ERJ Express. Published on February 27, 2009 as doi: 10.1183/09031936.00118408

Lung deposition of inhaled α_1-proteinase inhibitor in CF and α_1-antitrypsin deficiency

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ERS registration number : 121368

Short title: **DEPOSITION OF α_1-PROTEINASE INHIBITOR**

KEYWORDS: α_1-Antitrypsin, α_1-antitrypsin deficiency, controlled inhalation, cystic fibrosis, nebuliser, lung, healthy volunteers, deposition

Total word count (not including abstract, references, tables and figure legends): 3413

Tables: 3

Figures: 5

The study was sponsored by Inamed Research GmbH & Co. KG, Gauting, Germany, and was supported by a research grant from Talecris Biotherapeutics Inc, Research Triangle Park, NC, USA.

This study, carried out between 1 July and 30 September 2006, was registered with the European Union Drug Regulatory Authorities (EUDRA): clinical trial number 2005-003190-24.

A poster based on this study has been presented at the 2007 European Respiratory Society (ERS) Annual Congress, the 2008 International Congress of the American Thoracic Society (ATS) and at the 2008 Canadian Respiratory Conference (CRC), and the abstract has been published in their corresponding publications: *European Respiratory Journal* (Volume 30, supplement 51, September 2007), *American Journal of Respiratory and Critical Care Medicine* (Volume 177, Abstracts Issue, April 2008) and *Canadian Respiratory Journal* (in press*)*.

ABSTRACT

Individuals with α_1-antitrypsin (AAT) deficiency and cystic fibrosis (CF) have a protease-antiprotease imbalance in their lungs, which leads to early onset progressive lung disease. Inhalation of AAT may restore protective levels in the lungs.

The study aimed to determine the efficiency of delivering AAT (Prolastin®; alpha-1 proteinase inhibitor [human]) using a novel inhalation device (AKITA$^{2®}$ APIXNEB®) in subjects with AAT deficiency and CF compared with healthy subjects.

In total, 20 subjects (six healthy, seven with AAT deficiency, seven with CF) inhaled approximately 70 mg of radiolabelled active AAT, with controlled breathing patterns adjusted to lung function. Post inhalation, total and regional lung deposition and extrathoracic deposition of radiolabelled AAT were measured.

Total lung deposition of AAT was approximately 70% of the filling dose. The magnitude of deposition was similar in all treatment groups, with no adverse effect on lung function or any influence of disease severity on total lung deposition.

Inhalation with controlled breathing patterns using the AKITA^2 device (lung function–adapted) leads to high total lung deposition regardless of the degree of lung function impairment. Delivery of large amounts of AAT was achieved in a short period of time. This device may be an ideal option for aerosol therapy.

Word count: 200 words

INTRODUCTION

Cystic fibrosis (CF) and α_1-antitrypsin (AAT) deficiency are the most frequently inherited genetic disorders in Caucasians. Approximately one in every 2,000–2,500 people born in Europe and North America is affected by these diseases [1, 2]. In patients with CF, the submucosal bronchial glands are hypertrophied, and primary viscid secretions are frequently infected. Repeated infection leads to chronic neutrophilic inflammation, which is thought to be one of the factors responsible for early lung destruction [3–5]. The most frequent pathological phenotypic mutation, PI*Z, in AAT deficiency leads to the accumulation of AAT protein in the endoplasmic reticulum of hepatocytes. This is due to dysfunctional protein export from the liver, which causes an imbalance in the protease and antiprotease levels in the lungs. This results in premature development of pulmonary emphysema and chronic obstructive pulmonary disease. The evaluation of the lungs of AAT-deficient individuals with emphysema shows diffuse destruction of the alveoli, typically beginning in the lower lung zones and eventually throughout the entire lung [6].

Several studies have shown that the protease-antiprotease imbalance in individuals with both CF and AAT deficiency may be restored by inhalation of AAT [7, 8]. Intravenous AAT is currently licensed in several countries for augmentation therapy for AAT deficiency. However, the direct delivery of AAT to the target organ via nebulisation should be a more effective route of administration. The key to success for this new nebulisation route of AAT administration includes the following factors:

- The dose that is delivered must be reproducible both inter- and intra-subject
- The dose deposited in the lung must be therapeutic
- The regional location of deposition within the lung must be consistent and reproducible
- The procedure must be able to be performed with good reproducibility in individuals with differing degrees of disease severity.

