Nortriptyline Reverses Corticosteroid Insensitivity by Inhibition of Phosphoinositide-3-Kinase-δ[S]

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ABSTRACT

Corticosteroid insensitivity represents a major barrier to the treatment of chronic obstructive pulmonary disease (COPD) and severe asthma. It is caused by oxidative stress, leading to reduced histone deacetylase-2 (HDAC2) function through activation of phosphoinositide-3-kinase-δ (PI3Kδ). The tricyclic antidepressant nortriptyline has been identified in high-throughput screens as an agent that increases corticosteroid responsiveness. The aim of this study was to identify the molecular mechanism whereby nortriptyline increases corticosteroid sensitivity. Phosphorylation of Akt, a footprint of PI3K activation, and HDAC activity were evaluated by Western blotting and fluorescent activity assay in U937 monocyctic cells. Corticosteroid sensitivity was evaluated by the inhibition of tumor necrosis factor α (TNFα)-induced interleukin 8 (IL-8) production by budesonide. Hydrogen peroxide (H2O2) or cigarette smoke extract (CSE) increased the level of phosphorylated Akt (pAkt) and reduced HDAC activity. Pretreatment with nortriptyline inhibited pAkt induced by CSE and H2O2 as well as restored HDAC activity that had been decreased by H2O2 and CSE. In addition, nortriptyline inhibited PI3Kδ activity, but had no effect on the PI3Kα and PI3Kγ isoforms. Although CSE reduced the effects of budesonide on TNFα-induced IL-8 production in U937 cells, nortriptyline reversed CSE-induced corticosteroid insensitivity. Nortriptyline restores corticosteroid sensitivity induced by oxidative stress via direct inhibition of PI3Kδ and is a potential treatment for corticosteroid-insensitive diseases such as COPD and severe asthma.

Introduction

Corticosteroids are the most effective therapy for many inflammatory and immune diseases. However, in patients with chronic obstructive pulmonary disease (COPD) and severe asthma or asthmatic patients who smoke, corticosteroids are largely ineffective (Barnes and Adcock, 2009). Corticosteroid insensitivity represents a huge management problem, and novel treatments are urgently needed for the treatment of these diseases. The anti-inflammatory effects of corticosteroids are mediated by the binding to glucocorticoid receptors (GRs) and subsequent nuclear translocation. Activated GR inhibits proinflammatory gene transcription via inhibition of nuclear factor-κB-associated histone acetylation by both direct inhibitions of CREB-binding protein-associated histone acetyltransferase activity and recruitment of histone deacetylase 2 (HDAC2) to the promoter of actively transcribed inflammatory genes (Ito et al., 2006a). HDAC2 expression and activity are reduced in bronchial biopsies, bronchoalveolar lavage macrophages, and peripheral lung tissue obtained from patients with COPD, and the reduction correlates with disease severity (Ito et al., 2005). HDAC2 activity has also been shown to be decreased in some severe asthmatics and asthmatics who smoke (Ito and Mercado, 2009). Moreover, knockdown of HDAC2 expression in bronchoalveolar lavage macrophages induces corticosteroid insensitivity, whereas HDAC2 overexpression restores corticosteroid function (Ito et al., 2006b). Reactive oxygen species derived directly by cigarette smoke or indirectly from the inflammatory response to cigarettes can have a marked impact on HDAC2 expression and function and are one of the critical factors in the development of corticosteroid insensitivity (Marwick et al., 2007). For example, HDAC2 is downregulated by post-translational modifications, such as nitration and oxidation (Barnes, 2009a) after treatment with hydrogen peroxide (H2O2), a peroxynitrate generator 3-morpholinosydnonimine (Osoata et al., 2009), or cigarette smoke (Adenuga et al., 2009). In these studies, pretreatment with antioxidants, such as N-acetylcysteine (NAC) and glutathione...
one, prevent the post-translational modification and down-regulation of HDAC2 (Adenuga et al., 2009; Osoata et al., 2009). We have shown that oxidative stress induced phosphorylation and inactivation of HDAC2 through activation of the phosphoinositide-3-kinase (PI3K)/Akt pathway (To et al., 2010).

