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Editing out five Serpina1 paralogs to create a mouse model of genetic emphysema

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Chronic obstructive pulmonary disease affects 10% of the worldwide population, and the leading genetic cause is α1-antitrypsin (AAT) deficiency. Due to the complexity of the murine locus, which includes up to six Serpina1 paralogs, no genetic animal model of the disease has been successfully generated until now. Here we create a quintuple Serpina1a-e knockout using CRISPR/Cas9-mediated genome editing. The phenotype recapitulates the human disease phenotype, i.e., absence of hepatic and circulating AAT translates functionally to a reduced capacity to inhibit neutrophil elastase. With age, Serpina1 null mice develop emphysema spontaneously, which can be induced in younger mice by a lipopolysaccharide challenge. This mouse models not only AAT deficiency but also emphysema and is a relevant genetic model and not one based on developmental impairment of alveolarization or elastase administration. We anticipate that this unique model will be highly relevant not only to the preclinical development of therapeutics for AAT deficiency, but also to emphysema and smoking research.

Serpina1 | α1-antitrypsin | emphysema | CRISPR | mouse model

Chronic obstructive pulmonary disease (COPD) is the third leading cause of mortality worldwide (1), and it affects about 10% of the world population (2). While cigarette smoking and exposure to air particulates are well-characterized environmental risk factors, α1-antitrypsin (AAT) deficiency is the most common known genetic factor (3). AAT deficiency is characterized by mutations in the SERine Proteinase Inhibitor family A member 1 (SERPINA1) gene. These mutations result in reduced or inexistent levels of serum AAT protein (4), a protease inhibitor whose physiological target is neutrophil elastase (NE). Low or no serum AAT therefore results in the unopposed action of neutrophil elastase on the alveolar interstitium thereby leading to destruction of the alveolar walls and lung parenchyma. Clinically, this results in pulmonary emphysema, which is characterized by fewer, larger air sacs with less recoil and decreased gas exchange, leading to increasing breathlessness.

The current standard of care is weekly or biweekly intravenous infusion of recombinant AAT protein. Unfortunately, because this disease is underdiagnosed, many patients start treatment after their respiratory function is significantly and irreversibly compromised. In addition, lifelong weekly or biweekly infusions remain a burden for patients, and alternative therapeutic options allowing for less frequent interventions are being actively investigated, including gene therapy (5–8) and genome editing (9). However, the development of new therapeutics is hindered by the absence of an animal model (10). Current study goals for protein replacement therapies are based on the FDA-defined endpoint of 11 μM serum AAT and not on a physiologically relevant endpoint, such as respiratory measurements, which may limit approval of functional candidates. The absence of a mouse model is due to the presence of Serpina1 paralogs in the murine genome (11), which made the generation of a full knockout a very difficult target using traditional methods. In addition, some reports have dissuaded these efforts due to the possibility of an embryonic role for these genes in mice. In fact a murine Serpina1a knockout was recently described to be embryonically lethal (12), as well as a murine Serpina1b knockout (13). However, it is unclear why mice not only amplified the gene but also developed an embryonic role for it and why deleting only one of several highly similar murine paralogs would be lethal while SERPINA1 null humans are viable. Prompted by this incongruity and the advent of CRISPR technology, we sought to confirm these surprising findings by generating guide RNAs (gRNAs) that target a sequence in exon 2 that is conserved in all Serpina1 genes. Here, we demonstrate the successful generation of a murine complete Serpina1a-e knockout with biallelic editing of five genes in a single round of zygote injections. This mouse model has a normal lifespan but presents with a respiratory phenotype that recapitulates many aspects of the human disease and therefore constitutes a true and robust model in which to validate novel therapeutics and investigate the biology of emphysema.

