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Structure of the Q237W mutant of Hhal DNA methyltransferase: an insight into protein-protein interactions

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Abstract

We have determined the structure of a mutant (Q237W) of Hhal DNA methyltransferase, complexed with the methyl-donor product AdoHcy. The Q237W mutant proteins were crystallized in the monoclinic space group C2 with two molecules in the crystallographic asymmetric unit. Protein-protein interface calculations in the crystal suggest that the dimer interface has the specific characteristics for homodimer protein-protein interactions, while the two active sites are spatially independent on the outer surface of the dimer. The solution behavior suggests the formation of Hhal dimers as well. The same Hhal dimer interface is also observed in the previously characterized binary (M.Hhal-AdoMet) and ternary (M.Hhal-DNA-AdoHcy) complex structures, crystallized in different space groups. The dimer is characterized either by a non-crystallographic two-fold symmetry or a crystallographic symmetry. The dimer interface involves three segments: the amino-terminal residues 2–8, the carboxy-terminal residues 313–327, and the linker (amino acids 179–184) between the two functional domains – the catalytic methylation domain and the DNA target recognition domain. Both the amino- and carboxy-terminal segments are part of the methylation domain. We also examined protein-protein interactions of other structurally characterized DNA MTases, which are often found as a 2-fold related ‘dimer’ with the largest dimer interface area for the group-β MTases. A possible evolutionary link between the Type I and Type II restriction-modification systems is discussed.

Keywords: DNA methyltransferase; evolutionary link; protein-protein interactions; Type I and II restriction-modification systems.

Introduction

The DNA cytosine methyltransferase (MTase) M.Hhal recognizes the sequence 5′-CGCG-3′ and methylates the internal cytosine by flipping the target cytosine completely out of the DNA duplex (Klimašauskas et al., 1994). The remainder of the duplex is left as nearly intact B-form and the DNA gap created by base flipping is filled by insertion of the side chain of Gin237. No covalent bonds are broken to carry out the base flipping (Roberts and Cheng, 1998) – only the base-pairing hydrogen bonds are broken and the π-stacking interactions between adjacent base pairs are lost. Insertion of Gin237 into the π-gap restores the hydrogen-bonding network to the orphan guanine but interrupts the aromatic manifold by which charge migration through the DNA can occur. However, a mutant of M.Hhal in which Gin237 is replaced with tryptophan (G237W), an aromatic heterocyclic amino acid, appeared to restore charge migration through the DNA duplex, implying that the tryptophan insertion into the DNA gap maintains the π-stacked array (Rajski et al., 1999).

In an effort to study the nature of tryptophan insertion into the DNA gap, we attempted to crystallize the ternary complex containing the Q237W mutant, the methyl-donor product AdoHcy, and a short oligonucleotide containing the Hhal recognition sequence. Although no DNA is incorporated in the crystal, the mutant enzyme was crystallized in a new space group with two molecules per asymmetric unit. This observation prompted us to examine the protein-protein interactions in different crystal lattices as well as in solution.

Early solution studies suggested that some DNA MTases exist predominantly as dimers: M.RsrI shows partial dimerization in solution (Kaszubskas et al., 1989), two DpnI MTases appear to exist as dimers (de la Campa et al., 1987), and M.MspI dimerizes in solution at high concentration (>3 mg/ml; Dubey et al., 1992), while some MTases remain monomeric in solution (M.BamHI, Nardone et al., 1984; M.EcoRI, Rubin and Modrich, 1977). In experiments involving crosslinking of the BamHI MTase subunits, it was shown that the enzyme in a free state exists as a dimer (Malygin et al., 2001). A similar behavior was observed for adenine M.CcrM from C. crescentus dimerized at physiological concentrations, and the dimerization does not affect DNA methylation (Shier et al., 2001).

