Codon-optimized Carbonic Anhydrase from *Dunaliella species*: Expression and Characterization

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Abstract—Carbonic anhydrases (CAs) has been focused as biological catalysis for \( \text{CO}_2 \) sequestration process because it can catalyze the conversion of \( \text{CO}_2 \) to bicarbonate. Here, codon-optimized sequence of \( \alpha \)-type CA cloned from *Dunaliella species* (DsCAopt) was constructed, expressed, and characterized. The expression level in *E. coli* BL21(DE3) was better for codon-optimized DsCAopt than intact sequence of DsCAopt. DsCAopt enzyme shows high-stability at pH 7.6/10.0. In final, we demonstrated that in the \( \text{Ca}^{2+} \) solution, DsCAopt enzyme can catalyze well the conversion of \( \text{CO}_2 \) to \( \text{CaCO}_3 \), as the calcite form.

Keywords—Carbonic anhydrase, Codon-optimization, *Dunaliella species*, \( \text{CO}_2 \) sequestration

I. INTRODUCTION

Anthropogenic activities cause of accumulation of greenhouse gases in the atmosphere. However, natural capacities - forest storage, ocean storage, and natural carbonate mineralization are not enough to maintain \( \text{CO}_2 \) level revoked by abrupt industrialization, population growth, energy consumption, and so on. Recently, many researchers have focused on the development of \( \text{CO}_2 \) sequestration processes, for example post-combustion carbon capture and storage (PCCCS). In this commercial PCCCS processes, various amine-based compounds have been used [1]. Although such chemical materials have good \( \text{CO}_2 \) absorption capacities, they have several drawbacks such as corrosion, solvent loss, generation of heat-stable salts, and high-energy consumption during regeneration [2]. At present, researchers are looking for more efficient ways to control the atmospheric \( \text{CO}_2 \) concentration [3]. In such view-point, much attention has been paid to biological \( \text{CO}_2 \)-sequestration technology, in particular an enzyme-based \( \text{CO}_2 \) capture system [4, 5]. This enzyme-based system is prominent for development of efficient PCCCS process because enzyme-catalyzed reactions have high chemo-, regio-, and stereo-selectivity for \( \text{CO}_2 \) capture [6].

Carbonic anhydrase (CA; EC 4.2.1.1) is such biological catalysis for reversible hydration of \( \text{CO}_2 \) (\( \text{CO}_2 + \text{H}_2\text{O} \leftrightarrow \text{HCO}_3^- \)). CA is important in biological systems because the natural hydration of \( \text{CO}_2 \) (un-catalyzed) is slow at ambient condition.

CA is fundamental to many biological processes like photosynthesis, respiration, pH homeostasis and ion transport [7]. Presently CAs are divided into three main classes, \( \alpha, \beta \) and \( \gamma \), which are supposed to be evolutionarily independent [8]. The existence of additional \( \delta \) [9] and \( \zeta \) - classes of CAs have also been reported [10]. Recently, several reports showed that CA genes from two or even all three known classes are identified even in some prokaryotes or multiple genes from the same class are contained [8].

Nowadays, aquatic organisms have been focused as new biological resource to find novel enzymes, proteins, and organic materials because aquatic organisms have been evolved under unique or extreme conditions like high-salinity, high/low temperature, and dark or low illumination. Most of CA enzymes exhibit catalytic activity only under mild conditions, and they may get structural/functional damage when exposed to high temperatures, extreme pH or high salinity. In contrast, CA enzymes from aquatic halophiles or thermophiles maintain properly-folded structures and/or show functions optimally under extreme salt concentrations [11,12] or elevated temperature [13].

Most of the reports describe that \( \alpha \)-type carbonic anhydrase (aCA) from halo-tolerant green alga *Dunaliella salina* maintains its functionality over nearly the entire range of salinities [14, 15]. However, the acquired amount of purified enzyme fractions is not sufficient or the bacterial recombinant expression / purification systems are not set up well, so that its accurate characterization has not been studied well. In this study, we focused on DsCA from *Dunaliella* species growing in hypersaline environment. Codon-optimized sequence of the CA (DsCAopt) was constructed and its efficient expression/purification system was set up. We characterized some of its enzymatic properties like pH stability, \( \text{CO}_2 \) sequestration ability. Results obtained here would be useful for further development of biological \( \text{CO}_2 \) converting/capturing processes.