Nortriptyline is a second-generation tricyclic antidepressant that has also been used to treat nicotine addition and smoking cessation in patients with COPD and has also shown a marked improvement in certain respiratory symptoms (Borson et al., 1992). High-throughput screening has been used to identify drugs showing synergistic effects with corticosteroids on tumor necrosis factor α (TNFα) production in peripheral blood mononuclear cells (Lehár et al., 2009). Nortriptyline was identified as a drug that unexpectedly increased the anti-inflammatory effect of prednisolone. However, the effects of nortriptyline have not been evaluated in clinical models, and the molecular mechanism of nortriptyline in restoring corticosteroid sensitivity is unknown. The aim of this study was to verify whether nortriptyline could restore corticosteroid sensitivity in an in vitro model of corticosteroid insensitivity induced by reactive oxygen species and cigarette smoke and to identify the molecular mechanisms involved.

Materials and Methods

Cell Culture and Stimulation. Human monocytic U937 cells were maintained in continuous cell culture at 37°C and 5% CO2 in RPMI medium containing 10% fetal calf serum and 15 mM glutamine. For stimulation with H2O2 (Sigma Chemical, Poole, Dorset, UK) or cigarette smoke extract (CSE), U937 cells were seeded (0.5 × 10^6 cells/ml) using starvation medium RPMI 1640 (phenol red free) with 1% fetal calf serum and 15 mM l-glutamate at 37°C and 5% CO2.

Preparations of Cigarette Smoke Extract. CSE was prepared using two full-strength Marlboro cigarettes with filters removed (Phillip Morris, Richmond, VA), which were combusted through a modified 60-ml syringe apparatus into 20 ml of RPMI medium (as described previously (Walters et al., 2005)). CSE was then passed through a 0.25-μm filter to sterilize and remove particulate matter and was used immediately. The optical density was measured at 320 nm wavelength, and values were diluted to achieve a value of 0.15 to provide a concentration that stimulated the cells without inducing cell death.

PI3K Activity Assay. PI3K enzyme inhibitory activity was determined by time-resolved fluorescence resonance energy transfer (HTRFPI3K enzyme assay; Millipore, Watford, UK). Nortriptyline or LY294002 was added at the desired final concentrations to a mixture of phosphatidylinositol bisphosphate substrate and recombinant PI3K α, δ, or γ enzymes (Millipore), and the mixture was incubated for 2 h at room temperature. After this incubation period, ATP (20 μM) was added to the enzyme/compound/phosphatidylinositol bisphosphate substrate mixture, and the resulting mixture was incubated for 30 min at room temperature. The percentage of inhibition of each reaction was calculated relative to vehicle-treated control, and the IC50 value was calculated from the concentration-response curve.

Statistical Analysis. Data are expressed as means ± S.E.M. Results were analyzed using paired t test or one-way analysis of variance for repeated measures with Dunnett post-test for multiple comparisons. EC50 values of budesonide were determined from the concentration-inhibitory response curves of IL-8 production, and the differences of EC50 values of budesonide were assessed using Bonferroni’s multiple comparison test. Prism software (GraphPad Software, Inc., San Diego, CA) was used for statistical calculations. Experiments were repeated at least three times. P < 0.05 was considered statistically significant. Synergy of two compounds was analyzed by isobologram by the method of Chou and Talalay (1977) using CalcuSyn software (BISOPP, Cambridge, UK).

Results

Nortriptyline Prevents CSE- and H2O2-Induced Phosphorylation of Akt. Phosphorylation of Akt at serine 473 was used to measure PI3K activation. S473Akt phosphorylation was increased by H2O2 (3.4 ± 0.2-fold increase versus control; p < 0.01) and CSE (3.3 ± 0.2-fold increase versus control; p < 0.01) (Fig. 1A). Preincubation with nortriptyline (1–10 μM; p < 0.01) significantly prevented Akt phosphorylation by H2O2 (Fig. 1A) and CSE (p < 0.01), and the IC50 value was calculated to be 1.67 μM (Fig. 1B). LY294002 also produced a concentration-dependent inhibition of CSE-induced pAkt with an IC50 at 0.25 μM (Supplemental Fig. 1A). Thus, nortriptyline was only 6.7-fold weaker than LY294002 in inhibiting CSE-induced PI3K activation. In the in vitro enzymatic assay that measures PI3Ka, γ, and δ
activity, nortriptyline concentration-dependently inhibited PI3Kα activity (IC_{50} 0.82 μM), and the efficacy was similar to that of LY294002 (IC_{50} 0.98 μM), whereas nortriptyline had no effect on PI3Kα or PI3Kγ (Table 1).