In this study, inhalation of radiolabelled AAT (Prolastin®; alpha-1 proteinase inhibitor (human); Talecris Biotherapeutics Inc, Research Triangle Park, NC, USA) with a new inhalation device, the

AKITA$^{2®}$ APIXNEB® (Activaero GmbH, Gemünden, Germany), was investigated in three populations (healthy subjects, subjects with AAT deficiency, and subjects with CF). The AKITA^2 APIXNEB combines a vibrating mesh nebuliser (Pari) with low drug residual volumes and the ability to control inhalations [9–11] such that both inhalation flow rate and inhaled volume are controlled by a computerised compressor. This inhalation device has been specially designed for the efficient inhalation of substances such as AAT, with the breathing pattern being normalised to the subject's lung function in order to obtain individually optimised inhalation parameters.

METHODS

Subjects

Twenty subjects (six healthy subjects, seven subjects with AAT deficiency, seven subjects with CF) participated in this study (table 1). Subjects were male or female and between 18 and 65 yrs of age with no clinically significant or uncontrolled cardiac, hepatic, renal, gastrointestinal, endocrine, metabolic, neurological, or psychiatric disorder. All were non-smokers or required to have been ex-smokers for at least 2 yrs prior to enrolment in the study. Subjects with AAT deficiency were included if they had a PiZZ, PiZ(Null), Pi(Null, Null), or PiSZ phenotype confirmed by isoelectric focusing or genotyping, and the presence of emphysema confirmed by chest X-ray or computer tomography scan. Two AAT-deficient subjects received long-term oxygen therapy prior to study entry. Subjects with CF were included if the diagnosis was established by a sweat or genetic test.

AAT deficiency and CF patients must have had an inspiratory capacity of at least 0.77 L and a forced expiratory volume in 1 s (FEV_1) between 25% and 80% predicted. AAT or CF subjects were excluded if they had a history of lung transplant, pulmonary surgery within the last 2 yrs, any pulmonary infection/exacerbation in the last 1 month, or were on any thoracic surgery waiting list. All subjects were excluded from the study if they were pregnant or lactating, were not using reliable contraceptive methods, had a history of anaphylaxis to AAT or blood products, known IgA deficiency, history of transfusion reactions, infection in the last 2 months, history of drug abuse in

the last 12 months, had participated in another investigational drug study in the last 1 month, or were unable to provide independent informed consent. Written informed consent was obtained from each subject. The protocol was approved by the ethics committee of the "Bayerische Landesärztekammer" Munich, the German Competent Drug Authority ("Paul-Ehrlich-Institut") and the German Federal Office for Radiation Protection ("Bundesamt für Strahlenschutz").

Radiolabelling of AAT

The labelling of AAT was similar to the technique described by LAFONT [12]: on each study day a vial of AAT was reconstituted according to the manufacturer's instructions using the kit provided by the manufacturer. All AAT used in this study was from one lot. Half a millilitre of technetium pertechnetate (160 megabecquerel (MBq)) was incubated with 1.5 mL of AAT for at least 30 mins, and then 0.5 mL (<19 MBq) of radiolabelled AAT was mixed with 9.5 mL unlabelled AAT.

The specific activity of the diluted radioactive AAT solution was measured by gamma scintillation. Validation of the labelling process was performed by comparing the particle size distribution of AAT within the unlabelled commercial product with the size distribution of the drug in the radiolabelled product and the size distribution of the radiolabel (see figure A in the online supplement). These particle size distributions were measured using a "Next Generation Impactor" with a flow of 15 L/min for all three particle size distributions; identical mass median aerodynamic diameters (4.0 μm) and geometric standard deviations (1.6) were measured. The fine particle fractions were found to be between 67% and 70% (see table A in the online supplement). The stability of the radiolabel/protein complex was tested in *in vitro* leaching tests using a dialysis tube. Within 5 h, less than 10% of the radiolabel was dissociated from the protein. The radiolabelled drug was administered to all subjects within 3 h after reconstitution. Thus the radiolabel was considered stable between the time of reconstitution of the drug and the end of the radiolabel measurements.

Inhalation procedure

Inhalation of AAT was performed using the AKITA^2 APIXNEB device. This device consists of a nebuliser handset (APIXNEB) that uses vibrating mesh technology (Touchspray, PARI GmbH, Starnberg, Germany) and an electronic unit (AKITA^2 APIXNEB) that controls and supplies air to the individual. Using this device, individually adapted breathing patterns were performed, in which the air flow rate and inhalation volume (IV) are controlled for each subject.

In this study the flow rate was set at 0.25 L/s. The IV was normalised to the subject's inspiration capacity, as shown in figure B in the online supplement. In every case the total IV was a maximum of 65% of the inspiration capacity. There are no data about the inhalation time with the AKITA^2 APIXNEB device and AAT, but from *in vitro* data it can be assumed that inhalation of the study medication takes about 10 min in healthy subjects.