Results

Generation of the Serpina1a–e Knockout. Due to gene amplification events, six Serpina1 genes exist in the murine genome. These are designated in the current nomenclature as Serpina1a through Serpina1f, although only Serpina1a–e are expressed in the liver. The genes are 11 kb long and span about 230 kb on chromosome 12. In our mouse strain of choice, C57BL/6j, those five Serpina1 genes (a–e) are present and expressed (11). The corresponding proteins are designated as α1-antitrypsin (AAT) 1-1 through 1-5. Of these, AAT 1-1 and AAT 1-2 inhibit both neutrophil and
pancreatic elastases, while AAT 1-3 and AAT 1-4 do not, and AAT 1-5 is not well characterized (14). Four gRNAs were designed in a region conserved in all Serpina1 paralogs, exon 2 (Fig. L4), and validated in vitro with a GFP-based single strand annealing assay. Genetically modified mice were generated using previously described methods (15). Briefly, zygotes were microinjected with Cas9 mRNA and all four gRNAs, and subsequently implanted in 13 pseudopregnant females. A total of 45 pups were born, of which 87% survived weaning (Fig. 1B) and their sera was screened for total murine AAT using by ELISA using a polyclonal antibody. Out of the 39 viable animals, 3 were identified as complete biallelic homozygous knockouts, as determined by serum AAT ELISA, demonstrated germline transmission. (E) Three independent founder lines were generated by backcrossing: line 7A from founder #7, line 24B from founder #24, and line 31C from founder #31 (line 31C is currently at F4 only). (F) Backcrossing male founders #7 and #24 resulting in 100% of the progeny being heterozygous, as determined by serum AAT ELISA, demonstrated genetic linkage (pups 45–67, line 7A; pups 69–86, line 24B; –, negative control; C57F, wild-type mouse, positive control). The serum of the three founders is devoid from AAT protein, as confirmed by Western blot (G). (H) Immunohistochemistry shows absence of AAT in liver tissue from knockout animals. These representative images show hepatocytes surrounding a blood vessel. (Scale bar, 100 μm.) (J) Serum from the three founders has reduced antielastase activity, as determined by quantification of elastase activity. The – inhibitor bar is an internal assay control representing an uninhibited reaction, and its value is normalized at 100. C57M, male wild-type mouse; 7M, male founder #7; 24M, male founder #24; 31F, female founder #31; C57F, female wild-type mouse; and AAT control, commercial pooled mouse serum.

Phenotypic and Functional Characterization. AAT is produced in the liver, secreted in the bloodstream, and eventually reaches the lungs, which is its main site of action. In the lungs, AAT protects the lung alveoli and interstitial elastin from destruction by inactivating neutrophil elastase. To assess whether the protein was present in the circulation, blood serum was sampled and analyzed by Western blot using an antimouse AAT primary antibody. The three founders demonstrated undetectable levels of AAT (Fig. 1G), confirming the results of the initial ELISA screening (Fig. 1C). Next, liver sections were subjected to immunohistochemical staining. While a strong staining reflects the high abundance of hepatic AAT in wild-type mice, the Serpina1-e knockout mice revealed a complete lack of staining, denoting absence of the protein (Fig. 1H). Finally, we assessed the biochemical consequences of the lack of circulating AAT by analyzing the ability of the sera to neutralize elastase activity. Blood serum was incubated with elastase and an analog substrate, and relative elastase activity was derived from a colorimetric quantification of the kinetics of substrate degradation. While serum from wild-type male and female C57BL/6 mice exhibited a high capacity to inhibit elastase, sera from the three founders showed a reduced capacity to do so (Fig. 1I, red bars). The reduced capacity of the serum samples from the three founders to inhibit elastase was similar to the results obtained when using a commercial elastase inhibitor (Fig. 1J, black bar). This indicates that absence of serum AAT shown in Fig. 1 C and G translates to a loss of its physiological antielastase function. Any remaining antielastase activity in the sera of the founders might be due to other serum serine protease inhibitors (serpins) with antielastase activity.