**Nortriptyline Prevents CSE or H_{2}O_{2} Reduction of HDAC Activity.** H_{2}O_{2} significantly reduced HDAC activity (39 ± 12% versus control; p < 0.05), and this was completely prevented by nortriptyline at 1 μM (p < 0.05) (Fig. 2A). Incubation with CSE also resulted in a significant decrease of HDAC activity (9 ± 3% at 33% CSE and 19 ± 3% at 100% CSE; p < 0.05) (Fig. 2B). Preincubation with nortriptyline (1 μM) also completely restored HDAC activity (p < 0.05 versus CSE) reduced by CSE (Fig. 2B). Because HDAC2 protein expression was not reduced after CSE (Supplemental Fig. 1B), the decrease in HDAC activity was not explained by a decrease in HDAC2 protein expression.

**Nortriptyline Prevents CSE-Induced Corticosteroid Insensitivity.** Budesonide concentration-dependently inhibited TNFα-induced IL-8 release in U937 cells with an EC_{50} value of 9.3 × 10^{-10} M and E_{max} of 56%. Pretreatment with CSE (33%) resulted in a decrease in budesonide sensitivity (EC_{50} 1.2 × 10^{-9} M; p < 0.05 versus Nt) and reduced E_{max} (24%; p < 0.05 versus Nt) (Table 2). This was inhibited by pretreatment with NAC (10 mM) (EC_{50} 6.1 × 10^{-10} M with NAC), suggesting the reduction of budesonide sensitivity was mediated by oxidative stress (Fig. 3A). Nortriptyline also prevented CSE-induced corticosteroid insensitivity. CSE (EC_{50} 5.9 nM; E_{max} 24 ± 2%) induced budesonide insensitivity compared with control (EC_{50} 0.85 nM, p < 0.01 versus Nt; E_{max} 56 ± 6%, p < 0.05 versus Nt) (Fig. 3B). Nortriptyline reversed budesonide insensitivity with CSE (EC_{50} at 1 μM: 0.54 nM, p < 0.001 versus CSE, EC_{50} at 3.3 μM: 1.00 nM, p < 0.001 versus CSE). E_{max} was also reduced by nortriptyline, however, not significantly (E_{max} at 1 μM: 33 ± 6% and at 3.3 μM: 32 ± 8%). LY294002 (1 μM) also reversed CSE-induced budesonide insensitivity (EC_{50} of budesonide 1.07 nM with LY294002 in the presence of CSE versus 2.67 nM in CSE control; p < 0.05), but did not have any impact on E_{max} (Fig. 3C).

Nortriptyline is also known to be a potent histamine (H1) receptor antagonist (Taylor and Richelson, 1980) as well as a partial inhibitor of α1 adrenergic receptors (Brown et al., 1980) and 5-HT2 receptors (Sánchez and Hyttel, 1999). Accordingly, we measured the inhibitory effect of antagonists for H1 receptor (mepyramine), 5-HT2 receptor (ketanserin), and α1 adrenergic receptor (prazosin) in our CSE-induced corticosteroid insensitive model. The use of the various antagonists did not have an effect on EC_{50} or E_{max} (Supplemental Table 1), whereas nortriptyline was shown to restore EC_{50}.

