Oral Delivery of Angiotensin-Converting Enzyme 2 and Angiotensin-(1-7) Bioencapsulated in Plant Cells Attenuates Pulmonary Hypertension

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Abstract—Emerging evidences indicate that diminished activity of the vasoprotective axis of the renin–angiotensin system, constituting angiotensin-converting enzyme 2 (ACE2) and its enzymatic product, angiotensin-(1-7) [Ang-(1-7)] contribute to the pathogenesis of pulmonary hypertension (PH). However, long-term repetitive delivery of ACE2 or Ang-(1-7) would require enhanced protein stability and ease of administration to improve patient compliance. Chloroplast expression of therapeutic proteins enables their bioencapsulation within plant cells to protect against gastric enzymatic degradation and facilitates long-term storage at room temperature. Besides, fusion to a transmucosal carrier helps effective systemic absorption from the intestine on oral delivery. We hypothesized that bioencapsulating ACE2 or Ang-(1-7) fused to the cholera nontoxin B subunit would enable development of an oral delivery system that is effective in treating PH. PH was induced in male Sprague Dawley rats by monocrotaline administration. Subset of animals was simultaneously treated with bioencapsulated ACE2 or Ang-(1-7) (prevention protocol). In a separate set of experiments, drug treatment was initiated after 2 weeks of PH induction (reversal protocol). Oral feeding of rats with bioencapsulated ACE2 or Ang-(1-7) prevented the development of monocrotaline-induced PH and improved associated cardiopulmonary pathophysiology. Furthermore, in the reversal protocol, oral ACE2 or Ang-(1-7) treatment significantly arrested disease progression, along with improvement in right heart function, and decrease in pulmonary vessel wall thickness. In addition, a combination therapy with ACE2 and Ang-(1-7) augmented the beneficial effects against monocrotaline-induced lung injury. Our study provides proof-of-concept for a novel low-cost oral ACE2 or Ang-(1-7) delivery system using transplastomic technology for pulmonary disease therapeutics. (Hypertension, 2014;64:00-00.) ● Online Data Supplement.

Key Words: chloroplast ▪ molecular farming ▪ plant-made pharmaceuticals ▪ pulmonary hypertension ▪ renin-angiotensin system

Pulmonary hypertension (PH) is a devastating lung disease characterized by elevated blood pressure in the pulmonary circulation, which eventually leads to right heart failure and death. Although significant advances have been made in recent years to improve the quality of life of patients with PH, none of the current treatments are successful in reversing PH or decreasing mortality. This has led to the realization that novel mechanism-based therapies must be developed to accomplish this goal.2

It is well-recognized that activation of the vasodilatory axis of the renin–angiotensin system (RAS), comprising of angiotensin-converting enzyme (ACE), angiotensin II, and angiotensin type I receptor (AT1R), is involved in the development of PH.1 However, the clinical use of ACE inhibitors or AT1R blockers have yielded mixed results, thereby failing to reach a consensus opinion about their use for PH therapy. Nonetheless, the recent discovery of a close homolog of ACE, ACE2 has resulted in the reevaluation of the role of RAS in PH.5 6 ACE2 is widely expressed in the lungs,7 predominantly on the pulmonary vascular endothelium, and catalyzes the conversion of angiotensin II to Angiotensin-(1-7) [Ang-(1-7)]. Ang-(1-7) is a vasoactive heptapeptide that mediates its effects by stimulating the Mas receptor.8 Thus, ACE2–Ang-(1-7)–Mas receptor constitutes the vasoprotective axis of the RAS, which

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counterbalances the deleterious actions of the ACE–angiotensin II–AT1R axis.

Recent reports indicate that decreased tissue and circulating levels of ACE2 are associated with lung diseases in humans. However, restoration of ACE2 through genetic overexpression, administration of recombinant protein, or use of pharmacological ACE2 activators resulted in cardiopulmonary protective effects against animal models of pulmonary diseases. These findings provided compelling evidence for initiating clinical trials with recombinant ACE2 or Ang-(1-7) in treating pulmonary disorders. Although clinical trials are currently underway, the cost of manufacturing, protein stability, repetitive intravenous dosing, and patient compliance pose major impediments in realizing full therapeutic potential of this therapy. We think that development of a plant-based oral delivery system will be an ideal approach to overcome these aforementioned challenges and achieve clinical success.

Therefore, our objective in this study was to develop a low-cost oral delivery system for administering ACE2 or Ang-(1-7) and test its efficacy in an experimental model of PH. We took advantage of transplastomic technology that enables chloroplasts to generate high levels of therapeutic proteins within plant leaves. This technology presents minimal risk of human pathogen or endotoxin contamination, eliminates complex protein purification steps, and abolishes cold chain and sterile delivery requirements that are commonly associated with protein therapy. Efficacy of plant-based pharmaceuticals has been validated by the fact that Food and Drug Administration has recently approved the use of taliglucerase alfa (Trade name: Elelyso) in the treatment of Gaucher disease. This study provides evidence for the development of an oral delivery system to administer ACE2 and Ang-(1-7) using transplastomic technology and demonstrates its efficacy in an established rat model of monocrotaline-induced PH.

Materials and Methods
The online-only Data Supplement includes detailed descriptions of all the methods and additional supporting data.

Results
Creation and Characterization of CTB-ACE2 and CTB-Ang-(1-7) Expressed in Plant Chloroplasts
The native human ACE2 cDNA and synthetic Ang-(1-7) DNA sequences were cloned into the chloroplast transformation vector (pLDutr; Figure 1A). For efficient delivery of the proteins into circulation, a carrier protein, cholera nontoxic B subunit (CTB), was fused to the N terminal of both therapeutic proteins (Figure 1A), which facilitates their transmucosal delivery by binding to monosialotetrahexosylganglioside receptors (GM1) present on the intestinal epithelial cells. Hinge (Gly-Pro-Gly-Pro) and furin cleavage site (Arg-Arg-Lys-Arg) were placed between CTB and therapeutic proteins (Figure 1A) to eliminate steric hindrance and aid systemic release of these therapeutic proteins after they are internalized via ligand–receptor complex formation on the surface of epithelial cells. The expression of the fusion genes was driven by light regulated strong chloroplast psbA promoter, and the transcripts were stabilized by placing the psbA untranslated region at the 3’ end of the fusion genes (Figure 1A). To select the chloroplast transformed with the fusion genes, aminoglycoside-3′-adenyl-transferase gene (aadA), driven by the chloroplast ribosomal RNA promoter (PrpsbA), was incorporated into the expression cassette to confer the transformants resistance to spectinomycin (Figure 1A). This expression cassette was flanked by DNA sequences of isoleucyl-tRNA synthetase (trnl) and alanyl-tRNA synthetase (trnA) genes, identical to the native chloroplast genome at both flanks (Figure 1A). The flank sequences serve to facilitate transgene integration into the chloroplast genome (Figure 1A) via double homologous recombination. Chloroplast transformation vectors expressing the ACE2 and Ang-(1-7) genes were coated onto gold particles and delivered into chloroplasts using the biolistic particle delivery system.