Genomic and Transcriptomic Characterization. Genomic editing alterations were characterized by targeted sequencing. Briefly, high molecular weight genomic DNA (gDNA) was isolated from liver tissue of one mouse per founder line. This gDNA was subsequently sheared to a size of ~6 kb, and fragments of interest were captured using probes specific to the 230-kb region of interest (Fig. 1L). The ~2-kb captured fragments were sequenced by long-read PacBio sequencing, to allow for discrimination between highly homologous Serpina1 paralogs. Analysis revealed excisions of up to 90 kb in lines 7A and 24B, and up to 76 kb in line 31C (Fig. 2 and Figs. S1–S3). In line 24B, complementary targeted locus amplification (TLA) sequencing revealed a small excision of 73 bp in Serpina1b, at the location of gRNA#2 (Figs. S5 and S6).

To confirm the excisions and nonsense-mediated decay (NMD)-causing frameshifts, RNA was isolated from liver tissue of two of the three founder lines for a transcriptome analysis. Four mice from the F4 generation of line 7A and four mice from the
Genomic characterization. A 230-kb genomic region was sequenced by PacBio-LITS for a wild-type C57BL/6J mouse and for a mouse from each founder line. Overview of the reads mapping to the 230-kb targeted region. (A) Line 7A; (B) line 24B; (C) line 31C. WT, wild type. Red lines indicate the location of the gRNAs.

F4 generation of line 24B, were compared with five C57BL/6 mice (all mice were 10-wk-old males) by RNA-Seq [single-end 50 base pair (bp) reads]. Founder #31 being female, the 31C line is at an earlier generation and was therefore not included in this analysis; however, preliminary data from a single animal do show a significant reduction of transcripts for all five paralogs (Dataset S1). RNA-Seq generated >50 million clean reads for each sample. A total of 231 genes were dysregulated in line 7A: 126 up-regulated genes and 105 down-regulated genes (Fig. 3A). A total of 299 genes were dysregulated in line 24B: 133 up-regulated genes and 166 down-regulated genes (Fig. 3B). The Serpin1 genes were the top down-regulated genes in both 7A and 24B lines (Datasets S2 and S3). The only exception to this was Serpin1b in line 24B. Reads mapping to Serpin1b were not decreased (fold change 0.9916; adjusted P value 0.9869). However, analysis of the reads revealed a deletion of two bases at position 314–315 of the mRNA, and additional deletions of four bases at position 347–350 and nine bases at position 351–359. These deletions overlap with the 73-bp genomic excision reported above, which corresponds to position 320–353 of the mRNA. Taken together with the genomic data, this suggests a combination of genomic excision events along gene disruptions resulting in unstable or truncated transcripts. In total, 106 genes were dysregulated in line 7A and line 24B jointly, 48 were up-regulated (marked in red, Fig. 3C) and 58 were down-regulated (marked in green, Fig. 3C and Dataset S4) including four of the Serpina genes (a–c–d–e). Pathway analysis revealed that the top dysregulated pathways were monocarboxylic acid and fatty acid metabolic processes, rhythmic process and circadian rhythm for line 24B (Fig. 3D), and rhythmic process and circadian rhythm for line 24B (Fig. 3E).

Off-targets for all four gRNAs were predicted using two independent algorithms: Cas OFFinder (16) and COSMID (17), and all results were compiled in Datasets S5 and S6. Results from these predictions were cross-referenced with the list of dysregulated genes (Datasets S2 and S3). No predicted off-target genes were identified as being dysregulated. Additionally, gene expression levels were manually checked for the predicted off-targets located within an ORF; no significant difference in gene expression was detected (Datasets S5 and S6). This supports the view that the described phenotype is not due to CRISPR off-targeting.