The pooled radiolabelled/non-radiolabelled AAT was held in a glass vial and 2 mL was transferred into the medication chamber with a pipette immediately before inhalation. Inhalation was performed until the nebuliser automatically determined the inhaler to be totally depleted.
The total applied dose of labelled and unlabeled protein consisted of approximately 100 mg of total protein containing 70 mg active AAT in 2 mL solution.

Assessment of lung deposition

One minute after complete inhalation of the test drug, gamma camera images of the lung were taken using a Siemens Diacam gamma camera with a 40-cm field of view and a low-energy parallel-hole collimator. Radioactivity was assessed for the lung region (A_L) and the extrathoracic region, including the oropharynx, trachea, oesophagus and stomach (A_{ET}). The amount of radioactivity from each filled nebuliser (A_O), exhalation filter (A_{Ex}) and empty inhaler (A_I) was measured by scintillation counter (Helmholtz Zentrum München, German Research Center for Environmental Health). From these activity data, the following parameters were calculated:

- Total lung deposition relative to filled activity: $D_L = (1 – A_I/A_O – A_{Ex}/A_O) \cdot (A_L/(A_L + A_{ET})) \cdot 100$

- Extrathoracic deposition relative to filled activity: $D_E = (1 - A_I/A_O - A_{Ex}/A_O) \cdot (A_{ET}/(A_L + A_{ET})) \cdot 100$
- Residues in the device (M_D) (relative): $M_D = A_I/A_O \cdot 100$
- Exhaled drug (M_E) (relative): $M_E = A_{EX}/A_O \cdot 100$

The determination of central and peripheral lung regions, the ratio of central to peripheral (C/P) counts of deposited activity, and whole-lung rectangular regions of interest (ROI) for each lung were drawn at the boundaries of the krypton (Kr) ventilation scan (the boundaries were defined at 15% of the peak Kr counts for the entire lung (figure 1)). Central ROI, with dimensions equal to half the whole lung ROI width and one half its height, were positioned on the interior boundary of the lung, centred by height; the central ROI was 25% of the area of the whole lung ROI. The peripheral region was that area lying between the central and whole lung outline. These regions were displayed over the aerosol deposition (^{99m}Tc) and Kr scan to determine the counts in each region $A_{central}$ and $A_{peripheral}$.

Central and peripheral depositions were calculated similar to total lung deposition:

$D_{central} = (1 - A_I/A_O - A_{Ex}/A_O) \cdot (A_{central}/(A_L + A_{ET})) \cdot 100$

$D_{peripheral} = (1 - A_I/A_O - A_{Ex}/A_O) \cdot (A_{peripheral}/(A_L + A_{ET})) \cdot 100$

The C/P (deposition) ratio of the drug was determined and normalised (divided) by the C/P ratio for the Kr scan. This normalisation was calculated to account for the difference in relative lung areas and thickness between the central and peripheral regions [13]. While both the central and peripheral regions overlay alveoli and intermediate/small airways, the central region also incorporates large bronchial airways not present in the peripheral region. Thus, increases in the C/P ratio reflect an increase in large bronchial airway deposition relative to intermediate/small bronchi/bronchioles and alveolar airspaces. Hence, a difference in the distribution of drug deposition within the lung, *i.e*. the ratio of deposition in the large and small airways, can be

assessed (but does not necessarily reflect absolute amounts of drug in a certain anatomical region).

Tissue attenuation correction was calculated using the subject's sagittal thorax diameter and the equation given by PITCAIRN *et al.* [14]. In order to assess the lung contours for the assessment of total lung deposition with the gamma camera, an ^{81m}Kr gas ventilation scan was performed for each subject.

Lung function measurement

Lung function tests (Bodyplethysmography and spirometry) were performed using a commercial device (Jäger-Masterlab, Viasys-Erich Jaeger GmbH, Würzburg, Germany). The following parameters were recorded: forced vital capacity (FVC), FEV_1, forced inspiratory volume in 1 s (FIV_1) and residual volume (RV). Measured lung function parameters were normalised to the reference values as described by the European Community for Coal and Steel [15].

Statistics

Statistical analysis was performed using the SAS Software (version 9.1.3 (SAS Institute, Inc., Cary, NC, USA)). Deposition values in each subpopulation were summarised with descriptive methods. Differences in group averages were tested for statistical significance by calculating an analysis of variance (SAS Proc GLM with the group index as independent variable).

RESULTS

Baseline characteristics and lung function data of the study population are shown in table 1. Subjects with AAT were older than the healthy subjects and those with CF, and subjects with CF weighed less than the subjects in other groups. Healthy subjects and patients differed considerably in FEV_1% predicted but the mean values in AAT-deficient and CF patients were similar (106±14% in healthy, 51±15% in subjects with AAT, and 62±15% in subjects with CF,

respectively). All other baseline lung function parameters measured were similar among these three groups.