The bombarded plant leaves were then grown on spectinomycin-containing plant regeneration media. The shoots regenerated from the media were investigated for the site-specific integration of the transgenes into the chloroplast genome and homoplasmyn of the transgenes (absence of untransformed genomes) using Southern blot analysis with the radioisotope-labeled probe spanning trnl and trnA flanking sequences. HindIII-digested chloroplast genomic DNA from 3 independent transplastomic lines for each transplastomic line showed 2 hybridizing fragments at 8.59 and 3.44 kb for CTB-ACE2 because of an internal Hind III site of ACE2 (Figure 1A) and a fragment at 9.71 kb for CTB-Ang-(1-7), which confirm the absence of untransformed chloroplast genomes (Figure 1B and 1C). Thus, stable integration of the transgenes was confirmed, and the homoplasmic lines were used for further studies. The confirmed homoplasmic lines were multiplied using another round of antibiotic selection under aseptic conditions. Then they were cultivated in a controlled greenhouse for increasing biomass. CTB-ACE2 expression varied between 1.69% and 2.14% of the total leaf proteins (Figure 1D), depending on the harvest time because this transgene is regulated by light via the chloroplast psbA promoter. Similarly, the expression level of CTB-Ang-(1-7) varied between 6.0% and 8.7% of total leaf proteins (Figure 1E), at different durations of illumination, reaching maximum expression at the end of the day. Hence, for performing in vivo experimental studies, the therapeutic leaf materials were harvested at 6 PM and powdered in liquid nitrogen.

Both the therapeutic proteins were fused to the transmucosal carrier, CTB. The B subunit has a single intrasubunit disulfide bond that stabilizes the CTB monomer. The monomers then assemble to form ring-shaped pentameric structure via intersubunit interactions including hydrogen bonds, salt bridges, and hydrophobic interactions. Upon oral administration, only the pentameric form of CTB binds to the gut epithelial GM1 receptor for internalization. Hence, we investigated the proper formation of pentameric structure of the CTB-fused proteins and their binding affinity to GM1 receptor using GM1-ELISA. The binding affinity between CTB pentamers and the receptor was measured spectrophotometrically as a function of absorbance at 450 nm. The therapeutic proteins from the fresh leaf materials showed comparable absorbance to CTB (Figure 1F), confirming that chloroplasts form disulfide bridges, fold, and assemble these fusion proteins. We also lyophilized the leaves expressing ACE2 and Ang-(1-7) and evaluated their affinity to the GM1 receptor (Figure 1F).
Lyophilization not only maintained proper folding, disulfide bond, and pentamer assembly but also facilitated long-term storage at room temperature (Figure 1F). Furthermore, the Western blot assay performed under nonreducing conditions without dithiothreitol and boiling showed that there was no monomeric form or cleaved fragments of CTB-Ang-(1-7) (Figure 1G). In the Western blot image, the major bands for pentameric assembly of CTB were detected around ≈50 kDa (Figure 1G, arrow head), and the expected bands for pentameric assembly of CTB-Ang-(1-7) were detected (Figure 1G, arrow). Therefore, these results confirm that the therapeutic proteins expressed in chloroplasts exist in an intact and pentameric form.

**Oral Feeding of Bioencapsulated ACE2 or Ang-(1-7) Prevents Monocrotaline-Induced PH**

Oral gavage of the frozen powdered leaves (500 mg in sterile phosphate-buffered saline) from untransformed wild type, CTB-ACE2 or CTB-Ang-(1-7) transplastomic plants was performed twice daily for 4 weeks in monocrotaline-challenged rats. Monocrotaline injection caused robust elevation in right ventricular systolic pressure (RVSP; Figure 2A) that was associated with the development of RV hypertrophy (RVH; Figure 2B). In contrast, monocrotaline animals gavaged with either ACE2 or Ang-(1-7) showed considerable reduction in RVSP and RVH (Figure 2A and 2B). Furthermore, measurement of hemodynamic parameters in monocrotaline animals revealed increases in RV end-diastolic pressure (153%), +dP/dt (88%), and −dP/dt (107%). Conversely, treatment with ACE2 or Ang-(1-7) restored all these parameters to near-control levels (Figure 2C–2E). Echocardiography of monocrotaline rats revealed an increase in the ratio of RV to left ventricle end-diastolic area, implying dilation of the right heart (Figure 2F; Figure S1A and S1B in the online-only Data Supplement), which was accompanied with a decrease in ejection fraction (EF), measured as a ratio of RV to left ventricle end-diastolic area.
ventricle EF (Figure 2G; Figure S1C and S1D). In addition, the pulsed Doppler blood flow measurement revealed decreased flow rate in the RV outflow tract (Figure 2H). Furthermore, video of the echocardiography revealed mal-adaptive structural remodeling in monocrotaline rat hearts as compared with controls (Movies SI and SII). However, oral delivery of ACE2 or Ang-(1-7) exhibited improved cardioprotective effects. Both ACE2 and Ang-(1-7) were effective in decreasing RV dilation (Figure 2F), increasing EF (Figure 2G), and preventing monocrotaline-induced decrease in RV outflow tract blood flow (Figure 2H). These beneficial effects were associated with reduced cardiac remodeling as evidenced by echocardiography videos (Movies SIII and SIV). Concurrently, RV fibrosis and pulmonary vessel wall thickness were also decreased (Figure 3A and 3B). Oral ACE2 feeding was associated with ~37% increase in circulating ACE2 activity compared with monocrotaline alone rats (Figure 3C) and a 2-fold increase in circulating levels of Ang-(1-7) (Figure S2). Interestingly, ACE2 or Ang-(1-7) did not alter the basal systemic blood pressure (control, 120±5; monocrotaline, 123±7; monocrotaline +ACE2, 118±2; monocrotaline+Ang-(1-7), 116±4; n=5/ experimental group).