Induced Emphysema Following a Two-Hit, 2-Wk Lipopolysaccharide Challenge. Patients with AAT deficiency are subjected to lung damage when they are exposed to a bacterial infection. Bacterial infection leads to a neutrophilic response in the alveoli and the absence of AAT results in unopposed NE damage. The resulting emphysema leads to increased pulmonary compliance and decreased elastance. To determine whether the Serpin1a–e knockout mouse mimicked the clinical phenotype associated with this deficiency in humans, we exposed the airways of the mice to a mild lipopolysaccharide (LPS) challenge. The LPS challenge was titrated to a dose that wild-type mice could easily overcome but could hypothetically lead to pathology in Serpin1a–e knockout mice due to the unabated activity of the secreted NE from the recruited neutrophils. For the LPS challenge, mice (n = 11–12 per group) received two doses of LPS on day 1 and day 12 before characterization of their pulmonary mechanics and lung morphology at the end of the second week (Fig. 4A). At endpoint, pulmonary mechanics including maximal pressure-volume (PV) loops were assessed. The AAT knockout mice had evidence of

Fig. 2. Genomic characterization. A 230-kb genomic region was sequenced by PacBio-LITS for a wild-type C57BL/6J mouse and for a mouse from each founder line. Overview of the reads mapping to the 230-kb targeted region. (A) Line 7A; (B) line 24B; (C) line 31C. WT, wild type. Red lines indicate the location of the gRNAs.

Fig. 3. Transcriptomic characterization. The transcriptome of five wild-type C57BL/6J mice, four mice from line 7A, and four mice from line 24B was characterized. The animals were aged and gender matched. Differential gene expression in knockout line vs. wild-type, for (A) line 7A, (B) line 24B. Solid line, fold change = 2; dashed line, fold change = 4. (C) Genes commonly dysregulated in lines 7A and 24B. Red, up-regulated genes; green, down-regulated genes. Pathway analysis for (D) line 7A and (E) line 24B.
Increased lung compliance as indicated by a PV loop that shifted up and to the left, as would be expected in an emphysematous lung (Fig. 4B). In addition, the inspiratory capacity of the knockouts was significantly increased from 0.78 mL to 0.91 mL (Fig. 4C). These changes were confirmed by measuring the quasistatic compliance which confirmed a significant increase from 0.066 mL/cmH2O in the wild-type mice compared with 0.080 mL/cmH2O in the AAT-deficient mice (Fig. 4D). In summary, the pulmonary mechanics phenotype observed in the knockout mice is very comparable to that of patients with emphysema.

Next, alveolar morphometry, i.e., the quantitative assessment of alveolar architecture and structure, was determined. AAT-deficient patients present with panacinar emphysema, i.e., alveoli and alveolar ducts are uniformly enlarged (18). Therefore, a subset of the mice (n = 7 per group) was analyzed to assess their lung morphology. Following pulmonary testing, the lungs were filled with a mixture of agarose and formalin to preserve their internal structure, and tissue sections were stained by H&E (example shown in Fig. 4E) before quantitative measurements described earlier (19). The total volume showed a trend toward the knockout group having on average a 22% higher volume (1.7 mL) than the wild-type group (1.4 mL, Fig. S44) as well as a higher total surface area (knockout 149.2 ± μm², wild type 130.8 ± μm², Fig. S4B). The mean linear intercept, i.e., the mean free distance in the acinar air space complex, was significantly increased from 43.1 μm for the wild type to 47.05 μm for the knockouts (Fig. 4F). Taken altogether, these measurements indicate that in the Serpin1a−/− knockout mice, the alveolar ducts, and alveoli are enlarged, which recapitulates the clinical characteristics of emphysema.

Spontaneous Emphysema in Unchallenged, Aged Serpin1a−/− Knockouts.