A graph of the lung deposition of AAT, relative to the FEV_1 predicted, for each individual subject and for each of the three subject groups, is shown in figure 2. In one subject it was not possible to assess deposition parameters owing to an inhalation device failure. Total mean lung deposition of AAT in all three subject groups was between 70% and 73% of the amount filled into the nebuliser (mean±SD; healthy, 70.3±7.9%; AAT-deficient, 72.6±3.2%; CF, 70.6±5.8%) (figure 3). Peripheral deposition was 40.9±4.5% of filled activity in healthy subjects, 42.3±6.6% in subjects with AAT deficiency, and 43.3±5.3% in subjects with CF. Central deposition was 29.4±4.8% of the filled activity in healthy subjects, 30.3±4.3% in subjects with AAT deficiency, and 27.3±4.7% in subjects with CF (figure 3). As shown in table 2, peripheral deposition was considerably higher than central deposition in all subject groups, and among groups the peripheral deposition remained similar. The C/P ratios were 1.48±0.19 in healthy subjects, 1.66±0.46 in subjects with AAT deficiency, and 1.37±0.24 in subjects with CF (no statistically significant differences).

Extrathoracic deposition was between 15% and 20%: 18.8±6.8% in healthy subjects, 14.7±3.1% in AAT-deficient subjects and 19.7±4.9% in subjects with CF (figure 3). Again, there were no statistically significant differences among treatment groups. The amount of drug remaining in the device (M_D) was approximately 9% (healthy subjects, 9.0±1.6%; subjects with AAT deficiency, 9.1±1.3%; subjects with CF, 8.4±2.8%; figure 3), amounting to less than 200 µL. No significant differences were observed among subject groups. The amount of drug exhaled, M_E, was 1.4±0.7% in healthy subjects, 2.6±1.7% in subjects with AAT deficiency and 1.3±0.2% in subjects with CF (figure 3). The difference between subjects with CF and subjects with AAT deficiency was statistically significant (p=0.046). On average, the inhalation time was 6.9±3 min for healthy subjects, 13±10 min for subjects with AAT deficiency and 8.3±3.6 min for subjects with CF; however, these differences were not statistically significant.

A comparison of ventilation and inhalation scans of all individuals with AAT deficiency demonstrated that the scans were well matched, with very little extrathoracic and central deposition. (See figure 4 for an example of scans from an AAT-deficient subject; the complete set of scans for all 19 subjects for which a deposition assessment was available is included in the online supplement).

All subjects were able to complete the inhalation of AAT, including two AAT-deficient subjects receiving long-term oxygen therapy. However, because the inhalation procedure had to be interrupted several times, inhalation in these two subjects took longer than for the other AAT-deficient subjects (between 20 and 30 min; figure 5), which contributed to the longer mean inhalation time in patients with AAT deficiency. Table 3 lists all adverse events. Only two subjects experienced adverse events for which relationship to the study medication or the inhalation effort could not be excluded (headache in one subject with CF and tongue vesicles/dysphagia in one healthy subject).

DISCUSSION

The concept of controlled inhalation was developed after it was shown that the breathing pattern is one of the main determinants of good drug deposition with nebuliser systems [16]. In earlier studies it was shown that the use of controlled and optimised breathing patterns (slow and deep inhalation [9, 16]) not only increases total drug deposition but also reduces its variability and reduces differences in deposition between healthy individuals and those with lung diseases. The AKITA device was developed to perform controlled inhalations in practice. This device included a modified PARI LC Star nebuliser. Use of this device for the inhalation of AAT in subjects with AAT deficiency in the nebuliser cross-over study by BRAND *et al*. [10] has shown that peripheral deposition of ATT was highest for the AKITA device. Peripheral deposition was approximately 30–35% for the PARI LC Star and Medic Aid HaloLite devices, and was 50–60% for the AKITA device, thus showing that it was possible that a high drug concentration could be effectively deposited in a target region of interest, specifically the peripheral lungs. However, in this same study deposition

was expressed as a fraction of the inhaled drug amount so that drug loss in the nebuliser system, which can be significant, was not determined.

The current study showed that approximately 70% of the AAT from the AKITA2 APIXNEB inhalation system was deposited directly into the lungs. There were no significant differences in mean drug deposition among the three populations studied (healthy subjects, subjects with AAT deficiency and subjects with CF); however, it should be noted that the fractionation of the lung dose into a single central region and a single peripheral region in two dimensions is a very crude method to determine the anatomical site of deposition. A large proportion of the drug (approximately 40%) was deposited in the peripheral lung regions. Since the central region (defined by the ROI specified in this study) contains a large amount of alveolar airspaces, which was not attributed to the peripheral deposition count, it would underestimate peripheral deposition. In actuality, the peripheral deposition should be considerably higher than 40%. Mean extrathoracic deposition was less than 20% suggesting a very efficient delivery of drug into the target organ (lung). Another practical consideration affecting compliance was that the average inhalation times for the different populations tested were extremely short, approximately 7–13 min to deliver approximately 100 mg of the AAT protein directly into the subjects' lungs. This short time for inhalation will be of critical importance for patient acceptability and compliance. In addition, the inhalation of AAT in this short timeframe was well tolerated with few adverse events.