Oral ACE2/Ang-(1-7) Treatment Arrests the Progression of Established PH

We next tested whether oral feeding of ACE2 or Ang-(1-7) after the initiation of PH could arrest the disease progression. We observed that 2 weeks of monocrotaline challenge induces significant elevation in RVSP (>45 mmHg) compared with controls (Figure S3A). Hence, for this study, oral therapy was initiated after 2 weeks of monocrotaline challenge, and the treatment continued for additional 15 days. This regime of treatment with ACE2 or Ang-(1-7) inhibited further elevation in monocrotaline-induced RVSP and RVH (Figure 4A and 4B) and was associated with increased circulating levels of Ang-(1-7) (Figure S2). Improvements in hemodynamic parameters with regard to lowering RV end-diastolic pressure, decreasing +dP/dt, and reducing −dP/dt were also observed (Figure S3B–S3D). In addition, ACE2/Ang-(1-7) therapy
was initiated after 2 weeks of monocrotaline challenge, and was followed for this study, wherein the combination therapy and Ang-(1-7) plant material was combined. Reversal protocol ACE2 and Ang-(1-7), wherein 500 mg or 250 mg each of ACE2 and next, we evaluated the effects of a combination therapy with Ang-(1-7) Feeding Rescues Established PH

Beneficial Effects of ACE2/Ang-(1-7) Oral Therapy Involving Inhibition of Proinflammatory Cytokines and Autophagy

We hypothesized that oral delivery of ACE2 or Ang-(1-7) would correct RAS imbalance and inhibit proinflammatory cytokines. Data in Figure 7 support this hypothesis. Monocrotaline rats revealed increased pulmonary mRNA levels of ACE and AT1R (Figure 7A and 7D), which resulted in 8-fold and 4-fold increases in the ACE/ACE2 and AT1R/AT2R ratios, respectively (Figure 7C and 7F). Conversely, mRNA levels of ACE2 and AT2R were increased, whereas that of AT1R was decreased in the ACE2 or Ang-(1-7)–fed monocrotaline rats, resulting in decreased ACE/ACE2 and AT1R/AT2R ratios. Furthermore, monocrotaline-challenged animals showed increased mRNA levels of tumor necrosis factor-α (4-fold), transforming growth factor-β (4-fold), and toll-like receptor-4 (5-fold), all of which were markedly reduced by ACE2 or Ang-(1-7) treatment (Figure 7G–7I). Recent reports indicate that the autophagic protein degradation pathway is activated in monocrotaline-challenged animals. Accordingly, we observed that the lung LC3B-II protein, an autophagy marker, was significantly increased in monocrotaline-challenged rats (Figure 7J). However, ACE2 or Ang-(1-7) decreased LC3B-II levels, implying inhibition of autophagy. Similar results with respect to RAS modulation, anti-inflammatory properties, and inhibition of autophagy were observed in the reversal protocol with monotherapy (either ACE2 or Ang-(1-7)) or combination therapy (Figure 8A–8J).

Discussion

The most significant finding of our study is that we have developed a system to generate human ACE2 and Ang-(1-7) within plant chloroplasts using plastidic technology, which when orally administered to rats attenuates PH. Although previous genetic interventions with ACE2/Ang-(1-7) have demonstrated beneficial effects in animals,11,12 there are several challenges that limit the clinical development of such approaches. The incidence of PH is increasing among the elderly global population, necessitating affordable medication for the masses. Although drugs made in plant cells have been approved by the Food and Drug Administration and are currently marketed, targeted gene therapy is still in the...
Experimental stage and far away from clinical applications. Even if gene therapy is approved as a valid approach, it would still be accessible to <1% of the global population because of the limited expertise available in hospitals for gene therapy. In contrast, oral delivery of plant capsules containing therapeutic proteins is feasible and much affordable. So, drug delivery is as important as drug discovery, and this study focuses on the development of a novel low-cost delivery system for administering therapeutic proteins like ACE2/Ang-(1-7), which have been found to be effective against experimental models of lung diseases, but not yet clinically approved. Injectable delivery of ACE2/Ang-(1-7) poses some unique challenges with respect to cost of manufacturing, protein stability, cold storage, shelf life, sterile delivery, and requirement of health professionals/hospitals for their administration. Most of these concerns are easily eliminated by orally delivering therapeutic proteins bioencapsulated in plant cells. Currently produced injectable protein drugs are not affordable to more than half of the global population, despite decades of optimization of their process development. By developing an oral delivery system for administering ACE2 and Ang-(1-7), as reported here, we have made tremendous advancement to move the field forward and take ACE2/Ang-(1-7) toward translational/clinical research for the treatment of pulmonary diseases.

ACE2 and Ang-(1-7) were expressed in plant chloroplasts as fusion proteins with CTB. Although Ang-(1-7) is not a gene product, a synthetic gene encoding for Ang-(1-7) was used in this study. Chloroplasts are ideal bioreactors for producing human therapeutic proteins. The total copy number of the transgene per cell is expected to be ≤100,000, resulting in hyperexpression (≤70% of total leaf protein). A single plant cell has ~100 chloroplasts, and each chloroplast has ~100 copies of ACE2 and Ang-(1-7)
chloroplast genome. So, ≤10,000 copies of transgene in each transformed plant cell is observed. This copy number has been quantified by quantitative polymerase chain reaction in our previous studies.30 However, the most practical way in the literature to evaluate homoplasmy (transformation of all chloroplast genomes in each plant cell) is by showing the absence of native untransformed chloroplast genomes as shown in Figure 1B and 1C. Moreover, this system allows for appropriate disulfide bond formation, proper protein folding, and assembly.17,18 Also, biocapsulation of proteins within plant cells protects them from gastric degradation. Most importantly, when fused with transmucosal carriers such as CTB, therapeutic proteins are effectively released into systemic circulation by microbes colonizing the gut, which lyse plant cells, after CTB-GM1 interaction.18–21 GM1 is also present on the cell membrane of the retina and nervous system and hence can be targeted by CTB-fused therapeutic proteins, as reported in our recent study.31,32 Chloroplasts are capable of producing high level expression of foreign genes. However, the expression levels of ≈93 kDa of ACE2 were below our expectations compared with Ang-(1-7) (Figure 1C and 1D).