In the absence of DNA substrate, M.Hhal, M.TaqI, M.PvuII, and M.MboI were crystallized with two molecules per asymmetric unit (Cheng et al., 1993; Labahn et al., 1994; Gong et al., 1997; Osiptiu et al., 2003), while M.DpnI, M.RsrI, and M.EcoT4Dam with one molecule (Tran et al., 1998; Scavetta et al., 2000; Yang et al., 2003). In the presence of DNA substrate, M.Hhal-DNA existed as one protomer and a single copy of double-stranded DNA (Klimašauskas et al., 1994), while M.HaeIII-DNA and...
Figure 1  The M.HhaI dimer in the crystal lattices and solution.
(A) Two views of the dimer of the M.HhaI mutant Q237W. The insert shows the side chains from one protomer in yellow and from the other in black.
(B) HhaI MTase dimer in the presence of DNA. A schematic drawing shows the MTase domain in green, the TRD domain is indicated in red, and the dimer interface in yellow.
(C) Elution profile of M.HhaI on a Superdex 2000HR column.
(D) Cross-linking of M.HhaI with disuccinimidyl suberate (DSS). The concentration of protein and cross-linker and the size of the molecular mass marker are indicated. The amount of protein (5 μg) loaded onto the gel was the same in all five slots.

M.TaqI-DNA complexes contained two such complexes in the asymmetric unit (Reinisch et al., 1995; Goedecke et al., 2001).

For non-DNA AdoMet-dependent MTases, many enzymes are monomeric, while some exhibit features of dimerization and/or oligomerization. For example, small molecule glycine N-MTase is a tetrameric enzyme (Takata et al., 2003), guanidinoacetate MTase forms a dimer (Komoto et al., 2002), RNA MTases of the SPOUT family are dimers with their active sites constructed as a topological knot (Michel et al., 2002; Nureki et al., 2002), and protein arginine MTases (PRMTs) form ring-like dimers that can be further oligomerized in some cases (Weiss et al., 2000; Zhang et al., 2000; Zhang and Cheng, 2003). Here we examined the protein-protein interactions of M.HhaI in three different crystal lattices. The dimerization behavior of M.HhaI in solution and its potential link to other types of restriction-modification systems are also discussed.

Results

Structure of the Q237W mutant

Although a short DNA duplex containing a HhaI recognition site was used for crystallization, the cognate oligonucleotide was missing from the new crystal structure. There are two possible reasons. First, although the mutant methylates DNA in vivo and in vitro, the specific activity is only about 2% of the wild-type enzyme (Mi et al., 1995). Second, Trp237 radical formation would be thermodynamically feasible but appears not to yield significant amounts of kinetically trapped products (Rajski et al., 1999). However, the bound AdoHcy indicates that cofactor binding is not affected by the mutation.

Q237W mutant proteins were crystallized in the C-centered monoclinic space group C2 with two molecules in the crystallographic asymmetric unit. The two protomers present in the asymmetric unit are very similar: least squares superposition of the two molecules gave a root-mean-square-deviation of 0.647 Å for 307 pairs of Cα atoms. The overall structure of Q237W is shown in Figure 1A. The structure contains two parts: a catalytic methylation domain (green) and a DNA binding domain (red). The methylation domain is formed by a mixed seven-stranded β-sheet (green), a characteristic feature of the class-I AdoMet-dependent MTases (Schubert et al., 2003). While a contiguous region forms the DNA binding domain (red), the catalytic domain consists of two non-contiguous regions: the N-terminal region (green) and a carboxy-terminal helix αZ (yellow) located on one side of the β-sheet.
Table 1  Protein interface parameters.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>M.Hhal</th>
<th>32 homodimers examined (Jones and Thornton, 1996)</th>
</tr>
</thead>
<tbody>
<tr>
<td>ΔASA (Å²)</td>
<td>652.5</td>
<td>1685±1101 (range 584–2786)</td>
</tr>
<tr>
<td>Planaritya</td>
<td>1.9</td>
<td>3.5±1.7</td>
</tr>
<tr>
<td>Interface residue segmentsb</td>
<td>3</td>
<td>5±2.6</td>
</tr>
<tr>
<td>Hydrogen bonds</td>
<td>4</td>
<td>0.7±0.5 per 100 Å²</td>
</tr>
</tbody>
</table>

aFor definitions, see Jones and Thornton (1996).

bInterface residues separated by more than five residues were allocated to different segments.

Table 2  Summary of the dynamic light scattering experiments.

