Uncertainty in Particulate Deposition for 1 μm AMAD Particles in an Adult Lung Model

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ABSTRACT – The ICRP 66 lung model may be used to determine dose estimates for members of the public via the inhalation pathway. A significant source of uncertainty in internal dosimetric modeling is due to particulate deposition in regions of the respiratory tract. Uncertainties in estimates of particulate deposition are present because model input parameters have their own inherent variability. These sources of uncertainty need to be examined in an effort to better understand model processes and to better estimate doses received by individuals exposed through the inhalation pathway. An improved understanding of the uncertainty in particulate deposition will further guide research efforts and improve our ability to quantify internal dose estimates. The ICRP 66 lung deposition model is most sensitive to breathing rate when 1 μm AMAD particles are inhaled by members of the public. Uncertainties in deposition fractions are shown to span an order of magnitude with their distributions varying by gender for a particular lung region. The largest fractional deposition occurs in the deep lung alveolar and extrathoracic regions.

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INTRODUCTION

The use of inhalation models is an important part of estimating internal dose from contaminants in the atmosphere. Members of the public may have been exposed to small quantities of various radionuclides via the inhalation pathway from releases at Department of Energy (DOE) sites[1,2,3,4] and the incident at Chernobyl[5]. The uncertainty in internal dosimetry can be a considerable component of the overall uncertainty in dose assessment. An important calculational step in any lung model is the estimation of deposition fractions of particulates in various regions of the lung. Clearance via absorption, sequestration and surface transport, and thus the amount of material transferred to successive compartments or tissues, will be dependent upon regional deposition fractions of the particulate material. Therefore, variability in regional deposition within lung compartments may significantly contribute to the overall uncertainty of the lung model.

In the United States, ICRP 30[6] is the lung model of regulatory concern and, therefore, the more commonly employed. The ICRP 30 model, however, is one that is less sophisticated and does not offer the ability to input specific information relative to inhalation, deposition and clearance[7]. The International Commission on Radiological Protection developed and issued the "New Respiratory Tract Model" (ICRP 66) in 1994[7]. ICRP 66 incorporates recent knowledge and research into lung deposition, retention and clearance. In addition, the ICRP 66 methodology offers the ability to input data characteristic of specific materials. The model can be applied to all members of the world's population; it has the ability to consider the effects of modifying factors (smoking, pollution, and disease) on lung deposition, clearance and inhalation; and is more consistent with morphological, physiological and biological characteristics of the respiratory tract[7].

The uncertainty of regional deposition is dependent upon physiological and anatomical input parameters of individuals, as well as characteristics of the particulate material. Parameters describing particulates introduce uncertainty into estimates of regional deposition fractions due to their inherent variability. Being that anatomical and physiological input parameters are age dependent, the uncertainty in regional deposition for various age groups should be determined independently. There is also significant

variability in input parameters based on gender, therefore, adult males and females should be evaluated separately. This evaluation will determine the particulate deposition uncertainty and the sensitive parameters involved in modeling deposition of particulates in the adult male and female lung using the methods of ICRP 66.

METHOD

Fractional deposition estimates of 1 μm AMAD particles within regions of the lung were determined by multiple Latin Hypercube estimates following a simulated intake of particulate material via inhalation. One hundred Latin Hypercube estimates were determined by segregating input distributions into intervals of equal probability, with all intervals being sampled equally. Inhalability and regional deposition efficiency for inhalation and exhalation were estimated to determine total regional deposition. Numerical integration of the resultant deposition fractions was performed over the input distribution of particle aerodynamic diameter thus yielding an estimate of the deposition fraction for 1 μm AMAD aerosols. The integrated deposition fraction estimates using default values in ICRP 66 were compared to the published ICRP 66 values in Annex F. Estimates of deposition fraction were within four percent of the ICRP values, therefore demonstrating reasonable agreement and establishing a method of quality assurance.