The prokaryotic nature of chloroplast is not well-suited for the expression of eukaryotic human genes because of the bias in codon preference and usage.33,34 For example, native prokaryotic genes from Bacillus anthracis and Bacillus thuringiensis were expressed ≤45.3% of the total soluble protein in chloroplasts.16,35 Small native human genes such as insulin like growth factor-1 (≈7.8 kDa),36 proinsulin (≈12 kDa),16 and interferon-α2b (≈21.5 kDa)37 were expressed in chloroplasts at high levels. However, larger human native genes like blood clotting factors were expressed in chloroplasts at lower levels.20 From the analysis of the ACE2 nucleotide sequence, it was observed that 349 codons of 805 were rare codons (43.5%), which would readily exhaust the corresponding tRNA pools, leaving relatively abundant tRNAs unused. Therefore, for clinical development of ACE2, codon optimization and expression in an edible system (lettuce) should be considered.

We have used CTB as the transmucosal carrier to facilitate the uptake of ACE2 and Ang-(1-7) into circulation. Both CTB fusion proteins are disulfide bonded, form pentamers, and properly folded, as observed for other CTB fusion proteins.17,18 CTB is an approved adjuvant38 that has been used in several clinical settings. Administration of CTB-fused antigen (Behcet’s disease peptide) in humans with autoimmune eye disorders induced immunologic tolerance by suppressing...
This offers greater N-terminal protection to Ang-(1-7) and extends its stability for several hours in the sera compared with injectable Ang-(1-7). Actually, continued treatment with bioencapsulated Ang-(1-7) showed significant increases of the circulating levels of the peptide (Figure S2), which suggests that an oral gavage twice daily of bioencapsulated Ang-(1-7) results in sustained elevated plasma levels of Ang-(1-7) in the treated animals. Ang-(1-7) concentration in frozen leaf materials was found to be 584 μg/g, which translates to 292 μg in 500 mg. This dose compares well with previous studies, wherein 750 to 1000 μg/kg of Ang-(1-7) peptide was administered to rats (≥300 μg per 300 g rat).

Oral feeding of bioencapsulated ACE2 or Ang-(1-7) prevents the development and, most importantly, retards the progression of monocrotaline-induced PH. An upregulation of the deleterious ACE–angiotensin II–AT1R axis and downregulation of the protective ACE2–Ang-(1-7)–Mas axis contributes to PH pathogenesis. Thus, maintaining equilibrium between these 2 axes is crucial for preserving pulmonary vascular homeostasis. Oral delivery of ACE2 or Ang-(1-7) increased ACE2/ACE and decreased AT1R/AT2R ratios, signifying improvement in pulmonary RAS balance. It was interesting to note that the serum ACE2 activity in monocrotaline animals was decreased compared with controls. This, however, did not affect the circulating levels of Ang-(1-7), which could possibly be because of alternate endopeptidase pathways of Ang-(1-7) generation through neprilysin or thimet oligopeptidase. However, oral ACE2 feeding prevented the decrease in serum ACE2 activity of monocrotaline animals and was associated with a 2- to 3-fold increase in the circulating levels of Ang-(1-7) (Figure S2). In fact, ACE2 fed rats exhibited 37% increase in the enzymatic activity compared with monocrotaline alone animals. Most importantly, this increase was sufficient to exert beneficial effects against PH pathophysiology. Previous experimental studies have shown that exogenous administration of recombinant ACE2 increases serum ACE2 activity to exert therapeutic efficacy in several disease models. Increasing serum ACE2 levels is also clinically significant because abnormally low levels of serum ACE2 have been associated with PH. Surprisingly, pulmonary ACE2 mRNA levels were increased with oral ACE2 feeding. We speculate this increase to be a positive feed forward mechanism because similar increases in ACE2 have been reported previously.

The half-life of native Ang-(1-7) is short. However, in this study, the stability of Ang-(1-7) was found to increase in sera. In plant cells, CTB stabilizes Ang-(1-7) by formation of pentamers (Figure 1G) and thus confers protection from plant proteases. However, only monomers are observed in sera after delivery into the sera. Although furin cleavage site (NH2-R-R-K-R-COOH) should facilitate removal of CTB, efficiency of cleavage depends on the flanking amino acid sequence of the fused protein. Ang-(1-7) fused to CTB did not provide optimal furin cleavage site because it is not flanked by furin preferred basic amino acids at N-terminal side and serine–valine at C-terminal side. Therefore, it is anticipated that furin cleavage will not be rapid or efficient.
autophagy marker, in monocrotaline rats, which was significantly decreased with ACE2 or Ang-(1-7) treatment.

Collectively, aforementioned findings suggest that oral delivery of ACE2 or Ang-(1-7) corrects a dysregulated pulmonary RAS, reduces inflammation, decreases vascular remodeling, and inhibits autophagy to exert lung-protective effects. Importantly, ACE2/Ang-(1-7) treatment did not lower basal systemic blood pressure, which is important because induction of systemic hypotension can be detrimental in patients with PH. Similar phenomenon has also been observed in other studies, wherein chronic administration of Ang-(1-7) fails to decrease systemic blood pressure in a variety of models of hypertension.54–56 One possibility may be related to pulmonary vasculature being more sensitive to Ang-(1-7) or that abundant receptors for Ang-(1-7) is present on the pulmonary vessels.

One possibility may be related to pulmonary vasculature being more sensitive to Ang-(1-7) or that abundant receptors for Ang-(1-7) is present on the pulmonary vessels. Furthermore, a combination of ACE2 and Ang-(1-7) treatment produced beneficial effects on the cardiopulmonary system. We observed that the higher dose combination yielded better effects than the lower dose.