It was also shown that lung deposition can be converged in different populations by individualising the inhalation manoeuvre in inhalation volume and flow. Lung deposition of a given drug with a defined particle size can vary by a factor of 5 to 10 for any given patient just by changing the breathing pattern. Three components of the programming of the AKITA^2 APIXNEB reduce this variability. Firstly, lowering the inspiratory flow to very low values reduces turbulent flow and thereby early impaction of particles in extrathoracic or central airways [16]. Secondly, flushing the airways with clean air after a bolus delivery of the drug minimises the amount of drug either centrally deposited or exhaled and increases peripheral deposition. Thirdly, adjusting the

inspiratory volume and the length of the drug bolus inhalation to the individual lung function of each patient further optimises the total and peripheral lung deposition.

AKITA^2 APIXNEB was able to achieve a high delivered dose and minimise drug delivery loss by its optimised airflow geometry and high output rate utilising its vibrating mesh technology. This device was optimised for nebulisation of substances like AAT [9, 10]. The results from the first *in vivo* performance data of this device has shown that both high lung deposition values with only minor drug losses within the nebuliser were achieved.

This study also has shown that not only healthy individuals but also those with severe lung disease, *i.e.* individuals with AAT deficiency and individuals with CF, were able to perform the required breathing pattern. Even two AAT-deficient subjects with long-term chronic oxygen therapy were able to complete the inhalation, although the inhalation took longer in these two individuals than for other subjects since they had to interrupt the procedure several times.

In the study there were no statistically significant differences in deposition between healthy subjects and those with AAT deficiency or CF. However, it should be kept in mind that, owing to the low number of subjects in each group, the statistical power of the study is relatively low. Using the data obtained in the study, it was retrospectively calculated that only differences in lung deposition of more than about 13% (absolute deposition value) could be detected with a power of 80%. Therefore, the possibility that smaller differences were present but did not reach statistical significance cannot be excluded.

Several previous studies have investigated aerosol treatment with AAT, both in patients with AAT deficiency and in those with CF, in an attempt to restore the protease-antiprotease imbalance. It has been shown that aerosolised AAT can be deposited in the periphery of the lung and retains antiprotease activity [17]. Active AAT with an associated increase in anti-elastase activity has also

been shown after aerosolisation in individuals with AAT deficiency [8] and CF [5, 18]. However, so far aerosol treatment with AAT for either indication has not yet been approved for clinical use.

This study showed that use of the AKITA^2 APIXNEB inhalation system to inhale AAT (Prolastin®) was well tolerated and led to excellent lung deposition of AAT of approximately 70% or more of the drug amount loaded into the nebuliser. These results were obtained by controlling the breathing pattern of the subjects and by individualising inhaled volume based on the lung function of the subjects while minimising left-over medication in the nebuliser. The inhalation time was judged short and convenient by the majority of subjects (data not shown). All subjects, even those receiving long-term oxygen therapy, were able to perform the required breathing patterns. This new technology should improve inhalation delivery of AAT in individuals with AAT deficiency as well as in those with CF.

ACKNOWLEDGEMENT

Editorial assistance was provided by K. Ayling-Rouse and M. Kenig at PAREXEL and was supported by Talecris Biotherapeutics, Inc.

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TABLE 1 Baseline characteristics and lung function parameters of the study population

Parameter	Healthy	AAT deficiency	CF
N	6	7	7
Sex (female/male)	5/1	3/4	3/4
Age, yrs (mean±SD)	33.3±12.1	51.7±13.2	28.6±6.1
Height, cm (mean±SD)	168±6.8	169±10.7	171.3±8.7
Weight, kg (mean±SD)	70.2±16	68±16.4	60.6±10
FEV_1, L (mean±SD)	3.45±0.6	1.58±0.8	2.38±0.9
FEV_1% pred (mean±SD)	106±14	51±15	62±15
FIV_1, L (mean±SD)	4.1±0.9	3.92±1.2	3.56±1.1
FVC, L (mean±SD)	4.32±0.8	3.68±1.4	3.65±1.0
FVC% pred (mean±SD)	115±15	98±17	81±10
RV, L (mean±SD)	1.63±0.2	3.85±1.3	2.92±0.8
RV% pred (mean±SD)	103±11	193±55	186±55

AAT: α_1-antitrypsin; CF: cystic fibrosis; FEV_1: forced expiratory volume in 1 s; FIV_1: forced inspiratory volume in 1 s; FVC: forced vital capacity; RV: residual volume.