**Nortriptyline and Budesonide Showed Synergistic Effects.** U937 cells were treated with H_{2}O_{2} for 60 min and then stimulated with TNFα. The supernatant was collected 24 h after stimulation, and IL-8 was determined by ELISA. Budesonide and/or nortriptyline were given 30 min before TNFα stimulation. Budesonide and nortriptyline concentration-dependently inhibited IL-8 release. Different combina-

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**TABLE 1**

Inhibitory effects of nortriptyline and LY294002 on PI3K enzyme activity

<table>
<thead>
<tr>
<th></th>
<th>PI3Kα</th>
<th>PI3Kγ</th>
<th>PI3Kδ</th>
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<tbody>
<tr>
<td>Nortriptyline</td>
<td>0.82</td>
<td>No effect at 10 μM</td>
<td>No effect at 3.3 μM</td>
</tr>
<tr>
<td>LY294002</td>
<td>0.98</td>
<td>12.6</td>
<td>0.63</td>
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**Fig. 1.** Nortriptyline prevents oxidative stress activation of the PI3K/Akt pathway. A, U937 cells were preincubated with Nt (1–10 μM) for 30 min and treated with H_{2}O_{2} (200 μM) for 15 min. Levels of phosphorysine 473 Akt and total Akt1 were measured by Western blot in whole-cell extracts. B, U937 cells were preincubated with nortriptyline (1–33 μM) and treated with CSE for 5 min. Levels of phosphoserine 473 Akt and total Akt1 were measured by Western blot in whole-cell extracts, and IC_{50} values were calculated. *, p < 0.05; **, p < 0.01 compared with controls.

**Fig. 2.** Nortriptyline prevents oxidative stress reduction of HDAC activity. A, U937 cells were pretreated with Nt (1 μM) before stimulation with H_{2}O_{2} (200 μM) for 15 min. HDAC activity was measured by fluorometric activity assay in nuclear extracts. B, U937 cells were preincubated with Nt (1 μM) for 30 min before stimulation with CSE (33%) for 2 h, or cells were treated with CSE (100%) for 2 h. HDAC activity was measured by fluorometric activity assay in nuclear extracts. *, p < 0.05 compared with controls.
Inhibitory effects of nortriptyline and LY294002 on EC$_{50}$ and $E_{\text{max}}$ of budesonide

<table>
<thead>
<tr>
<th></th>
<th>Control</th>
<th>CSE</th>
<th>CSE + Nt (3.3 µM)</th>
<th>CSE + Nt (1 µM)</th>
<th>Control</th>
<th>CSE</th>
<th>CSE + LY294002 (1 µM)</th>
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<tbody>
<tr>
<td>EC$_{50}$ (nM)</td>
<td></td>
<td></td>
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<tr>
<td>0.85</td>
<td>5.9</td>
<td>1.00</td>
<td>0.54</td>
<td></td>
<td>1.28</td>
<td>2.67</td>
<td>1.07</td>
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<tr>
<td>$E_{\text{max}}$ (%)</td>
<td>56 ± 5</td>
<td>24 ± 2</td>
<td>32 ± 8</td>
<td>33 ± 6</td>
<td>49 ± 6</td>
<td>12 ± 3</td>
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</table>

Fig. 3. Nortriptyline prevents cigarette smoke-induced corticosteroid insensitivity. A, U937 cells were pretreated with NAC (10 mM) for 30 min followed by CSE (33%) for 2 h. Cells were seeded in 96-well plates and treated with budesonide (10$^{-12}$ to 10$^{-3}$ M) for 45 min before overnight stimulation with TNF$_{a}$ (10 ng/ml). Supernatants were collected, and IL-8 expression was measured by ELISA. B and C, U937 cells were pretreated with Nt (1 and 3.3 µM) (B) or LY294002 (LY; 1 µM) (C) for 30 min followed by CSE (33%) for 2 h. Cells were collected, seeded in 96-well plates, and treated with budesonide (10$^{-12}$ to 10$^{-7}$ M) for 45 min before overnight stimulation with TNF$_{a}$ (10 ng/ml). Supernatants were collected, and IL-8 expression was determined. The percentage of inhibition of IL-8 by budesonide was calculated, and corticosteroid sensitivity was measured by EC$_{50}$. Analysis demonstrated that this combination showed synergy (Fig. 4).