Of particular interest are the cardioprotective effects of oral ACE2/Ang-(1-7) therapy. Sustained pressure overload on the right heart induces ventricular remodeling and dysfunction.57 Echocardiography of monocrotaline rats revealed prominent structural changes in the heart. The RV assumed a round shape, with a shift in the intraventricular septum causing RV dilation with reduced EF. In addition, the pulmonary

**Figure 7.** Effects of angiotensin-converting enzyme 2 (ACE2) or angiotensin-(1-7) [Ang-(1-7)] treatment on the lung renin–angiotensin system, proinflammatory cytokines, and autophagy (prevention protocol). Relative change in lung mRNA levels of (A) ACE, (B) ACE2, (C) ACE/ACE2 ratio, (D) angiotensin type 1 receptor (AT1R), (E) angiotensin type 2 receptor (AT2R), and (F) AT1R/AT2R receptor. Relative mRNA levels of lung proinflammatory cytokines, G, tumor necrosis factor (TNF)-α, (H) transforming growth factor (TGF)-β, and (I) toll-like receptor-4 (TLR-4) from the monocrotaline (MCT) study. Autophagy marker, LC3-II is increased in the lungs of MCT-exposed animals. J, Immunoblot and densitometry analysis of the lung LC3I/II protein expression. Data are expressed as mean±SEM. *P<0.05, **P<0.01, and ***P<0.001 vs control rats. #P<0.05 vs MCT group. WT indicates wild type.
artery flow was significantly lowered in the monocrotaline group. All these changes were associated with development of RVH, increased interstitial fibrosis, and cardiac dysfunction. However, ACE2 or Ang-(1-7) treatment restored normal heart structure, inhibited RV dilatation, and improved EF. Also, RVH and interstitial fibrosis were significantly reduced, along with preserved cardiac function. Moreover, the combination therapy with ACE2 and Ang-(1-7) was found to exert superior cardioprotective effects.

**Perspectives**

Evidences have implicated the therapeutic potential of the ACE2/Ang-(1-7) axis in multiple diseases such as PH, lung fibrosis, heart failure, renal diseases, and diabetic retinopathy. This study provides proof-of-concept for a low-cost plant-based oral delivery system for ACE2 or Ang-(1-7) bioencapsulated in plant chloroplasts. This transplastomic technology offers the potential to scale-up and generate bulk quantities of therapeutically active ACE2/Ang-(1-7) toward undertaking translational studies with a simple oral delivery system. In this direction, we have lyophilized leaves expressing ACE2 or Ang-(1-7), which have concentrated these therapeutic proteins by ≈20.5- and 14.3-fold, respectively, with no loss of the binding affinity to GM1 receptor (Figure 1F). The concentration effect is because of the packaging of more proteins per milligram of lyophilized leaves, which is advantageous in that it reduces the cost associated with protein purification, eliminates microbial contamination, and facilitates long-term storage of these therapeutic proteins in capsules at room temperature, which are all important considerations for clinical development.

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Disclosures

None.

References


**Novelty and Significance**

**What Is New?**

- This study provides evidence for the first time the development of a low-cost oral delivery system for the administration of angiotensin-converting enzyme 2 and angiotensin-(1–7) using transplastomic technology that provides impressive protection against pulmonary hypertension.

**What Is Relevant?**

- Angiotensin-converting enzyme 2 and angiotensin-(1–7) have tremendous therapeutic potential for treating pulmonary hypertension. However, cost of manufacturing, protein stability, repetitive intravenous dosing, and patient compliance pose major impediments for successful clinical therapy. Development of a plant-based oral delivery system will overcome these challenges to realize full therapeutic potential of these proteins.

**Summary**

Oral delivery of angiotensin-converting enzyme 2 or angiotensin-(1–7) bioencapsulated in plant cells provides protection against pulmonary hypertension and associated cardiopulmonary pathology.
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The authors apologize for the error.
ONLINE SUPPLEMENT

ORAL DELIVERY OF ANGIOTENSIN CONVERTING ENZYME2 AND ANGIOTENSIN-(1-7) BIOENCAPSULATED IN PLANT CELLS ATTENUATES PULMONARY HYPERTENSION

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Supplementary Figure S1: Oral feeding of bioencapsulated ACE2 or Ang-(1-7) improves cardiac function in PH as measured by echocardiography.

Echocardiography was performed at the end of the study in M mode at the parasternal short axis view at the papillary muscle level as described in the Methods. Ejection fraction of the left ventricle was calculated using the following formula: (End Diastolic Volume – End Systolic Volume / End Diastolic Volume) X 100. In the parasternal short axis view, the transducer was slightly angled to record the image of both right and left ventricle and this image was used to analyze the right and left ventricular end diastolic
area. (A) End Diastolic Area of Left Ventricle (LV EDA), as visualized by echocardiography. LV EDA was significantly reduced in PH animals and the oral feeding of ACE2 or Ang-(1-7) prevented the reduction in the LV EDA. (B) End Diastolic Area of Right Ventricle (RV EDA), as visualized by echocardiography. RV EDA was significantly increased in the PH animals demonstrating the right ventricular dilation. Oral feeding of ACE2 or Ang-(1-7) significantly reduced the RV dilation and improved the cardiac function. (C) Ejection Fraction of Left Ventricle, as visualized by echocardiography. LV EF was slightly reduced in PH animals. Data represents mean ±SEM with n=5 animals. (D) Ejection fraction of Right Ventricle, as visualized by echocardiography. RV EF was significantly reduced in the PH animals demonstrating the cardiac dysfunction. Oral feeding of ACE2 or Ang-(1-7) attenuated the MCT induced decrease in RV ejection function. (MCT+ACE2-P and MCT+Ang-(1-7)-P represents the prevention protocol, while MCT+ACE2-R and MCT+Ang-(1-7)-R represents the reversal protocol. MCT+C-500 and MCT+C-250 represent the combination treatment using 500mg and 250mg respectively in the reversal protocol.) In both figures, data represent mean ±SEM with n=5 animals *** denoting p<0.001 as compared with normal controls, while # representing p<0.05 Vs untreated and wild type plant material fed MCT animals as assessed by One-Way ANOVA followed by Newman–Keuls test.
Supplementary Figure S2: Oral feeding of bioencapsulated ACE2 or Ang-(1-7) increases circulating levels of Ang-(1-7) in both prevention and reversal protocols.