II. MATERIAL METHODS

A. Strains, Plasmids, and Reagents

The *E. coli* hosts XL1-BlueMRF \( \{\Delta(mcr\lambda)\}182, \Delta(mcrCB-hsdSMR-mrr)172, \text{endA1, supE44, thi-1,recA, gyrA96, relA1, lac-, [}F, proAB, lacFZAM15, Tn10(Tc)\} \} \} \) was purchased from Statagene, and BL21(DE3) \( \{\text{F, ompT, hisD} \} \})
(r8; m9), gal, dcm (DE3)) and the expression vectors pETDuet-1 were obtained from Novagen (Madison, WI). DNA polymerase (ExTaq) was purchased from TaKaRa. Restriction enzymes were obtained from New England Biolabs. Ampicillin, bromophenol blue and 5-nitrophenylacetic acid were obtained from Sigma-Aldrich Co., Vernal buffer-5X from Lonza (Walkersville, MD USA), IPTG from Duchefa (Haarlem, The Netherlands), and Triton X-100 from Yakuhi Pure Chemicals (Osaka, Japan). EDTA-free protease inhibitor (Halt Protease Inhibitor Cocktail) and protein assay reagents were purchased from Thermo Scientific. All the molecular biology reagents and enzymes used in this study were of the highest grade.

B. Construction of Expression Plasmid Vector

Alpha-type CA gene, DsCA, cloned in T-easy vector from Dunaliella species has been kindly obtained from Professor ES Jin’s group at Hanyang University, Korea. The codon-optimized sequence, DsCAopt, was synthesized by Bionics (Seoul, Korea). The leader sequence was removed and the initiation codon was added. The sequence of DsCAopt was amplified by PCR with the forward [5'-GAA TTC GAG CGA ACC GCA GTAG-3’ (underlined: EcoRI site)] and reverse [5’- AAG CTT CGC CGC GCC GGT ATAG-3’ (underlined: HindIII site)] primers. The reaction conditions are as follow: 94°C for 7 min, followed by 30 cycles of 94°C for 1 min, 45°C for 1 min and 72°C for 1 min, and finally 74°C for 10 min. Amplification reaction volume is 50 µL composed of 0.5 µL of ExTaq Polymerase (2.5 Unit), 5 µL of 10x ExTaq buffer, 4 µL of dNTP (2.5 mM), 1 µL of forward primer (100 pmol), 1 µL of reverse primer (100 pmol), 1 µL of template (2 µg/ml) and 37.5 µL of ddH2O. The PCR product was separated by agarose gel-electrophoresis and was extracted using PCR extraction kit, Expi™ GEL SV (GeneAll Biotechnology, Korea). The purified DNA fragment was ligated into pGEM-T Easy vector (Promega, Madison, WI, USA) and introduced into competent E. coli XL 1 Blue MRF. Recombinant plasmids were isolated from positive clones using mini-prep DNA extraction kit - Exprep™ Plasmid mini (GeneAll Biotechnology, Korea) and the insert was confirmed by DNA sequencing. After treatment of EcoRI and HindIII on the mini-prepared plasmids, the fragment of 1611 bp was recovered and subcloned into EcoRI-HindIII site of pETDuet-1 vector. The resulting pETD: DsCAopt expression vector was introduced into competent E. coli BL21 (DE3). Other DNA recombinant methods were performed as described by Sambrook et al. [16].

C. Expression and Purification of Recombinant DsCAopt enzyme

For expression analysis, E. coli BL21 (DE3) harboring the pETD-DsCAopt plasmid was grown in LB-medium supplemented with ampicillin (100 µg/ml) on an orbital shaker (180 rpm) at 37°C. When the OD600 of the culture reached a value of 0.6, isopropyl β-D-thiogalactopyranoside (IPTG) was added at a final concentration of 1 mM and the culture was grown for 6 h at 37°C or for 24 h at 20°C. Induced culture was harvested by low speed centrifugation, washed and re-suspended in Tris–SO4 buffer (50 mM, pH 7.6), followed by sonication with Digital Sonifier–250 (Branson Ultrasonic Co., Mexico) for cell breakage. The supernatant and pellet fractions were separated by centrifugation at 12,000 rpm for 30 min at 4°C and then the protein expression was analyzed by SDS–PAGE (12% gels) as described by Laemmli [17].