<table>
<thead>
<tr>
<th>c (mg/ml)</th>
<th>Dn,µ (nm)</th>
<th>MW (kDa)</th>
<th>Polydispersity (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.87</td>
<td>382</td>
<td>4.04</td>
<td>85</td>
</tr>
<tr>
<td>2.32</td>
<td>385</td>
<td>4.01</td>
<td>30</td>
</tr>
<tr>
<td>7.94</td>
<td>383</td>
<td>4.03</td>
<td>28</td>
</tr>
</tbody>
</table>

Dn,µ=KBT/6πηRn, where K is the Boltzmann constant, T is the absolute temperature in Kelvin, η is the solvent viscosity (10% glycerol used in the experiment), and Rn is the hydrodynamic radius of the average scattering particle.

Table 3  Summary of DNA MTase interface surface area related by 2-fold NCS or CS.

<table>
<thead>
<tr>
<th>Enzyme</th>
<th>PDB</th>
<th>Space group</th>
<th>Molecule or complex per asymmetric unit</th>
<th>Molecule related by 2-fold symmetry</th>
<th>ΔASA (Å²)</th>
</tr>
</thead>
<tbody>
<tr>
<td>5 mC MTases</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>M.Hhal</td>
<td>1SVU (Q237W)</td>
<td>C2</td>
<td>2</td>
<td>+ (NCS)</td>
<td>699</td>
</tr>
<tr>
<td></td>
<td>2HMY</td>
<td>P2, 2</td>
<td>2</td>
<td>+ (NCS)</td>
<td>761</td>
</tr>
<tr>
<td></td>
<td>1HMT</td>
<td>R32</td>
<td>1 (protein/DNA)</td>
<td>+ (CS)</td>
<td>725</td>
</tr>
<tr>
<td></td>
<td>1DCT</td>
<td>P2, 2, 2, 1</td>
<td>2 (protein/DNA)</td>
<td>+ (NCS)</td>
<td>607</td>
</tr>
<tr>
<td></td>
<td>1G55</td>
<td>I4, 1</td>
<td>1</td>
<td>+ (CS)</td>
<td>782</td>
</tr>
<tr>
<td>Group α amino-MTases</td>
<td>2PDM</td>
<td>P2, 2, 2, 1</td>
<td>1</td>
<td>-</td>
<td></td>
</tr>
<tr>
<td></td>
<td>1QOT</td>
<td>P2, 2, 2, 1</td>
<td>2 (protein/DNA)</td>
<td>+ (NCS)</td>
<td>404</td>
</tr>
<tr>
<td></td>
<td>1QOS</td>
<td>P2, 2, 2, 1</td>
<td>1</td>
<td>-</td>
<td></td>
</tr>
<tr>
<td>Group β amino-MTases</td>
<td>1BOO</td>
<td>P2, 2</td>
<td>2</td>
<td>+ (NCS)</td>
<td>2317</td>
</tr>
<tr>
<td></td>
<td>1EG2</td>
<td>C22, 1</td>
<td>1</td>
<td>+ (CS)</td>
<td>1706</td>
</tr>
<tr>
<td></td>
<td>1G60</td>
<td>P2, 2</td>
<td>2</td>
<td>+ (NCS)</td>
<td>1966</td>
</tr>
<tr>
<td>Group γ amino-MTases</td>
<td>2ADM</td>
<td>P2, 2, 2, 1</td>
<td>2</td>
<td>+ (NCS)</td>
<td>164</td>
</tr>
<tr>
<td></td>
<td>1G38</td>
<td>P2, 2</td>
<td>2</td>
<td>-</td>
<td></td>
</tr>
</tbody>
</table>

While the mutant Q237W-AdoHcy was crystallized in the C-centered monoclinic space group C2, the M.Hhal-AdoMet complex was previously crystallized in the monoclinic space group P21 (Cheng et al., 1993; O’Gara et al., 1999). The crystallization conditions (polyethylene glycol 4000 vs. ammonium sulfate) and crystal properties such as space groups (P21 vs. C2) and unit cell dimensions (a=55.3 Å, b=74.68 Å, c=90.96 Å, and β=103° vs. a=155.0 Å, b=47.0 Å, c=122.7 Å, and β=121°) are completely different in these two cases. One common feature is that both crystals contain two molecules per asymmetric unit and the loop containing the residue 237 is not involved in any crystal packing contacts. Furthermore, in both monoclinic lattices, a pair of the protomers is related through the carboxy-terminal helix αZ by a two-fold non-crystallographic rotation. A more intriguing finding is that the same dimer interface also exists in the M.Hhal-DNA-AdoHcy complexes (Klimašauskas et al., 1994; Vilkaitis et al., 2000); in the ternary complexes, the dimer is characterized by a 2-fold crystallographic symmetry in the rhombohedral space group R32 (Figure 1B). The two DNA substrates, and hence the active sites, are located on the outer surface of the dimer. These observations prompted us to examine the protein-protein interactions in different crystal lattices.