The ICRP 66 model employs ten input parameters for determination of regional deposition fraction. These input parameters were varied according to their characteristic distributions, in an effort to perform uncertainty analysis of regional deposition fraction. The parameter, particle aerodynamic diameter (Table 1), is dependent upon the AMAD distribution of the aerosol and cannot be varied with respect to the uncertainty analysis. The remaining nine parameters (Table 1) are independent and are varied to determine the uncertainty in regional deposition fraction estimates. The resulting deposition fraction estimates are fit to known distributions and described by their characteristic parameters. Statistical analyses were performed on input parameter distributions to determine their sensitivity to fractional deposition. The calculational steps are discussed in greater detail in the subsequent sections and the methodology used is consistent with the ICRP 66 lung model[7].

Nose Breathers versus Mouth Breathers

The ICRP 66 model is based on the assumption that individuals are classified in one of two breathing categories, nose or mouth breathers. There are two pathways for the inspiration of air, nasal and

buccal. Nose breathing predominates as the typical breathing pattern, but mouth breathing is also significant within a typical population[7]. The fraction of air inhaled through the nose is assumed to be unity for nose breathers, except when breathing rates reach levels required for heavy exercise. The fraction of air inhaled through the nose and mouth is divided equally at breathing rates required for heavy exercise in the nose breather. For a mouth breather, air is inhaled through the mouth and nose at all levels of respiration. The amount of air inhaled through the nasal and buccal pathways varies, however, with breathing rate for the mouth breather. Therefore, a relationship between the fractions of air inspired through the nasal and buccal pathways as a function of breathing rate, has been determined for adult males and females[7].

Inhalability

Inhalability is defined as the intake efficiency of the human head for particles carried in moving air[7], or the aspiration efficiency of the human head for aerosols over representative ranges of aerosol size and external wind conditions[8]. The inhalability of air is used to determine the deposition efficiency in the initial compartment or "initial filter" of the respiratory system. Its numerical definition is the ratio of the number concentration of particles with a particular aerodynamic diameter inspired through the nose or mouth to the number concentration of particles with the same aerodynamic diameter present in the inspired volume of ambient air[7].

Extrathoracic Region Fractional Deposition

The extrathoracic region is assumed to consist of two physical compartments. Fractional deposition in the anterior nasal passage (ET_1 region) is determined solely by air inhaled through the nose. The total volumetric flow rate through the nasal region must be adjusted for the fraction of air being inhaled through the mouth. Therefore, deposition in the ET_1 region of mouth breathers is significantly reduced due to the low fraction of air being inhaled through the nose. Fractional deposition in the posterior nasal passage, pharynx and larynx (ET_2 region) is dependent upon the individual's breathing pattern (nose or mouth breather). For mouth breathers, ET_2 deposition is increased due to the larger volumetric flow rate and increased exposure to particulates inspired through the mouth. Total volumetric flow rate ventilating the lungs is a function of breathing rate and is the sum of the volumetric flow rates through the inhalation pathways.

Particle deposition occurs through aerodynamic and thermodynamic processes. Aerodynamic deposition occurs through impaction and sedimentation, which are dependent upon aerodynamic particle size, total volumetric flow rate, and the diameter of the airways. Thermodynamic deposition occurs through Brownian diffusion and is dependent upon the diffusion coefficient, along with total volumetric flow rate and airway diameter. The diffusion coefficient is a function of the particle's effective volume diameter and a slip correction factor. The slip correction factor accounts for particle slip caused by the relative velocity of gas molecules at the particle surface[7]. Deposition of particulates within all regions occurs upon both inhalation and exhalation.

Thoracic Region Fractional Deposition

The thoracic portion of the respiratory tract is assumed to be composed of three compartments: bronchial (BB), bronchiolar (bb), and alveolar-interstitial (AI). The bronchial (BB) region begins with the trachea and includes the bronchi to the eighth airway generation. The bronchiolar (bb) region is the second portion of the air conducting system in the lungs and consists of the bronchioles from airway generations nine to fifteen. The alveolar-interstitial (AI) region is comprised of respiratory bronchioles and alveolar ducts from airway generations sixteen to twenty-six. Fractional deposition in these regions is influenced by individual breathing patterns. Nose breathers have increased deposition in the extrathoracic region, thereby reducing subsequent deposition in the thoracic region of the respiratory tract. Mouth breathers, however, will have less deposition in the extrathoracic region, thus yielding greater particulate deposition in the thoracic region. The total volumetric flow reaching the thoracic region is assumed to be the same for all individuals, regardless of breathing pattern.