Given that a mild LPS challenge was able to recapitulate the hallmark of emphysema, we sought to investigate whether emphysema would naturally develop in these Serpin1a−/− knockout mice over time. Pulmonary mechanics were measured in age-matched, gender-matched wild-type and knockout mice at 35 (Fig. 5A and B) and 50 wk of age (Fig. 5 C–F). At 35 wk of age, seven knockout and 10 wild-type animals were analyzed. The PV loop of the knockouts showed significantly increased compliance compared with their wild-type controls as evidenced by a shift upwards (Fig. 5A), which is characteristic of emphysema. Similarly, the quasistatic compliance is significantly increased in the knockouts compared with the wild types (Fig. 5B). At 50 wk of age, nine knockout and 8 wild-type animals were analyzed. Again the PV loops are significantly different (Fig. 5C), and the difference between groups is larger at 50 wk than at 35 wk. The quasistatic compliance of the knockouts is also highly significantly increased from 0.0696 mL/cmH2O in the wild types to 0.0889 mL/cmH2O in the knockouts (Fig. SD, P ≤ 0.0001), and the elastance is significantly decreased (Fig. 5E, P ≤ 0.0002). The resistance is similar in the wild-type controls and the knockouts (Fig. 5F). Taken altogether, these results indicate that the Serpin1a−/− knockout mice spontaneously develop emphysema, with early signs detectable at 35 wk of age, and at 50 wk of age they present with a clear emphysematous phenotype.

Cellular and Histological Changes in the Lungs of Serpin1a−/− Knockouts.

To determine the mechanism driving the spontaneous emphysema, we analyzed the lung bronchoalveolar lavage fluid (BALF) of aging mice to see whether there was an active mechanism or process that could explain the progression of lung disease. We hypothesized that in the absence of an exogenous insult such as the LPS or a cigarette-smoke challenge the Serpin1a−/− knockout mice must have an autonomous increase in the protease/antiprotease imbalance in the lung despite being housed in a specific pathogen-free (SPF) facility.

Cell counts were determined in the bronchoalveolar lavage (BAL) of wild-type and Serpin1a−/− knockout mice at 8 and 42 wk of age. Consistent with our hypothesis, neutrophil, monocyte, lymphocyte, and macrophage counts were all increased in the 42-wk-old knockout mice (Fig. 6A), while no difference was detectable in the 8-wk-old mice. We then measured elastase activity in the BALF, to determine whether the increase in the cell infiltration was sufficient to increase the protease/antiprotease imbalance (Fig. 6B). These
AAT levels in serum samples were quantified by direct ELISA as described (22–24). This phenotype models α-1 antitrypsin deficiency lung disease, and should prove extremely valuable to the preclinical development of novel therapeutics for this disease that affects about 100,000 individuals in the United States and millions worldwide. This unique model may allow a precise dissection of the disease mechanism and bring further insight into the genetic pathways linked to the pathology. Additionally, the current clinical endpoint for therapeutic candidates is serum protein levels of 11 μM, a threshold defined through genotype/phenotype studies. However, studies using this animal model may allow a further refinement of this threshold, and the definition of alternate endpoints. Finally, this murine strain constitutes the ideal genetic background in which to introduce the most common human mutation associated with α-1 antitrypsin deficiency, the Z form of the protein (Z-AAT). Currently ongoing, this work will result in a mouse model that will genetically and phenotypically recapitulate two components of the human disease: a loss of function in the lungs and a gain of function in the liver. The generation of this model will support the preclinical development of genome editing therapeutics for α-1 antitrypsin deficiency.

It is well established that patients with α-1 antitrypsin deficiency are more likely to develop emphysema and/or develop it earlier if they are exposed to environmental inhalants, which include smoking (active or passive) and occupational exposure (25–27). This first animal model of α-1 antitrypsin deficiency will therefore be highly relevant to further investigate those findings. Beyond the scope of α-1 antitrypsin, this mouse model more broadly constitutes a unique model in which to study emphysema. It is a genetic model of emphysema, not one based on developmental impairment of alveolarization, or reliant upon administration of elastase or other proteases. It may therefore be used to test factors that influence development of postnatal or age-related emphysema. For example, the model might enable the investigation of occupational exposure to untested air particulates, smoking, and smoke exposure, as well as new behaviors such as vaping. In conclusion, this mouse model may have a significantly impact on preventive health for the α-1 antitrypsin patient community, but also for the COPD population at large, and constitutes a significant step forward for COPD research.

Materials and Methods

Animal Experiments. The institutional animal care and use committee at the University of Massachusetts Medical School approved all animal experiments. Further information is provided in SI Materials and Methods.