Hhal dimer formation in crystal lattices

We calculated all possible protein-protein interfaces in the lattices of P21, C2, and R32 based on the change in solvent accessible surface area (ΔASA) when going from a monomeric to a dimeric state (http://www.biochem.ucl.ac.uk/bsm/PP/server; Jones and Thornton, 1996). The largest change in ΔASA was found for a pair of the protomers related through the carboxy-terminal helix αZ (yellow) by a two-fold non-crystallographic rotation. A more intriguing finding is that the same dimer interface also exists in the M.Hhal-DNA-AdoHcy complexes (Klimašauskas et al., 1994; Vilkaitis et al., 2000); in the ternary complexes, the dimer is characterized by a 2-fold crystallographic symmetry in the rhombohedral space group R32 (Figure 1B). The two DNA substrates, and hence the active sites, are located on the outer surface of the dimer. These observations prompted us to examine the protein-protein interactions in different crystal lattices.
Figure 2 The 2-fold related DNA MTase structures. One protomer is shown in yellow and the other in green. The dimer is related by a 2-fold non-crystallographic symmetry (NCS) or crystallographic symmetry (NC). The dimer interface area ($\Delta$ASA) was calculated using AREAIMOL of CCP4.

HhaI dimer formation in solution

There are several indications that this structural dimer may also exist in solution: (i) gel filtration results suggest that M.HhaI has an apparent molecular mass of a dimer. On a Superdex 200 column (Pharmacia), M.HhaI eluted as a 60 kDa globular protein (Figure 1C), larger than the calculated molecular mass (37 kDa). (ii) Dynamic light scattering measurement at a range of protein concentrations suggested that the hydrodynamic radius of M.HhaI is 4 nm and would correspond to an 85 kDa globular protein (Table 2). This dimension ($2 \times 4 = 8$ nm) is between the shorter (4.7 nm) and the longer (12 nm) dimensions of the dimer (Figure 1A). (iii) A portion of M.HhaI formed a covalent dimer after cross-linking by glutaraldehyde or disuccinimidyl suberate (Figure 1D). These data suggest that the dimers seen in the crystal structures of M.HhaI could also exist in solution.

Comparison with other structurally characterized DNA MTases

At this time, the structural characterization of nine DNA MTases has been reported (Table 3). These include three generating 5mC (M.HhaI, M.HaeIII, and human Dnmt2), one generating N4mC (M.PvuII), and five generating N6mA (M.TaqI, M.DpnII, M.RsrI, M.MboIIA, and M.EcoT4Dam). We examined the protein-protein interactions in the crystal lattices to search for a pair of protomers related by a 2-fold rotation, either through non-crystallographic symmetry (NCS) if two proteins or protein-DNA complexes existed in the asymmetric unit or through crystallographic symmetry (CS) if only one protein or protein-DNA complex was present in each asymmetric unit.