(A) Data indicates significant elevation in circulating levels of Ang-(1-7) in both prevention and reversal protocols (n=5 rats per group). (MCT+ACE2 (P) and MCT+Ang-(1-7) (P) represents the prevention protocol, while MCT+ACE2 (R) and MCT+Ang-(1-7) (R) represents the reversal protocol. Data represent mean ±SEM with n=5 animals ** denoting p<0.01 as compared with normal controls, untreated and wild type plant material fed MCT animals as assessed by One-Way ANOVA followed by Newman–Keuls test.
Supplementary Figure S3: Oral feeding of bioencapsulated ACE2 or Ang-(1-7) exerts cardioprotective effects.

(A) Data indicates significant elevation of right ventricular systolic pressure (RVSP) after 2-weeks of MCT administration, signifying induction of PH (n=5 rats per group). Data are expressed as mean ± SEM; * p<0.05 versus controls using student t-test. Measurement of (B) right ventricular end-diastolic pressure (RVEDP), (C) +dP/dt, and (D) -dP/dt in in normal controls and MCT-challenged rats that were either untreated or orally fed with wild type leaf material or gavaged with bioencapsulated ACE2/Ang-(1-7). Data are expressed as mean ± SEM; ***p< 0.001; versus controls and # p<0.05 versus MCT group. n=5 animals per experimental group.
SUPPLEMENTARY MOVIE LEGEND

Supplementary Movie I: Para-sternal short-axis view at the papillary muscle level, showing anterior and posterior walls of left and right ventricles in control animals.

Videography was performed at the end of the study period using GE vivid7 ultrasound machine with a 12-Hz transducer. The recording demonstrates normal functioning of the right and left ventricles.

Supplementary Movie II: Para-sternal short-axis view of left and right ventricle in MCT animals.

Para-sternal short-axis view at the papillary muscle level, showing anterior and posterior walls of the right and left ventricles from a monocrotaline (MCT)-challenged animal following 28 days of MCT-injection. The recording shows clear enlargement and dilation of the right ventricle, with a concomitant decrease in the left ventricular area, signifying maladaptive cardiac remodeling associated with PH.

Supplementary Movie III: ACE2 prevents ventricular remodeling in MCT animals.

Para-sternal short-axis view at the papillary muscle level, showing anterior and posterior walls of the right and left ventricles from a MCT animal that was gavage-fed with ACE2 for a period of 28 days (prevention protocol). The recording demonstrates that the oral feeding of ACE2 prevents enlargement and dilation of the right ventricle, along with restoration cardiac function.

Supplementary Movie IV: Ang-(1-7) prevents ventricular remodeling in MCT animals.

Para-sternal short-axis view at the papillary muscle level, showing anterior and posterior walls of the right and left ventricles from a MCT animal that was gavage-fed with Ang-(1-7) for 28 days. The recording demonstrates that the oral feeding of Ang-(1-7) exerts cardioprotective effects by preventing MCT-induced enlargement and dilation of the right ventricle.

Supplementary Movie V: ACE2 arrests the progression of ventricular remodeling in MCT animals.

Para-sternal short-axis view at the papillary muscle level, showing anterior and posterior walls of the right and left ventricles from a MCT animal that was orally gavaged with ACE2, with treatment commencing after 2-weeks of MCT injection. The recording shows that oral feeding of ACE2 for 15 days attenuates MCT-induced enlargement and dilation of the right ventricle, along with an improvement in cardiac function.

Supplementary Movie VI: Ang-(1-7) arrests the progression of ventricular remodeling in MCT animals.

Para-sternal short-axis view at the papillary muscle level, showing anterior and posterior walls of the right and left ventricles from a MCT animal that was orally gavaged with
Ang-(1-7), with treatment commencing after 2-weeks of MCT injection. The recording demonstrates that oral feeding of Ang-(1-7) not only attenuates MCT-induced dilation of the right ventricle but also improves cardiac function.

**Supplementary Movie VII: Combination of ACE2 and Ang-(1-7) arrests the progression of ventricular remodeling in MCT animals.**

Para-sternal short-axis view at the papillary muscle level, showing anterior and posterior walls of the right and left ventricles from a MCT animal that was orally gavaged with a combination of ACE2 and Ang-(1-7) [500mg each], with treatment commencing following 2-weeks of MCT injection. The recording demonstrates that the combination therapy of ACE2 and Ang-(1-7) arrests the progression of MCT-induced dilation of right ventricle, along with improving cardiac function.

**Supplementary Movie VIII: Combination of ACE2 and Ang-(1-7) arrests the progression of ventricular remodeling in MCT animals.**

Para-sternal short-axis view at the papillary muscle level, showing anterior and posterior walls of the right and left ventricles from a MCT animal that was orally gavaged with a combination of ACE2 and Ang-(1-7) [250mg each], with treatment commencing following 2-weeks of MCT injection. The recording demonstrates that the combination therapy of ACE2 and Ang-(1-7) arrests the progression of MCT-induced dilation of right ventricle, along with improving cardiac function.
SUPPLEMENTARY MATERIALS AND METHODS

Chloroplast transformation vector construction and regeneration of transplastomic lines
The ACE2 gene (Accession: NM_021804) was amplified with specific primer sets. The sequence of PCR amplified cDNA fragment was confirmed and cloned into the CTB-containing chloroplast transformation vector, pLDutr. CTB-Ang-(1-7) fusion gene was amplified by using CTB-containing vector as template with a forward primer and a reverse primer including nucleotide sequence corresponding to 7 amino acid Ang-(1-7) peptide and cloned into the pLDutr vector. Delivery of the fusion genes into chloroplast genome and regeneration of transplastomic plants were performed as previously described in published methods.1

Southern blot analysis
To investigate transgene integration and homoplasmy, Southern blot analysis was performed as previously described.1 Total genomic DNA was digested with HindIII, separated on a 0.8% agarose gel at 15 V overnight, transferred onto nylon membrane. The 0.8-kb flanking region probe was generated by digesting the pUC-CT vector DNA with BamHI and BglII. The probe was labeled with dCTP using Klenow fragment (Promega M220A) and random primers (Promega C1181). After labeling the probe, the blotted membrane was hybridized with hybridization solution [0.5 M phosphate buffer pH 7.2, 1 mM EDTA pH 8.0, 7% (w/v) SDS, 1% (w/v) bovine serum albumin] at overnight at 65°C then washed with 2X SSC, 0.2% SDS for 30 min once and 1X SSC, 0.1% SDS for 15 min twice each. Radioisotope-labelled blots were exposed to X-ray film at -80°C for 8 h.