For purification of the recombinant protein, approximately 10 g of pelleted E. coli cells from 20°C culture was suspended in 40 mL of lysis buffer containing Tris–SO4 (25 mM, pH 7.6), Triton X-100 (0.1%), and 1 mL of EDTA-free protease cocktail. Cells were thawed in ice-cold water bath and DNase I, MgSO4, and ZnSO4 were added to the bacterial lysate (final concentrations: 20 µg/mL, 15 mM, and 0.5 mM, respectively). The lysate was spun at 15,000 rpm for 30 min in an ultracentrifuge (Gyrozen 1730MR, Incheon, Korea) at 4°C and the resulting supernatant was subjected to affinity-purification. The cell extract was loaded onto Talon resin column (HisPur™ Cobalt Spin Column) pre-equilibrated with equilibration buffer [Na-phosphate buffer (50 mM, pH 7.6) containing NaCl (300 mM)], and eluted with the elution buffer [Na-phosphate buffer (50 mM, pH 7.6) containing NaCl (300 mM) and imidazole (150 mM)] according to company manual. The different fractions having single band corresponding to correct size were collected and dialyzed extensively against Tris–SO4 buffer (25 mM) containing ZnSO4 (10 µM) and concentrated using Amicon Ultra centrifugal filter (Millipore). The entire purification procedure was carried out at 4°C. The purified protein was analyzed by SDS–PAGE (12% gels) as described by Laemmli [17]. Coomassie Brilliant Blue R-250 (Bio-Rad) was used for gel staining and then treated several times by de-staining solution until the proper protein bands appear. Protein quantity was determined by spectrophotometer at 595 nm according to the Bradford method, using bovine serum albumin as the standard [18].

D. Carboxic Anhydrase Assay

CO2 hydration assay was performed by recording pH variation in presence of indicator. Two mL of veronal buffer (pH 8.2), 0.2 mL of bromothymol blue (0.004%), 0.8 mL of diluted enzyme, and 2 mL of a CO2 solution (saturated at 0°C) were mixed. The time (t0) interval was determined between the addition of CO2 solution and the occurrence of a yellow-green color. In the same way, the time interval was recorded without an enzyme solution (tC). The activity was calculated from the formula given below [19]. One Wilbur-Anderson Unit = (tC – t0)/ t0

Esterase activity of carboxic anhydrase was measured by following the change in absorbance at 348 nm of p-nitrophenylacetate (pNPA) to p-nitrophenylate ion (Δε = 5000 m-1cm-1) over a period of 3 min at 4°C using a UV–VIS spectrophotometer (UVmini - 1240, Shimadzu Co.) according to the method described by Verpoorte [20]. The enzymatic reaction volume is 3.0 mL composed of 1.4 mL of Tris–SO4 buffer (50 mM, pH 7.6), 1 mL of p-nitrophenylacetate (3 mM), 0.5 mL of ddH2O and 0.1 mL of enzyme solution.
A reference measurement was obtained by preparing the same cuvette without enzyme solution.

E. CO₂ Sequestration

The hydration of CO₂ reportedly involves the transfer of hydrogen ions between the active sites of the enzyme and the surrounding buffer [21]. CO₂-saturated solution used as substrate was prepared by introducing CO₂ (standard grade) at ~1 bar (100 kPa) into 500 ml of MilliQ-grade pure water in the tube with a rubber cork for 1 h at 4°C. CO₂-saturated solution (10 ml) was mixed with 1 ml of Tris–SO₄ buffer (1 M, pH 8.3) containing free DsCAopt (100 μg) for 15 min. The bicarbonate solution was released into another vessel containing 10 ml of CaCl₂ solution (final concentration: 10.0 mM). To the mixture, 2 ml of Tris–SO₄ buffer (1.0 M, pH 9.5) was immediately added. The reaction mixture was incubated at 35°C and at 45°C, each for 5 min, to allow precipitation of CaCO₃. The precipitated CaCO₃ was filtered and dried at 60°C. The resulting CaCO₃ was weighed, and the amount of sequestered CO₂ (gram equivalent of CO₂ present in calcium carbonate) was calculated [22]. The results were corrected in terms of mg CaCO₃ formed by subtracting the amount from the control experiment carried out in the absence of enzyme.

