85% cleavage with similar results.

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The observation that both Aβ_{1–40} and β-endorphin are cleaved at unique sites by monomeric rIDE further suggests that substrate binding is different in the monomeric enzyme. Thus interactions between subunits in the oligomeric form of IDE likely contribute to the conformation of the enzyme-substrate complex.

It should be noted that we cannot rule out a mechanism in which dimer contacts are required for activation to occur within a subunit, although previous studies [11] with mixed dimers containing one catalytically active and one catalytically inactive subunit weigh against this alternative. It is also possible that loss of the C-terminal 18 residues directly affects the properties of the enzyme independent of the effect on oligomerization. Given the tenuous attachment of these residues to the rest of the enzyme, this possibility seems unlikely.

We find that in contrast to wild type IDE, the activity of monomeric IDE is not increased by small peptides or by polyphosphates. However binding of the nucleotide triphosphate TNP-ATP does occur as shown by an increase in its fluorescence in the presence of monomeric IDE. Thus the absence of activation of monomeric IDE in the presence of binding can be accounted for by the necessity of a conformational change induced by activator binding to one subunit and transmitted to the adjacent subunit. Alternatively or additionally the oligomeric form of IDE might be required for proper activator binding. That this may be a contributing factor is indicated by the observation of a smaller shift of the fluorescence maxima of bound TNP-ATP with monomeric IDE compared to oligomeric IDE.

**Materials and Methods**

**Preparation of an IDE C-terminal Deletion Mutant**

For construction of an IDE mutant with the C-terminal 18 amino acids deleted PCR was used to generate a 360 bp fragment containing a stop codon, which replaced a 415 bp Pst I – Xho I fragment from the rIDE cDNA in pFast Bac HTb. Oligonucleotides used for preparing the deletion mutant were:

5′ – TATCTGCAGAGTGCGCGAAGTACTAGG – 3′

Pst I stop codon

5′ – AGACTCGAG

TCA GCCGCGCTTGAATTCAGT – 3′

Xho I

**IDE Expression and Purification**

Native rIDE and its C-terminal deletion mutant, rIDE^{DC} were expressed in Sf9 insect cells and purified as hexahistidine fusion proteins on HIS-select Ni-NTA agarose (Sigma) as previously described [16,18]. This procedure generally yielded homogeneous native rIDE, however in those instances when contaminants were detected, anion exchange chromatography on a 1 ml MonoQ...
column was used to produce enzyme of ~90% purity. Recombinant rIDE<sup>MC</sup> did not express as well as wild type rIDE in Sf9 cells and yielded enzyme preparations of ~50–60% purity.

**Enzyme Activity Assay**

The internally quenched fluorogenic peptide Abz-GGFL-RKHGQ-EDDnp was used to routinely measure IDE activity as previously described [18]. Reaction mixtures (200 µl) contained 50 mM Tris-HCl, pH 7.4 with 10 µM Abz-GGFL-RKHGQ-EDDnp.

**Kinetic Analysis**

Kinetic data were fit using Graphpad software to either a hyperbolic substrate versus velocity response curve \( v = \frac{V_{\text{max}} [S]}{K_M + [S]} \) (Michaelis-Menten equation) or to a sigmoidal response curve \( v = \frac{V_{\text{max}} [S]^h}{K_M + [S]^h} \), where \( v \) is the observed rate, \( V_{\text{max}} \) is the maximal velocity, \( K_M \) is the Michaelis constant, \( S \) is the variable substrate, and \( h \) is the Hill coefficient. For reactions with physiological peptides, a fixed concentration of \( \beta \)-endorphin (10 µM) and amyloid \( \beta \) peptide (10 µM) was incubated with IDE (50 ng) or IDE<sup>MC</sup> (2 µg) for 15 min to 3 hrs. The rate of peptide cleavage was determined by following the disappearance of the parent peptide by HPLC [16]. Product peaks were collected and their identification determined by tandem mass spectrometry.

**Activation studies**

Activation of IDE by peptides or by triphosphates was determined by measuring their ability to increase the rate of Abz-GGFL-RKHGQ-EDDnp cleavage. Data were fit to a hyperbolic response curve using Prism Graphpad software.

**Molecular weight determination**

Gel filtration was performed on a Pharmacia Superdex S200 column equilibrated with 20 mM potassium phosphate buffer, pH 7.4 and run at a flow rate of 0.4 ml/min. The eluted fractions (1 ml) were assayed for IDE activity using Abz-GGFL-RKHGQ-EDDnp as substrate.

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Mass spectrometric analyses were performed at the University of Kentucky Center for Structural Biology Proteomics Core Facility.

**Author Contributions**

Conceived and designed the experiments: ESS DWR LBH. Performed the experiments: ESS. Analyzed the data: ESS DWR LBH. Contributed reagents/materials/analysis tools: DWR. Wrote the paper: LBH.

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