With the exception of M.DpnII, all other structurally characterized MTases can be found as a 2-fold related
‘dimer’ (Figure 2). The dimer interface does not block the active site or the DNA binding cleft. The ΔASA values are distributive: (i) the largest ΔASA values are from M.MboIIA (1966 Å²), M.RsrI (1706 Å²), and M.Pvull (2317 Å²) (Figure 2D–F). These values are at the high end of the homodimers examined by Jones and Thornton (1996). All three are β-group DNA MTases (Malone et al., 1995) and show, interestingly, a protomer interface between two molecules (Osiipiuk et al., 2003). Most likely, these β-group DNA MTases are dimeric in solution (Kaszubska et al., 1989; Osiipiuk et al., 2003). (ii) For the 5mc MTases examined (Figure 2A–C), the ΔASA values, being at the low end but within the limit of Jones and Thornton (1996), are approximately 3 times less than that of β-group enzymes. As demonstrated by M.MspI (Dubey et al., 1992), these enzymes could dimerize in solution in a concentration-dependent fashion. (iii) The smallest ΔASA value is from M.TaqI in the absence of DNA (164 Å²); this value is outside of the lower limit of Jones and Thornton (1996). This may explain that the M.TaqI interface shown in Figure 2G is not observed for the M.TaqII-DNA complex, even though two such complexes existed in the asymmetric unit. (iv) Similarly, the M.EcoT4Dam interface (Figure 2H) observed in the presence of DNA (404 Å²) does not exist in the substrate-free T4Dam nor in a GATC-related orthologous M.DpnII structure, although both α-group MTases were previously suggested to dimerize in solution (de la Campa et al., 1987; Evdokimov et al., 2002).

Discussion

The type II restriction-modification systems consist of two independent components that, respectively, restrict and modify DNA (Roberts and Halford, 1993). Restriction involves a homodimeric endonuclease (ENase) cleaving DNA by hydrolyzing the phosphodiester backbone on both strands, while modification involves a MTase adding a methyl group to a DNA base on one strand at a time. Both the restriction and the modification activities recognize the same DNA sequence. The cleavage occurs at fixed positions that are symmetrically-disposed relative to the symmetrical recognition sequence, and within or adjacent to that sequence. The methylation occurs at a position within the palindromic recognition sequence that blocks the paired restriction activity.

Most of the structurally characterized Type II ENase-DNA complexes comprise a protein dimer and a single copy of a double-stranded oligonucleotide in the crystallographic asymmetric unit, the smallest repeating unit within a crystal. However, for the R.BglII-DNA complex, there was only one protein subunit and one DNA strand in the asymmetric unit, and thus the biologically active homodimer was generated by a two-fold axis of crystallographic symmetry (Newman et al., 1998).

Although the functional significance, if any, of the Type II MTase dimer is unclear, one possibility is that the dimeric form of Hhal MTase allows formation of a large enzyme-substrate network with high molecular weight DNA, as demonstrated for Serratia nuclease (Franke et al., 1999). Although the two subunits of Serratia nuclease function independently of each other, they bind simultaneously to one macromolecular DNA, forming a large network between the enzyme and the substrate. Homodimeric DNA MTases may serve the same function. At present, we do not have any evidence against the notion that two monomers act independently from each other in the Hhal homodimer.

Type II MTase dimers might also provide an evolutionarily link to other types of restriction-modification systems. Type II MTases are bilobal molecules with a catalytic methylation domain (shown in green in Figure 1A and B), responsible for AdoMet binding and the methyl transfer reaction, and a target recognition domain (TRD) responsible for DNA binding. In some cases, MTases are expressed as two polypeptides that associate to form the active enzymes (Karreman and de Waard, 1990; Lee et al., 1996). In addition, the Type IIS systems consist of two MTases (sometimes expressed as a single fusion protein) that individually modify the two asymmetric strands of the recognition sequences.

The Type I systems are heteropentamers with two modification (M) subunits, one DNA specificity (S) subunit, and two restriction (R) subunits (Rao et al., 2000). With respect to the Type II systems, the Type I S subunit contains two TRDs (Sturrock and Dryden, 1997) and the M₅S complex is active as a MTase (see Dryden, 1999).

Interestingly, the Type IIS systems have Type II ENases and Type I-like MTases (G.G. Wilson, personal communication). The XcmI MTase likely is a dimer because the gene for the methylation domain (M) is fused to that for a single TRD (in effect one half of an S subunit). The AhdI MTase is active as a tetramer (two M subunits and two single TRDs) that is very similar to the artificial Type I systems (Marks et al., 2003). The Type IIL MTases form