III. RESULTS

DsCA cloned from Duneliala species consists of 1770 bp. DsCAopt gene (codon-optimized and leader sequence removed, 1611 bp) was cloned in pETD-DsCAopt and expressed well in E. coli BL21(DE3), and the proteins were obtained as soluble form. The soluble portion of the expressed DsCAopt was further optimized at 20°C. The expressed amount of soluble DsCAopt enzyme is 27.79 mg/L (at 20°C under 1.0 mM of IPTG induction). The crude extract of BL21(DE3) cell expressing DsCAopt was subjected to the affinity column and the differently-eluted fractions were analyzed by SDS-PAGE for purification procedures. A protein fraction that eluted with 50 mM min⁻¹, and Vₘₐₓ (the maximum reaction rate) were obtained by Lineweaver-Burk plotting estimations [23]. Apparent values of Kₘ (M-M constant) and Vₘₐₓ, were 0.09095 mM and 3.303×10⁻⁸ M-M min⁻¹, respectively (Kₘₐₓ value: 3.63166×10⁻⁵ min⁻¹).

CO₂ hydration activity was measured by pH change as a function of time. DsCAopt enzyme exhibited a specific activity of 712 WAU/mg proteins. The pH was determined from the absorbance of the reaction mixture using bromophenol blue [19], varying pH 8.3 to pH 6.0. CA activity is expressed in Wilbur-Anderson (WA) units per milligram of protein.

The effect of pH on stability of purified DsCAopt enzyme was also retained at the range of pH 10.0-11.0, even after 24 h incubation at 4°C (Fig. 1).

Interestingly, more than 80% enzyme activity was also retained at the range of pH 4.0-7.0. The purified DsCAopt enzyme was found to be stable at pH range 7.6 and 10.

Carbonic anhydrases has been focused as biological catalysis for CO₂ sequestration process. Here, we also investigated the ability of DsCAopt to mediate CO₂ to CaCO₃ formation under Ca²⁺ solution. CaCO₃ precipitation using free DsCAopt enzyme was carried out in Tris-Cl buffer (1.0 M, pH 10.0). CaCO₃ was precipitated from the hydrated CO₂ solution by addition of 4% CaCl₂ solution. The precipitated CaCO₃ was recovered by filtration, weighed and the gram equivalent of CO₂ present in the calcium carbonate was calculated.

However, 50-70% activity retained at the range of pH 4.0-7.0. The purified DsCAopt enzyme was found to be stable at pH range 7.6 and 10.

In preliminary attempts, we tested several vector systems such as pQE series and pET series, and also employed several E. coli hosts such as E. coli BL21(DE3), E. coli M15 [pREP4] and E. coli SG13009 [pREP4] to express DsCA gene. Mostly, in the transformed cells with DsCA gene expression system (non codon-optimized), the yield of the expressed CA protein as soluble form was quite low (negligible), even as insoluble form. To increase the obtained yield of soluble and active DsCA, we screened the effects of different parameters; growth media [LB, 2X YT or Super Broth (SB)], IPTG concentrations (0.1-2mM), growth temperature (20-37°C), and cell disruption methods (sonication, freezing, and thawing in the presence or absence of detergents such as Triton X-100 and lysozyme). But, most of the attempts were in vain (data not shown). The acquired amount of soluble DsCA enzyme is still negligible. We constructed the codon-optimized sequence of DsCA (DsCAopt) by chemical
synthesis to expression in E. coli. The leader sequence (first 162 bp) was removed and transcription initiation codon (ATG) was added before codon sequence of 55th amino acid. The codon-optimized DsCAopt gene (1611bp) was cloned into pETDuet-1-vector. The recombinant DsCAopt was expressed well as soluble form in E. coli BL21(DE3) (pETD-DsCAopt).

Calcite is the dominant polymorph at high pH and low temperature and is the most stable at room temperature under atmospheric conditions. While vaterite and aragonite are mostly produced at low pH and high temperature, they can transform to stable calcite. Calcite is especially abundant in nature, environmentally harmless, and widely utilized in industry due to its regular crystal size and smooth surface [31]. FE-SEM image revealed that the morphologies of CaCO$_3$ crystal obtained by precipitation of hydrated CO$_2$ (catalyzed by DsCAopt enzyme) were similar to the morphologies described previously [32]. SEM image revealed rhombohedral calcite crystals. XRD analysis of precipitated CaCO$_3$ also indicates the formation of a calcite phase. The diffraction peaks occurred at 23.07, 29.5, 36.1, 39.5, and 43.3°, corresponding to the calcite crystal faces (012), (104), (110), (113), and (202), respectively and the representative crystal surface of calcite was 20 = 29.42 data not shown).

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REFERENCES