Deposition in the thoracic region is the sum of aerodynamic and thermodynamic deposition of particulate material. Aerodynamic deposition is dependent upon aerodynamic particle size, total volumetric flow rate, anatomical dead space, tidal volume, functional residual capacity (combined residual and expiratory reserve volume or the amount of air remaining in the lungs after a tidal expiration), and diameter of the airways. Thermodynamic deposition is dependent upon anatomical and physical characteristics such as tidal volume, anatomical dead space, functional residual capacity, and the transit time of air within each region. Thermodynamic particle size, which is dependent upon the diffusion coefficient, will influence thermodynamic deposition.

PARAMETER DISTRIBUTIONS

Input parameter distributions and their characteristics are listed in Table 1. A discussion of each model parameter follows. Particle aerodynamic diameter was not varied when determining uncertainty in the model because estimates of regional deposition fraction are numerically integrated over this distribution to determine the deposition of 1 μm AMAD aerosols.

Breathing Rate (BR)

Breathing rate assumptions by age and level of exercise are taken from the ICRP Committee 2 report by the Lung Dynamics Task Group[9]. These data are also used in ICRP 66 as the basis for breathing rate estimates. ICRP 2 data were used to derive a distribution of annual breathing rates using a simple Monte Carlo technique to simulate assumed activity levels[10]. Two breathing rate distributions have been assumed for each gender, one for light-to-moderate exercise and one for heavy exercise. So, as to introduce the least amount of bias into the deposition uncertainty calculation and yet provide some weight to expected ventilation rates, the distributions describing breathing rates are assumed to be triangular. The light-to-moderate distribution has a mode equal to the light activity breathing rate default value and is bounded by the resting breathing rate and twice the light breathing rate[7]. The distribution describing heavy exercise ranges from twice the light breathing rate to the maximum sustained breathing rate of twice the heavy breathing rate with a mode equal to the heavy breathing rate default value[7].

Breathing rates were determined by assuming that the individual is engaged in light-to-moderate activity for 163 hr wk^{-1} and heavy exercise for 5 hr wk^{-1}. The distributions were sampled uniformly based on the amount of time an individual engages in each type of activity. The distribution best describing adult male breathing rate was found to be normally distributed with a mean of 1.74 m^3 hr^{-1} [7] and a 1-sigma standard deviation of 0.67 m^3 hr^{-1} [7]. Adult female breathing rate was found to be normally distributed with a mean of 1.37 m^3 hr^{-1} [7] and a 1-sigma standard deviation of 0.45 m^3 hr^{-1} [7]. The NRC[11] breathing rate default value is 0.91 m^3 hr^{-1}, demonstrating agreement within a factor of two. Therefore, these data were used as the basis for breathing rate in our determination of particle deposition in adult males and females. Each gender is addressed independently due to significant differences in certain input parameters.

Breathing rates at differing levels of activity were used to determine four input parameters for the ICRP 66 lung model. These parameters included tidal volume (V_T), total volumetric flow rate of air

ventilating the lung (V), and the fractions of air breathed through the nose (F_n) and mouth (F_m). Functions relating these four parameters to breathing rate were generated for various levels of exercise. Minimum breathing rate was limited to 0.1 m^3 hr^{-1} to prevent sampling of unusually low breathing rates, and total volumetric flow rate was limited to 2000 mL s^{-1}. Tidal volume was bounded by 100 mL and 2000 mL in the adult female and by 100 mL and 2500 mL in the adult male. Monte Carlo techniques were then used to determine estimates of parameter uncertainty.