<table>
<thead>
<tr>
<th>Table 4 Summary of crystallographic data.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Space group</td>
</tr>
<tr>
<td>Unit cell dimensions</td>
</tr>
<tr>
<td>Completeness (%)</td>
</tr>
<tr>
<td>Rmerge (Fo–Fc)</td>
</tr>
<tr>
<td>Resolution range (Å)</td>
</tr>
<tr>
<td>Refinement</td>
</tr>
<tr>
<td>Rfree (5% of the data)</td>
</tr>
<tr>
<td>Number of atoms</td>
</tr>
<tr>
<td>Estimated coordinate error</td>
</tr>
<tr>
<td>Ruzzatti plot (Å)</td>
</tr>
<tr>
<td>Mean B value (Å²)</td>
</tr>
</tbody>
</table>
a clear link between Type I and Type II restriction-modification systems by utilizing gene fusions and the shuffling of structural and functional domains (Dryden, 1999). The M.Hhal dimer, mediated mainly by the catalytic domain (or M subunit) and the linker, but not the DNA binding domain (or S subunit), may simply reflect such an evolutionary relationship.

Materials and methods

The mutant protein Q237W was engineered, expressed, and purified as described previously (Kumar et al., 1992; Mi et al., 1995). For recording the elution profile of M.Hhal on a Superdex 2000HR column (Pharmacia, Piscataway, USA), the protein was loaded onto the column at a concentration of 5 mg/ml. The column buffer was 20 mM HEPES pH 7.0, 50 mM NaCl, 0.1 mM Na2EDTA, 5% glycerol and 0.1% 2-mercaptoethanol. Cross-linking of M.Hhal with disuccinimidyl suberate (DSS) was performed at room temperature for 30 min in buffer containing 20 mM HEPES pH 7.0, 0.2 M NaCl, 0.1 mM EDTA, 5% glycerol and 0.1% 2-mercaptoethanol. Total protein (5 μg) was loaded on a 10% SDS polyacrylamide gel. The dynamic light scattering experiments were performed at 16 °C using a DynaPro Molecular Sizing Instrument (Protein Solutions, High Wycombe, UK). Because polydispersity is greater than 25%, a multiple-exponential algorithm (regularization analysis) was employed.

The cofactor-free Q237W protein in 20 mM Tris-HCl, 100 mM NaCl, 5% glycerol, 1 mM EDTA, 1 mM DTT was concentrated to 25 mg/ml (0.68 mM) and incubated with AdoHcy and DNA (5'-TATGAGGCGTCT-3') in an equal molar ratio. Crystals were grown under the conditions of 2.2 M ammonium sulfate, 50 mM 2-mercaptoethanol. Total protein (5 mg/ml) was loaded onto the column at a concentration of 5 mg/ml. The column buffer was 20 mM HEPES pH 7.0, 50 mM NaCl, 0.1% 2-mercaptoethanol. Cross-linking of M.Hhal with disuccinimidyl suberate (DSS) was performed at room temperature for 30 min in buffer containing 20 mM HEPES pH 7.0, 0.2 M NaCl, 0.1 mM EDTA, 5% glycerol and 0.1% 2-mercaptoethanol. Total protein (5 μg) was loaded on a 10% SDS polyacrylamide gel. The dynamic light scattering experiments were performed at 16 °C using a DynaPro Molecular Sizing Instrument (Protein Solutions, High Wycombe, UK). Because polydispersity is greater than 25%, a multiple-exponential algorithm (regularization analysis) was employed.

The structure was solved by the molecular replacement program AmoRe (Navaza, 2001) using the refined protomer T250G structure (Vilkaitis et al., 2000) as the search model by deleting the side chain of residue 237; two solutions were found indicating each asymmetric unit contains two molecules. The solution was confirmed by the appearance of the electron densities corresponding to the side chains of Thr250 and Trp237. Numerous cycles of model refinement using XPLOR (Brunger et al., 1998) and manual rebuilding using O (Jones and Kjeldgaard, 1997) were conducted. A series of simulated annealing omit maps were used to correct the model. The non-crystallographic restraints were imposed on the two protein molecules throughout the refinement and were only released from protein side chains at the last cycle to account for a different packing environment with each molecule. The final model consists of 307 out of the 328 amino acids in protein chain A, 314 amino acids in protein chain B, and two AdoHcy molecules. The missing residues, amino acid residues 80–99 in protomer A and residues 84–96 in protomer B that could not be modeled due to the poor quality of the electron density, are part of the active site loop that undergoes large conformational changes upon DNA binding (Cheng et al., 1993; Klímašauskas et al., 1994).

Acknowledgments

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