TABLE 2 Regional deposition of inhaled AAT

		AAT		
	Healthy	**deficiency**	**CF**	**p–value**
Central deposition (%)	29.4±4.8	30.3±4.3	27.3±4.7	Not significant
Peripheral deposition (%)	40.9±4.5	42.3±6.6	43.3±5.3	Not significant
C/P ratios	1.48±0.19	1.66±0.46	1.37±0.24	Not significant

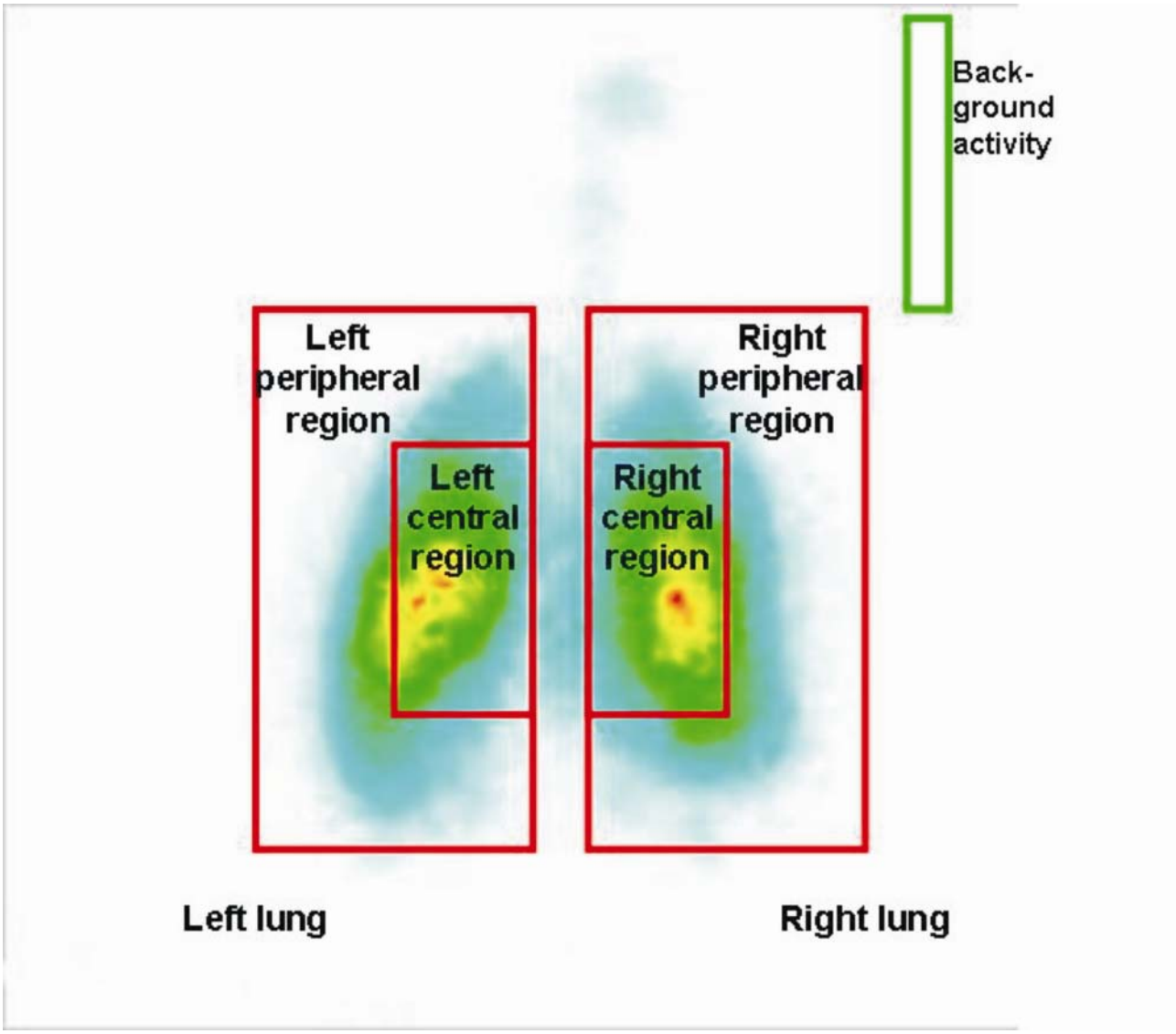
AAT: α_1-antitrypsin; CF: cystic fibrosis; C/P: central to peripheral.