Windspeed (U)

Ambient windspeed of the air breathed affects particulate inhalability. Windspeeds typically encountered vary within the range of about 0 to 10 m s^{-1} in both indoor and outdoor environments[7,8,12]. When determining inhalability for an occupational worker, windspeeds are within the range of 0 to 4 m s^{-1} for most occupational environments[8,12]. It is assumed herein that the distribution of windspeeds is uniform from 0 to 10 m s^{-1} with no preference for one speed over another[8,12].

Aerodynamic Diameter (d_{ae})

Environmental exposures to the general public are assumed to be from 1 μm AMAD aerosols, therefore, particulate aerodynamic diameter is assumed to be log-normally distributed with a geometric mean of 1 μm and a geometric standard deviation of 2.47[7]. The aerodynamic particle diameter is the diameter observed due to irregularities in shape and is used in the determination of aerodynamic deposition. This parameter was not varied to determine estimates of uncertainty; it cannot be varied because it is a function of the aerosol distribution, over which the resulting deposition fractions are numerically integrated.

Particle Mass Density (p)

Particle mass density is assumed to be triangularly distributed ranging from 1 to 10 g cm^{-3} with a mode of 3 g cm^{-3} [7]. The ICRP recommends a reference value of 3 g cm^{-3} because it is a typical value for many natural materials. The assumed range includes particles such as polystyrene, teflon, iron oxide, and uranium oxide[7].

Particle Shape Factor (χ)

The shape factor is a dimensionless constant used to relate drag force on an irregular particle moving in air to the particle's equivalent volume diameter[7]. The shape factor and the mass density are

used to determine the particle's thermodynamic diameter in the model, but in practice, the thermodynamic diameter can be measured for small particles. The shape factor is assumed to have a triangular distribution ranging from 1.1 to 1.9 with a mode of 1.5[7]. The ICRP 66 default for the particle shape factor is 1.5.

Functional Residual Capacity (FRC)

The functional residual capacity (FRC) is the combined residual and expiratory reserve volume, or the amount of air remaining in the lungs after a tidal expiration[13]. An individual's FRC varies by gender and age. For adult males, functional residual capacity is normally distributed with a mean of 3,300 mL and standard deviation of 600 mL[7,14,15]. In adult females, FRC is normally distributed with a mean of 2,680 mL and standard deviation of 500 mL[7,14,15].

Anatomical Dead Space (V_D)

Anatomical dead space refers to the volume of air in the lung that does not undergo gas exchange. Total anatomical dead space and regional anatomical dead space values for regions with the respiratory tract can be found in ICRP 66. Anatomical dead space is assumed to be normally distributed with a mean of 146 mL and standard deviation of 25.5 mL[7,14,16] for adult males. For adult females, V_D is normally distributed with a mean of 124 mL and standard deviation of 21 mL[7,14,16].

Diameter of Trachea (d_0), Bronchiole (d_9), and Terminal Bronchiole (d_{16})

Scaling factors used in the ICRP 66 methodology for regional deposition of particulates are dependent upon the diameter of airways within the respiratory tract. These factors are based on average airway diameters of the adult male and are used to estimate airway diameters at various generations as functions of gender and age. Aerodynamic and thermodynamic deposition of particulate material within the ET_1, ET_2 and BB regions are dependent on the diameter of the trachea. Thermodynamic deposition of particulate material within the bb region is dependent on the diameter of the bronchiole at airway generation nine. Aerodynamic and thermodynamic deposition of particulates within the AI region are dependent on the diameter of the terminal bronchiole.

Mean values of airway diameter (Table 1) can be found in the literature[17,18,19,20,21] , but reference values for their corresponding standard deviation are more difficult to determine. Airway diameter correlates well with an individual's height[18]. The variability in height[22,23,24], and thus airway diameter is shown to be normally distributed and the relative standard deviation in height has been applied as a

measure of the variability in airway generation diameter. Height and airway diameter data are both age and gender specific.