Quantification of CTB-ACE2 and CTB-Ang-(1-7) fusion protein
Leaves ground in liquid nitrogen was resuspended in extraction buffer [100 mM NaCl, 10 mM EDTA, 200 mM Tris-Cl pH 8.0, 0.1% (v/v) Triton X-100, 400 mM sucrose, 2 mM PMSF, and protease inhibitor cocktail] in a ratio of 100 mg to 300 µL, then vigorously mixed using vortex (~30 s) and sonicated twice (pulse on for 5 s and pulse off for 10 s). Homogenate protein was quantified using Bradford assay. For the quantification of CTB-ACE2 protein, ELISA was performed. Ninety-six-well plates were coated with serially diluted CTB standard (25 - 12.5 - 6.25 - 3.13 - 1.56 -0.781 - 0.391 - 0.195 pg/µL; Sigma C9903) and CTB-ACE2 proteins (4,000 - 8,000 - 16,000) in bicarbonate buffer (15 mM Na2CO3, 35 mM NaHCO3, 3.08 mM NaN3, pH 9.6), then incubated overnight at 4°C. After washing the plates with 1X phosphate buffered saline (Fisher IC-N2810307) containing 0.05% (v/v) Tween 20 (1X PBST), the coated plates were blocked with 1X PBST containing 3% skim milk (PTM) for one and half hr at 37°C and incubated with rabbit anti-CTB polyclonal antibody (1:10,000 in PTM; GenWay 18-511-245283) overnight at 4°C. The plates were followed by incubating with goat anti-rabbit IgG-HRP secondary antibody (1:4,000 in PTM; Southern Biotechnology 4030-05) for one and half hr at 37°C and incubated with rabbit anti-CTB polyclonal antibody (1:10,000 in PTM; GenWay 18-511-245283) overnight at 4°C. The plates were followed by incubating with goat anti-rabbit IgG-HRP secondary antibody (1:4,000 in PTM; Southern Biotechnology 4030-05) for one and half hr at 37°C and incubated with rabbit anti-CTB polyclonal antibody (1:10,000 in PTM; GenWay 18-511-245283) overnight at 4°C. The plates were followed by incubating with goat anti-rabbit IgG-HRP secondary antibody (1:4,000 in PTM; Southern Biotechnology 4030-05) for one and half hr at 37°C after washing with 1X PBST thrice. The antibody-bound plates were washed with 1X PBST thrice and 1X PBS once before adding the 100 µL of tetramethyl benzidine (TMB) solution substrate (American Qualex Antibodies UCFL-C5801). The reaction was stopped by adding the 50 µL of 2N H2SO4 and read on a plate reader at 450 nm. CTB-Ang-(1-7) was quantified using western blot and
densitometric analysis. Total homogenate protein (0.5 µg) and CTB standards (3, 6, and 9 ng) was separated on SDS-PAGE and transferred to nitrocellulose membranes. Rabbit anti-CTB polyclonal antibody (1:10,000 in PTM; GenWay) and goat anti-rabbit IgG-HRP secondary antibody (1:4,000 in PTM; Southern Biotechnology) was used to detect the fusion proteins. SuperSignal West Pico Chemiluminescent Substrate (Pierce 34080) was used for autoradiographic detection. Then the developed films were analyzed by densitometry using Image J (IJ 1.46r; NIH). The known amounts of CTB standard were plotted and then the protein samples were interpolated on the graph. For the separation of proteins under non-reducing conditions, proteins were extracted as described above. The extracted proteins were combined with tricine sample buffer (Bio-Rad 161-0730), in the absence of reducing agents and without boiling prior to running on SDS-PAGE gels.

**GM1 binding assay**

To evaluate pentameric structure, GM1 binding assay was performed. Ninety-six-well plates were coated with monosialoganglioside-GM1 (Sigma G-7641) (3.0 µg/mL in bicarbonate buffer: 15 mM Na₂CO₃, 35 mM NaHCO₃, pH 9.6) overnight at 4°C. The plates were washed with PBST thrice and blocked with PTM. After washing the plates with 1X PBST, homogenate plant protein was diluted to concentration of 0.1 µg/µL with the same plant extraction buffer and incubated in the GM1 coated plates overnight at 4°C, along with CTB (1 ng/µL, Sigma), bovine serum albumin (1% w/v BSA) and untransformed wild type plant protein (0.1 µg/µL) as controls. The plates were blocked with PTM for one and half hr at 37°C. After discarding the PTM, rabbit anti-CTB polyclonal antibody (1:10,000 in PTM; GenWay) was incubated overnight at 4°C. Following washing three times with 1X PBST, goat anti-rabbit IgG-HRP secondary antibody (1:4,000 in PTM; Southern Biotechnology) was incubated for one and half hr at 37°C. The plates were washed with PBST thrice and with PBS once and 100 µL of tetramethyl benzidine (TMB) solution substrate (American Qualex Antibodies UCFL-C5801) was added to the wells and incubated under dark for 5 min. The reaction was stopped by adding 50 µL of 2N H₂SO₄, and read the absorbance at 450 nm using plate reader (Bio-rad Model 680).

**Lyophilization**

Frozen leaf tissues stored at -80°C were crumbled into small pieces and transferred to 200 ml containers and sealed with porous 3M Millipore Medical Tape. The plant samples were freeze-dried in vacuum at -52°C at 0.036 mBar for three days, with the aid of VirTis BenchTop 6K freeze dryer system. Lyophilized leaf material was stored in sealed container at room temperature with silica gel.

**PH Study design**

We used the monocrotaline (MCT) animal model of PH to evaluate the therapeutic efficacy of oral feeding of ACE2, Ang-(1-7) or their combination against disease pathogenesis. Animals were randomly assigned to respective experimental groups based on their body weights at the time of MCT administration. The study design consisted of prevention and reversal protocols. All animal procedures were approved by the Institutional Animal Care and Use Committee at the University of Florida and
complied with National Institutes of Health guidelines.