Discussion

Oxidative stress, such as H$_2$O$_2$ and CSE, may play an important role in the development of corticosteroid insensitivity in COPD and severe asthma (Adcock and Barnes, 2008). As shown in Fig. 3, CSE reduced the effects of budesonide with nortriptyline showed greater inhibitory effects than either compound alone, and isobologram analysis demonstrated that this combination showed synergy (Fig. 4).

<table>
<thead>
<tr>
<th>Budesonide (nM)</th>
<th>100</th>
<th>33</th>
<th>10</th>
<th>3.3</th>
<th>1</th>
<th>0.33</th>
<th>0.1</th>
<th>0</th>
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<td></td>
</tr>
<tr>
<td>% Inhibition</td>
<td>75.4</td>
<td>75.0</td>
<td>76.9</td>
<td>83.4</td>
<td>88.2</td>
<td>87.2</td>
<td>85.7</td>
<td>85.5</td>
</tr>
</tbody>
</table>

Nortriptyline (% inhibition)

Fig. 4. Synergistic interaction between nortriptyline and budesonide. U937 cells were treated with H$_2$O$_2$ (200 µM) for 60 min and then stimulated with budesonide (10$^{-10}$ to 10$^{-3}$ M) and/or Nt (1–33 µM) for 30 min before stimulation with TNF$_{a}$ (10 ng/ml). The supernatant was collected 24 h after treatment, and IL-8 was determined by ELISA. Inhibitory percentages on TNF$_{a}$-induced IL-8 release in U937 cells are shown. The PI3K-dependent Akt pathway has been reported to induce HDAC2 phosphorylation and decrease activity (Adenuga et al., 2009). In fact, both H$_2$O$_2$ and CSE induce phosphorylation of Akt at serine 473 (Lahair et al., 2006) (Fig. 1) with concomitant reduction of HDAC activity (Fig. 2) (To et al., 2010). LY294002, a nonselective PI3K inhibitor, concentration-dependently inhibited CSE-induced Akt phosphorylation (Supplemental Fig. 1). We reported previously that LY294002 inhibited Akt phosphorylation and reversed HDAC activity in U937 cells in vitro and in mice exposed to cigarette smoke in vivo (To et al., 2010).

Four different isoforms of PI3K have been identified, α, β, γ, and δ (Ito et al., 2007). Studies have found that pAkt is increased in COPD lung tissue and cells, which is caused by...
increased activation of the PI3Kiso form (To et al., 2010). Another study found that PI3Kδ (−/−) null mice were protected from cigarette smoke-induced corticosteroid resistance and down-regulation of HDAC2 activity (Marwick et al., 2009). Furthermore, 2-(6-aminoquin-9-ylmethyl)-3-(2-chlorophenyl)-6,7-dimethoxy-3H-quinoxalino-4-one (IC87114), a selective PI3Kδ inhibitor (Sadhu et al., 2003), increased the effects of a corticosteroid in mice exposed to smoking (To et al., 2010). In addition, cells with knocked-down PI3Kδ by RNA interference did not develop corticosteroid insensitivity in response to H₂O₂ (To et al., 2010). Thus, PI3Kδ seems to be crucial in mediating corticosteroid insensitivity after oxidative stress via decreased activity of HDAC2.

Nortriptyline is a tricyclic drug that is the major metabolite of amitriptyline and has been used for a long time in the treatment of depression and nicotine addiction (Wagena et al., 2005). High-throughput screening has been used to identify drugs that had synergistic effects with the anti-inflammatory effects of corticosteroids in suppressing TNFa release (Lehár et al., 2009). Isofabogram analysis has demonstrated the synergistic anti-inflammatory effects of nortriptyline and prednisolone. We confirmed the synergy between budesonide and nortriptyline in suppressing TNFa-induced IL-8 release in U937 cells exposed to H₂O₂ for 20 min using isofabogram analysis (Fig. 4). In this study, nortriptyline also selectively inhibited both CSE- and H₂O₂-induced Akt phosphorylation and selectively inhibited PI3Kδ enzyme activity (Table 1). At lower concentrations nortriptyline also restored the lowered levels of HDAC activity after both H₂O₂ and CSE exposure. Thus, nortriptyline was able to restore corticosteroid insensitivity by inhibiting PI3Kδ enzyme activated by oxidative stress.