RESULTS

Regional deposition fractions of a 1 μm AMAD aerosol, their distributions and characteristics have been determined as functions of gender and breathing pattern (Table 2) and are shown to follow similar trends (Fig. 1). The data in Figure 1 are divided into ten equally sized regions of deposition fraction and plotted as a histogram. The ordinate refers to the frequency that the deposition fraction result is in the corresponding interval of the histogram. Figure 1 also shows a continuous function representing the best fit distribution of the data. The frequency distributions of regional deposition fraction are best described by a normal distribution for the BB and extrathoracic regions. The bb and AI regions are best described by a lognormal distribution. The plots of deposition fraction in the BB and bb regions (C and D of Fig. 1) demonstrate a significantly different area under the curve and the histogram. This is due to the very small standard deviation of deposition fraction in these regions and the resulting calculation using the normal and lognormal distribution functions.

The ICRP 66 recommended values shown in Table 2 do compare well with those developed herein. The ICRP 66 values are for deposition of 1 μm particles, specifically, for members of the public engaged in light exercise. The deposition fractions determined in this assessment are for members of the public exposed to particles characterized by a 1 μm AMAD aerosol and characteristic breathing rate distributions. Parameter sensitivity analysis was performed by the rank transformation method[24,25] for each region based on breathing pattern and gender (Table 3). Breathing rate, diameter of the trachea, and particle mass density have the greatest influence on deposition in all regions of the lung.

DISCUSSION

Uncertainty of Regional Deposition Fraction

Particulate deposition occurs upon inhalation and exhalation, therefore, deposition distributions are dependent upon the entire respiratory cycle. The larger the aerodynamic particle size, the greater the deposition of that material within the ET_1 region, as well as the entire extrathoracic region. Particles with large aerodynamic diameters will have increasing difficulty in penetrating the respiratory tract due to reduction in airway size as the particle moves deeper into the lung. The BB region of the respiratory tract

has a reduced amount of deposition due to its small surface area, and rapid transit time of air conduction to subsequent regions. Deposition begins to increase in the bb region because as airway diameters decrease more particles become deposited. The greatest amount of thoracic deposition occurs in the deeper regions of the lung due to the ability of small particulates to interact with the large surface area of the respiratory bronchioles and alveoli. These trends are consistent for all adults, regardless of breathing pattern and gender.

The greater the fractional deposition in the extrathoracic region, the larger the dose estimate to this region of the respiratory tract. Increased deposition in ET_1, however, will lead to a greater amount of clearance through physical removal, thus tending to decrease the dose to the respiratory tract. Extrathoracic clearance is due to movement of cilia on the mucosal surface and the upward flow of mucous. Particles can then be removed by swallowing, coughing, and sneezing, therefore, increased extrathoracic deposition will lead to a lower committed dose equivalent to the lung, but increased amounts of particulate material will enter the transfer compartment (blood) due to the effect of swallowing some particulate material. Conversely, increased deposition in the thoracic regions will increase the committed dose equivalent to the lung before subsequent clearance to the GI tract and blood. These are general observations and specific information based on radionuclide, particulate material and chemical form are of great importance for estimating an individual's inhalation dose.

Distributions of fractional deposition are similar for all individuals, regardless of gender and breathing pattern. As an example, particle deposition in each region of the respiratory tract of adult female mouth breathers is shown in Fig.1. For 1 μm AMAD aerosols, the greatest regional deposition occurs in the extrathoracic regions of the respiratory tract and the largest thoracic fractional deposition occurs in the AI region or deepest portion of the lung. When particles are large, deposition in the AI region is significantly reduced because large particles are deposited in the extrathoracic region of the respiratory tract. Individuals that breathe primarily through the nose have greater deposition in the extrathoracic regions of the respiratory tract and decreased deposition in the thoracic regions as compared to mouth breathers.