TABLE 3 Adverse events reported by all subjects

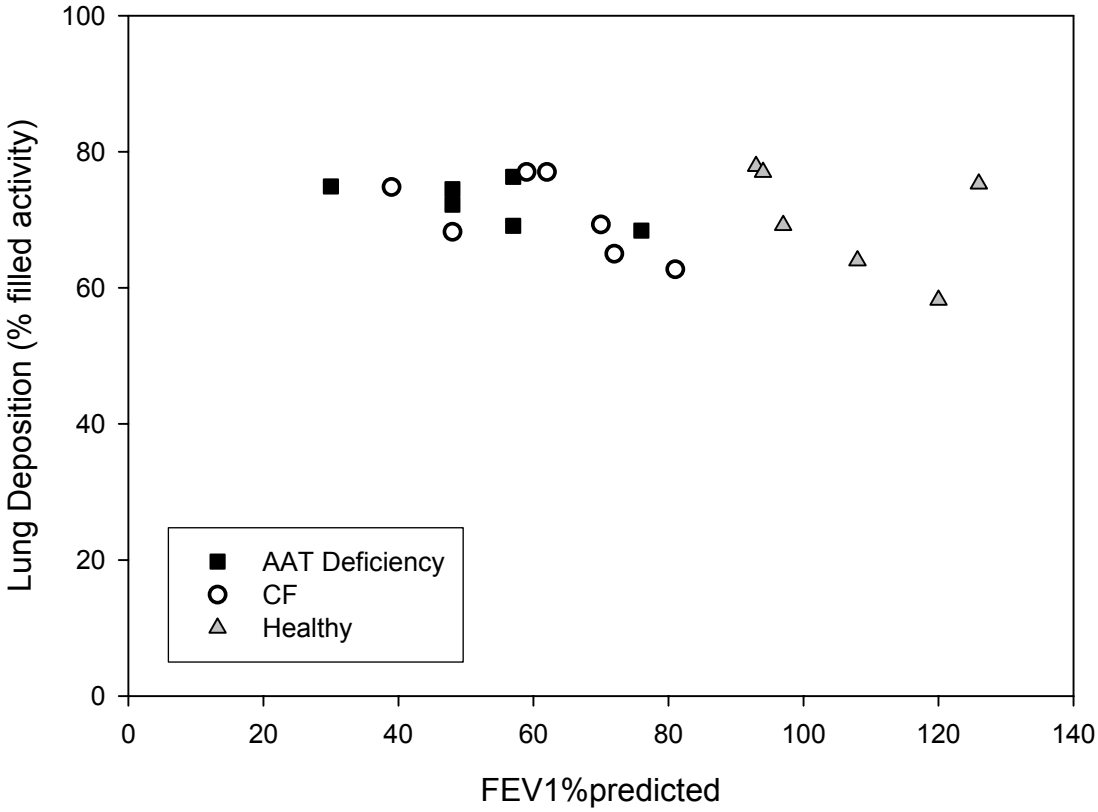
Subject	Adverse event	Treatment group	Relationship to study drug
1	Tongue vesicles and dysphagia	Healthy	Possible
2	Mild headache	CF	Possible
4	Cold symptoms	CF	Unlikely
11	Diarrhoea and dizziness	CF	Unlikely
12	Cold symptoms	CF	Unlikely
17	Gastroenteritis	CF	Unlikely

CF: cystic fibrosis.