As shown in Table 2 and Fig. 3, although nortriptyline reversed budesonide insensitivity under conditions of oxidative stress, it did not have a significant impact on \( E_{max} \) of LY294002 also failed to reverse the reduced \( E_{max} \) after CSE, suggesting that the reduction of \( E_{max} \) was not PI3K-dependant. We have reported previously that LY294002 modified EC₅₀ but not \( E_{max} \) in peripheral blood mononuclear cells obtained from patients with COPD (To et al., 2010). Nortriptyline is also known to inhibit histamine (H₁) (Taylor and Richelson, 1980), α₁ adrenergic (Brown et al., 1980), and 5-HT2 receptors (Sánchez and Hyttel, 1999). The use of an antagonist for these receptors did not have any impact on EC₅₀ or \( E_{max} \), suggesting that nortriptyline’s restoration of corticosteroid sensitivity is independent of these pathways.

Another widely used drug, theophylline, is also able to restore corticosteroid responsiveness under conditions of oxidative stress by increasing HDAC2 through selective inhibition of PI3Kδ (Ito et al., 2002; Cosio et al., 2004; To et al., 2010). The inhibitory effect of theophylline on PI3Kδ is markedly enhanced by oxidative stress, suggesting some allosteric effect on the enzyme, whereas nortriptyline seems to act directly in the enzyme, suggesting that it may act at a different site than theophylline.

In conclusion, nortriptyline was found to be a direct PI3Kδ inhibitor and thereby able to reverse corticosteroid insensitivity induced by oxidative stress via restoration of HDAC activity. Thus, the combination therapy of nortriptyline and corticosteroids may be a useful treatment of corticosteroid-insensitive diseases, such as severe asthma and COPD, because many patients with COPD and severe asthma suffer from clinical depression (Hill et al., 2008; Ng et al., 2009) this may be a useful therapeutic combination. Clinical trials of nortriptyline in patients with COPD are now indicated, because the inhibitory effect of this drug is within the range of drug concentrations currently used in the treatment of depression.
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**Supplement Table 1.** Effects of nortriptyline, prazosin, ketanserin and mepyramine on EC$_{50}$ and E-max of budesonide.

<table>
<thead>
<tr>
<th></th>
<th>Control</th>
<th>CSE</th>
<th>CSE +P (1 μM)</th>
<th>CSE +Nt (1 μM)</th>
<th>CSE +K (1 μM)</th>
<th>CSE +M (1 μM)</th>
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<tbody>
<tr>
<td>EC$_{50}$ (nM)</td>
<td>0.143</td>
<td>0.640 *</td>
<td>0.726</td>
<td>0.080 #</td>
<td>0.366</td>
<td>0.795</td>
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<tr>
<td>Emax (%)</td>
<td>63± 5</td>
<td>34± 7</td>
<td>28± 12</td>
<td>38± 5</td>
<td>30± 2</td>
<td>35± 2</td>
</tr>
</tbody>
</table>

CSE: cigarette smoke extract, Nt: Nortriptyline, P: Prazosin, K: Ketanserin, M: Mepyramine, Emax: Maximal % inhibition of TNFα induced IL-8, EC$_{50}$: Value of budesonide that inhibits 50% TNFα induced IL-8, LY: LY294002. * p<0.01 vs Control. # p<0.01 vs CSE.
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Supplement Figure 1A. U937 cells were pre-incubated with LY294002 (LY: 0.033-1 μM) and treated with cigarette smoke extract (CSE) for 5 min. Levels of phospho-serine 473 Akt and total Akt1 were measured by Western blot in whole-cell extracts and IC₅₀ values were calculated. * p<0.05, ** p<0.01 compared to controls.

Supplement Figure 1B. U937 cells were treated with cigarette smoke extract (CSE: 100%) for 2 h and HDAC2 and lamin A/C protein expression measured from nuclear extracts using SDS-PAGE/Western blotting.
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A

B

CSE (100%)
HDAC2
Lamin A/C