Parameter Sensitivity Analysis

Sensitivity analyses were conducted to determine the parameters influencing deposition fraction in

all regions of the respiratory tract. Rank correlation coefficients were calculated (Table 3), the value of which demonstrates the degree of importance that an input parameter has on output variability[25,26]. The rank correlation coefficient may be positive or negative, demonstrating whether the model output is increasing or decreasing, respectively, with the magnitude of a given input parameter. The deposition model of ICRP 66 requires ten different input parameters. Parameter sensitivity is dependent upon the input parameter distribution and its characteristics, along with the mathematical structure of the model.

The estimate of deposition in the respiratory tract is generally most sensitive to the input parameters of trachea diameter (d_0), particle mass density (ρ), and breathing rate (BR). Breathing rate is always the most sensitive parameter in the model. As shown by the rank correlation coefficients (Table 3), breathing rate has a more significant influence on regional deposition than other parameters in the extrathoracic and BB regions. The influence of breathing rate on regional deposition in the bb and AI regions is also more important than other parameters but to a lesser degree. Breathing rate is positively correlated in the BB and extrathoracic regions but negatively correlated in the bb and AI regions. Extrathoracic regional deposition is also significantly influenced by the diameter of the trachea, being negatively correlated with extrathoracic deposition of particulate material. Particle mass density plays an important role in particulate deposition in the bb and AI regions and particle mass density is positively correlated with deposition in the deep lung regions. Adults, regardless of gender and breathing pattern, demonstrate a similar relationship with respect to which parameters are most sensitive. The model's sensitivity was tested with and without numerical integration. The numerical integration process does not appear to play a significant role in model sensitivity to input variables.

CONCLUSIONS

Improved estimates of fractional deposition will improve our ability to estimate the committed dose equivalent to the lung and subsequent movement of particles to the bloodstream. The regional deposition of particulate material within the lungs has inherent uncertainty, which is dependent upon input parameters, breathing patterns and gender. The resulting distribution and characteristics of each region contribute to the total uncertainty of particulate deposition and thus the overall uncertainty of inhalation dose estimates. These differences must be accounted for to better estimate regional lung deposition of particulates.

Generally, fractional deposition in the lung, as modeled in ICRP 66, is directly dependent upon particle mass density and breathing rate, and inversely dependent on trachea diameter. Other parameters play a relatively minor role in regional deposition within the respiratory tract. Research into these more sensitive parameters and their distributions may lead to reduction in the uncertainty of the deposition model of ICRP 66. Dose estimate uncertainties also can be reduced when data on particle size and density are gathered at the time of exposure to particulate material.

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Table 1. Input parameter distribution assignments.[a]

Symbol	Parameter (Units)	Distribution type[b]	Mean[c]	Standard deviation[d]
U	Windspeed (m s^{-1})	U	-------	0, 10
d_{ae}	Aerodynamic particle size (μm)	LN	1.00	2.47
χ	Particle shape factor	T	1.5	1.1, 1.9
ρ	Particle mass density (g cm^3)	T	3.0	1.0, 10.0
			Mean[c](Standard Deviation[d])	
			Male	Female
BR	Breathing Rate (m^3 hr^{-1})	N	1.74 (0.67)	1.37 (0.45)
d_0	Diameter of trachea (cm)	N	1.65 (0.067)	1.53 (0.06)
d_9	Diameter of airway at generation 9 (cm)	N	0.165 (0.007)	0.159 (0.006)
d_{16}	Diameter of airway at generation 16 (cm)	N	0.051 (0.002)	0.048 (0.002)
V_d	Anatomic dead space (mL)	N	146 (25.5)	124 (21.0)
FRC	Functional residual capacity (mL)	N	3301 (600)	2681 (500)

[a] References are given in the text.
[b] Distributions: N = normal; LN = lognormal; T = triangular; U = uniform.
[c] Arithmetic mean for normal distributions, geometric mean for lognormal distributions and the mode for triangular distributions.
[d] Standard deviation for normal distributions, geometric standard deviation for lognormal distributions, and minimum and maximum for triangular and uniform distributions.

Table 2. Deposition fractions (unitless) for lung regions by gender and breathing characteristics[a].