**Gavage feeding of MCT rats with bioencapsulated ACE2 or Ang-(1-7)**

8-week-old male Sprague Dawley rats (Charles River Laboratories) were injected with a single subcutaneous dose of MCT (50 mg/kg, Sigma Aldrich, USA). Control animals received an equivalent amount of sterile saline (~500 µL). For the prevention protocol, a subset of MCT animals was simultaneously orally gavaged with wild type leafy material, bioencapsulated ACE2 or Ang-(1-7) [500 mg, twice daily in sterile phosphate-buffered saline (PBS)] for a period of 28 days. For the reversal protocol, ACE2, Ang-(1-7) or their combination [500 mg or 250 mg each of ACE2 and Ang-(1-7)] was gavage-fed after 2 weeks of MCT administration and continued for additional 15 days.

**Echocardiography Measurement**

Four weeks after MCT injection, transthoracic echocardiography was performed using GE vivid7 ultrasound machine with a 12-MHz transducer (GE Healthcare, NJ, USA). Rats were anesthetized with the 2% isoflurane-oxygen mixture. M-mode echocardiography was measured at the parasternal short-axis view at the level of papillary muscles. Left ventricular ejection fraction (LVEF) was calculated from the M-mode. Further, at this view, right and left ventricular end diastolic area (RVEDA and LVEDA) and right ventricular ejection fraction (RVEF) were also measured. Pulsed Doppler recordings performed at the parasternal short-axis view at the base of the heart to measure the right ventricle outflow tract (RVOT Vmax). ECG was recorded simultaneously for all the assessments. All the recordings were performed in triplicates. Ejection fraction was obtained from both right and left ventricles and was represented as the ratio between right and left ventricle. Similarly, end diastolic area was also represented as the ratio between right and left ventricle. Blood flow at the right ventricular outflow tract was represented as RVOT Vmax (m/s). Three consecutive cycles from each recording (totally 9 cycles) were averaged to assess each parameter. Following the echocardiographic measurements, animals were subjected to hemodynamic measurements.

**Right Ventricular Systolic Pressure (RVSP) Measurements**

The RVSP was measured in anesthetized animals [subcutaneous injection of a mixture of ketamine (30 mg/Kg) and Xylazine (6 mg/Kg)] using a fluid-filled silastic catheter, which was inserted inside the right descending jugular vein and advanced to the right ventricle. The catheter was connected to a pressure transducer that was interfaced to a PowerLab (AD Instruments, USA) signal transduction unit. The waveform was used to confirm the positioning of the catheter in the right ventricle. RVSP, +dP/dt, -dP/dt and right ventricular end diastolic pressure (RVEDP) were obtained using the Chart program supplied along with the PowerLab system. For both prevention and reversal protocols RVSP was measured after 4 weeks of MCT-challenge.

**Hypertrophy and Histological Analysis**

Following RVSP measurements, a thoracotomy was performed, and after exsanguination, the heart and lungs were removed en bloc. To calculate right ventricular hypertrophy (RVH), the wet weight of RV and left ventricle plus ventricular
septum (LV+S) was determined. RVH was expressed as the ratio of RV/[LV+S] weights. The RV was further processed for histological analysis of collagen content. Briefly, RV was fixed in 10% neutral buffered formalin, embedded in paraffin, sectioned at 5 μm and stained with picro-sirius red. Interstitial fibrosis was determined at 100X magnification using the ImageJ program from National Institutes of Health, as previously described. A minimum of 5-8 separate images from different (non-overlapping) regions of the right ventricle were obtained. The results for each animal were then averaged for subsequent statistical analysis. To carry out histological examination of the lung, the left lung alone was perfused with PBS followed by 10% neutral buffered formalin. For measuring pulmonary medial wall thickness, 5 μm thick lung sections were cut paraffin embedded and stained for α-smooth muscle actin (1:600, clone 1A4, Sigma Aldrich, USA). Vessels with an external diameter of <50 μm were considered to measure the medial wall thickness. For each rat, around 10 vessels were counted and the average was calculated. The percent medial wall thickness was calculated using the formula: % Medial wall thickness = [(medial thickness x 2)/external diameter] x100 (n=5 rats per group) Media thickness was defined as the distance between the lamina elastica interna and lamina elastica externa.

**Real-Time RT-PCR Analysis**

Semi-quantitative real time RT-PCR was used to determine mRNA levels of the renin-angiotensin system components viz. ACE, ACE2, AT1R, and AT2R, and pro-inflammatory cytokines (PICs) viz. Tumor Necrosis Factor-alpha (TNF-α), Transforming Growth Factor-beta (TGF-β) and toll-like receptor-4 (TLR-4) as described previously. Total RNA isolation, cDNA synthesis and RT-PCR were performed as previously described. In brief, total RNA was isolated from punched tissues using TRIzol reagent (Invitrogen, USA) according to the manufacturer’s specifications. The RNA concentration was calculated from the absorbance at 260 nm and RNA quality was assured by 260/280 ratio. Only RNA samples exhibiting an absorbance ratio (260/280) of >1.6 were used for further experiments. The RNA samples were treated with DNase I (Ambion, USA) to remove any genomic DNA. First strand cDNA was synthesized from 2 μg RNA with iScript cDNA synthesis kit (Bio-Rad, USA). Real-time RT-PCR was performed in 384-well PCR plates using iTaq SYBR Green Super mix with ROX (Bio-Rad) in triplicate using the ABI Prism 7900 sequence detection system (Applied Biosystems, USA). The PCR cycling conditions were as follows: 50°C for 2 min, 95°C for 3 min, followed for 45 cycles (15s at 95°C, and 1 min at 60°C). To confirm the specific PCR product, a dissociation step (15s at 95°C, 15s at 60°C, and 15s at 95°C) was added to check the melting temperature. Gene expression was measured by the ΔΔCT method and was normalized to 18S mRNA levels. The data are presented as the fold change of the gene of interest relative to that of control animals.

**Measurement of Ang-(1-7):**

Circulating levels of Ang-(1-7) were measured using a commercially available EIA kit from Bachem Laboratories as per manufacturer’s instructions.
**Statistics**
Prism 5 (GraphPad) was used for all analyses. Values are presented as means ± SEM. Data were analyzed using one-way ANOVA followed by the Newman-Keuls test for multiple comparisons. *P* values less than 0.05 were considered statistically significant.

**References:**