Design and Validation of Guide RNAs. National Center for Biotechnology Information (NCBI) blast search was used to identify conserved regions within the mouse SerpinA1 paralogs. CRISPR/Cas9 target sites present in all isoforms and with low predicted off-target activity were identified using the Bioconductor software package CRISPRseek (28). Four CRISPR/Cas9 target sequences were selected that are conserved in each of the mouse SerpinA paralogs.

ELISA. AAT levels in serum samples were quantified by direct ELISA as described (29). Briefly, serum proteins were immobilized in each well, and AAT was detected by incubating with a polyclonal goat anti-mouse AAT antibody (GA1T-90A-Z, ICL), followed by incubation with an HRP-conjugated rabbit anti-goat antibody (ICL) and a peroxidase substrate (KPL Scientific). OD₅₆₂₅nm was read and a four-parameter logistic model was fit to the standard curve (RS-90A1T, ICL); subsequently, AAT concentration of the unknown samples was derived. Samples were run in technical triplicates.

Targeted Genome Sequencing. A 230-kb region of chromosome 12 (chr12:103,726,970–103,955,013) was sequenced by PacBio-large insert targeted sequencing (PacBio-LITS), following a protocol adapted from ref. 30. Briefly, high molecular weight gDNA was isolated from fresh liver tissue of adult mice (Genomic-tip 500, Qiagen), sheared to ~6 kb (g-TUBE, Covaris), preamplified,
hybridized with custom probes (Roche Nimblegen) designed based on mm10/GRCh38 for target enrichment by bead capture, and the captured libraries were amplified. Finally, SMRT libraries were constructed and sequenced on a PacBio instrument at the Yale Center for Genome Analysis. Raw reads were broken into separate subreads after removing adapters and trimming away low-quality regions. PacBio sequencing generated >640,000 subreads for each sample. Subreads were aligned to the 230-kb target region by Burrows-Wheeler aligner (BWA)-maximal exact matches. Using Canu (31), all the reads with high coverage (>30) are assembled locally into contigs. Additionally, TLA was performed on line B as described earlier (32). Splenocytes were isolated from a wild-type mouse and a knockout mouse from line B and sent to Cergentis B.V. for TLA analysis. Briefly, DNA was cross-linked, fragmented, and religated. Primer pairs complementary to sequences of each SerpinA7 paralog were then used to amplify the surrounding loci. PCR products were purified and library was prepped using the Illumina TruSeq XT protocol. Sequencing was performed on an Illumina HiSeq 4000 instrument at the Beijing Genomics Institute. After sequencing, the raw reads were filtered, which includes removing adapter sequences, contaminations, and low-quality reads. RNA-Seq generated >50 million clean reads for each sample. Using TopHat2 (33), at least 70% of the clean reads mapped at a single location of the mouse reference genome (mm10) for each replicate sample. Normalization and differential expression gene analysis were performed with HTSeq-count (34) and DESeq2 (35) software packages. Pathway analysis was performed as described in ref. 36.

FlexiVent. Measurements of pulmonary mechanics were performed using forced oscillometry (FlexiVent system; SCIREQ). Respiratory mechanics were obtained and calculated using flexiWare software (SCIREQ) as previously described (37).

Morphometry. Immediately following measurements of lung mechanics (FlexiVent), lungs were harvested for morphometric analysis as previously described (19, 38).

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RNA-Seq. Total RNA was isolated from snap-frozen liver tissue of 10-wk-old male mice using TRIzol (Life Technologies) following the manufacturer’s instructions. Barcoded libraries were sequenced as 50-nt single end reads on an illumina HiSeq 4000 instrument at the Beijing Genomics Institute. After trimming, the reads were mapped at a single location of the mouse reference genome (mm10) for each sample. Using TopHat2 (33), at least 70% of the clean reads mapped at a single location of the mouse reference genome (mm10) for each replicate sample. Normalization and differential expression gene analysis were performed with HTSeq-count (34) and DESeq2 (35) software packages. Pathway analysis was performed as described in ref. 36.

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