Parameter	Mean[b]	Standard Deviation[c]	ICRP 66 Recommended Value[d]
Adult Male			
Nose Breather			
ET_1	0.17	0.035	0.18
ET_2	0.22	0.045	0.23
BB	0.013	0.0023	0.013
bb	0.018	1.21	0.015
AI	0.10	1.23	0.099
Mouth Breather			
ET_1	0.12	0.015	
ET_2	0.16	0.024	
BB	0.025	0.0069	
bb	0.021	1.20	
AI	0.13	1.15	
Adult Female			
Nose Breather			
ET_1	0.17	0.030	0.18
ET_2	0.22	0.042	0.23
BB	0.013	0.0018	0.013
bb	0.016	1.32	0.015
AI	0.098	1.23	0.099
Mouth Breather			
ET_1	0.13	0.015	
ET_2	0.17	0.024	
BB	0.024	0.0060	
bb	0.022	1.19	
AI	0.13	1.17	

[a] ET_1, ET_2, and BB regions are described by a normal distribution. AI and bb distributions are described by a lognormal distribution.
[b] Mean for normal distributions and geometric mean for lognormal distributions.
[c] Standard deviation for normal distributions and geometric standard deviation for lognormal distributions.
[d] ICRP 66 deposition fractions are for members of the public that breathe 1 μm AMAD particles through the nose and are engaged in light exercise (values for mouth breathers are unavailable).

Table 3. Parameter sensitivity for particulate deposition in adults using rank correlation coefficients. Absolute values less than 0.05 have been excluded to increase clarity and the two most sensitive parameters are shown in bold.

Male Nose Breather					
Parameter	ET_1	ET_2	BB	bb	AI
ρ	-0.09	-0.08		**0.57**	**0.49**
FRC	-0.09	-0.09		-0.08	
d_0	**-0.16**	**-0.17**		-0.05	0.05
d_9				-0.18	
d_{16}			0.07	-0.10	-0.15
U	-0.09	-0.12	**-0.14**	0.27	0.18
V_d				0.16	-0.14
χ	0.08	0.08	0.11	-0.13	-0.16
BR	**0.86**	**0.86**	**0.97**	**-0.76**	**-0.80**
Male Mouth Breather					
Parameter	ET_1	ET_2	BB	bb	AI
ρ				**0.58**	**0.45**
FRC			-0.10		0.22
d_0	**-0.42**	**-0.42**	-0.10	0.36	0.20
d_9	-0.06	-0.06	-0.10	-0.11	0.07
d_{16}	-0.16	-0.16	**-0.18**	0.21	0.05
U	0.15	0.14	0.05	0.06	0.08
V_d	-0.09	-0.08	-0.06	0.08	-0.24
χ			-0.07		-0.08
BR	**0.84**	**0.84**	**0.97**	**-0.67**	**-0.73**
Female Nose Breather					
Parameter	ET_1	ET_2	BB	bb	AI
ρ			0.11	**0.50**	**0.37**
FRC	-0.10	-0.10	-0.12	0.06	0.17
d_0	**-0.33**	**-0.32**	-0.23	0.09	0.19
d_9	-0.06	-0.06			0.09
d_{16}	-0.11	-0.11	-0.10	0.09	
U				-0.06	
V_d	0.20	0.20	**0.24**		-0.34
χ	-0.07	-0.08	-0.12	-0.13	
BR	**0.94**	**0.94**	**0.96**	**-0.80**	**-0.86**
Female Mouth Breather					
Parameter	ET_1	ET_2	BB	bb	AI
ρ				**0.59**	**0.41**
FRC	0.09	0.09	0.07	-0.10	-0.05
d_0	**-0.49**	**-0.48**	**-0.22**	0.34	0.26
d_9			-0.07	-0.09	
d_{16}				0.07	-0.11
U				0.05	0.09
V_d		-0.05		0.15	-0.23
χ				-0.13	-0.16
BR	**0.90**	**0.90**	**0.98**	**-0.71**	**-0.81**