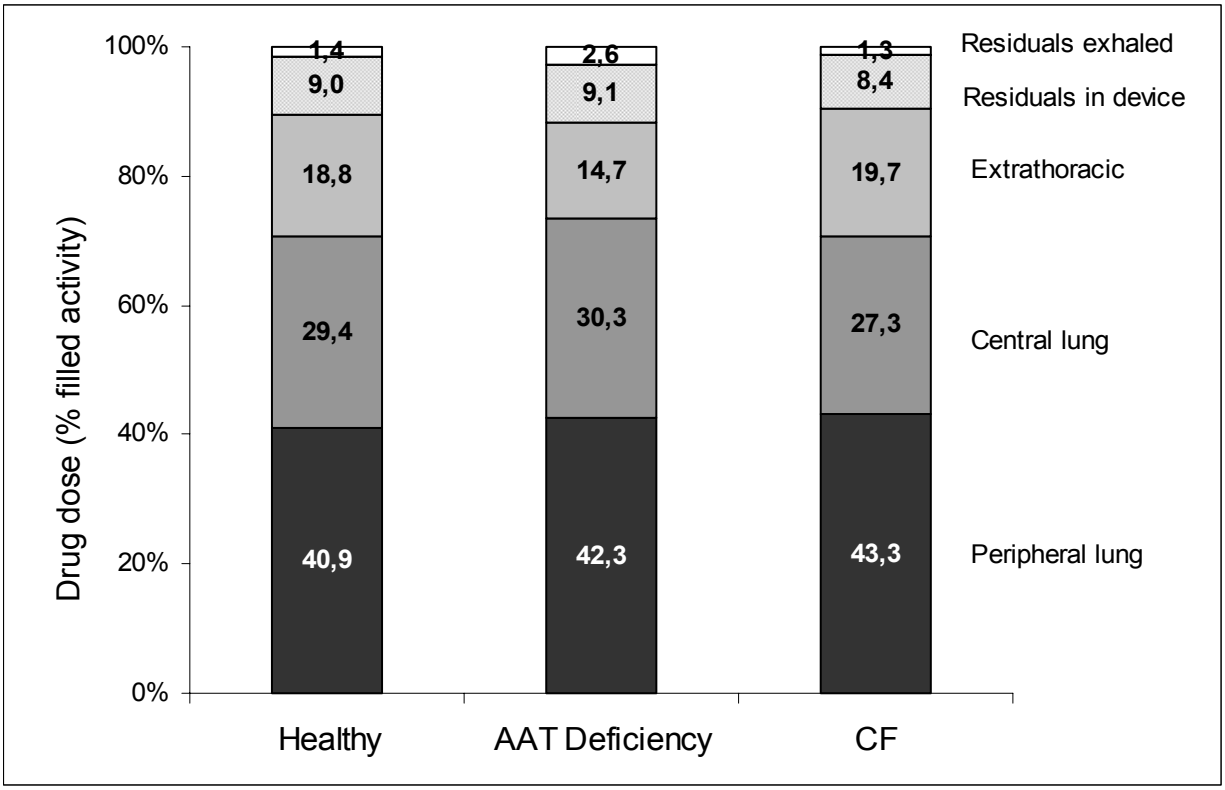
FIGURE 1. Determination of central and peripheral regions.



[NEW] **FIGURE 2.** Lung deposition in relation to FEV_1% predicted for each individual subject and for each subject group. The total lung deposition exceeded 60% of the filled activity in all individuals regardless of their lung disease and lung function impairment.

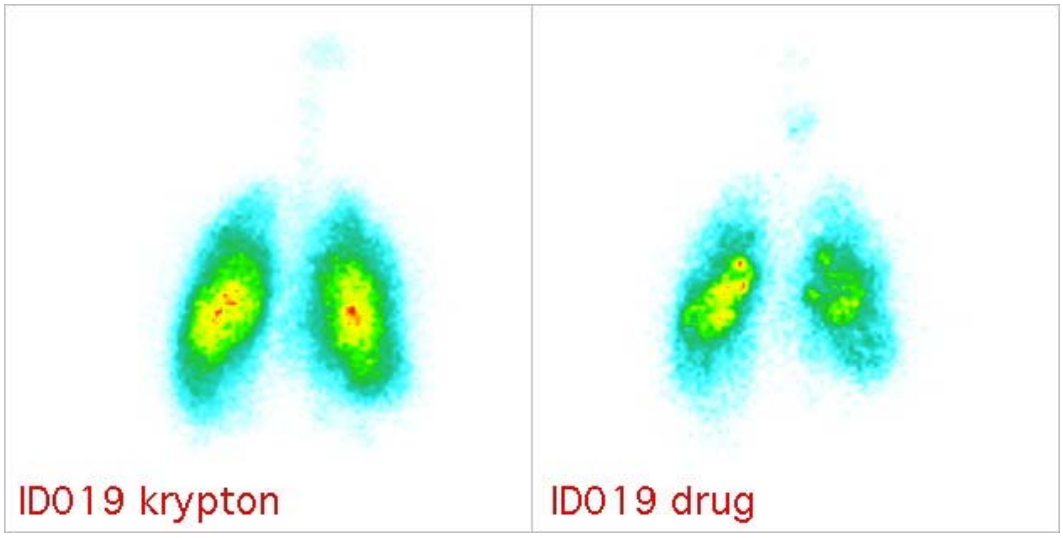


[NEW] **FIGURE 3.** Average values of the drug doses in the different lung regions, exhaled drug amount, and residuals in the device for the three study populations (CF: cystic fibrosis)



Owing to the limited measuring precision of the deposition measurement, individual deposition values were rounded to one decimal place. Therefore, the mean deposition values in the figure do not add up to 100% for each group.

FIGURE 4. Example of ventilation scan and drug deposition in a subject with α_1-antitrypsin deficiency.



[NEW] **FIGURE 5.** Relationship between forced expiratory volume in 1 s (FEV_1) (L) and the inhalation time.