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Original article

Development of Korean Representative Headforms for the Total Inward Leakage Testing on Filtering Facepiece Respirators

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ABSTRACT

Background: The lack of headforms that accurately reflect the head characteristics of Koreans and the demographic composition of the Korean population can lead to inadequate FFR testing and reduced effectiveness of FFRs.
Method: Direct measurements of 5,110 individuals and 3D measurements of 2,044 individuals, aged between 9 and 69 years, were sampled from the data pool of Size Korea surveys based on the age and gender ratios of the Korean resident demographics. Seven head dimensions were selected based on the ISO 16976-2, availability of Size Korea measurements, and their relevance to the fit performance of FFRs. A principal component analysis (PCA) was performed using the direct measurements to extract the main factors explaining the head characteristics and then the main factors were standardized and remapped to 3D measurements, creating five size categories representing Korean head shapes. Lastly, representative 3D headforms were constructed by averaging five head shapes for each size category.
Results: The study identified two main factors explaining Korean head characteristics by the PCA procedure specified in ISO 16976-2 and developed five representative headforms reflecting the anthropometric features of Korean heads: medium, small, large, short & wide, and long & narrow.
Conclusion: This study developed representative headforms tailored to the Korean population for conducting total inward leakage (TIL) tests on filtering facepiece respirators (FFRs). The representative headforms can be used for TIL testing by employing robotic headforms to enhance the performance of FFRs for the Korean target population.

1. Introduction

In filtering facepiece respirators (FFRs) designed to protect against external contaminants, preventing the leakage of contaminants through the gap between the face and the mask seal is equally crucial as ensuring the effectiveness of the filtration medium and the performance of the inhalation and exhalation valves [1]. The Korean Food and Drug Administration (KFDA) specifies three tests such as dust collection efficiency test, inhalation pressure test, and total inward leakage (TIL) test to determine the protection level of FFRs [2]. However, in the case of the inhalation pressure test, a fixed-size headform is used, which may not accurately represent the diversity of face sizes in the Korean population. Similarly, for the TIL test, the use of 10 human subjects without

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Abbreviations: FFR, filtering facepiece respirator; KFDA, Korean Food and Drug Administration; NIOSH, National Institute for Occupational Safety and Health; PCA, principal component analysis; PC1, first principal component; PC2, second principal component; StAH, Static Advanced Headform; TIL, total inward leakage.

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Table 1
Anthropometric data of the 6th and 7th Size Korea surveys

Age	Direct measurements						3D measurements		
	6th Size Korea (2010)			7th Size Korea (2015)			6th Size Korea (2010–2014)		
	Male	Female	Total	Male	Female	Total	Male	Female	Total
9	325	299	624	—	—	—	92	93	185
10–19	3,846	3,106	6,952	996	928	1,924	1,106	1,052	2,158
20–29	629	530	1,159	869	668	1,537	235	208	443
30–39	519	507	1,026	654	676	1,330	203	202	405
40–49	299	277	576	310	360	670	200	201	401
50–59	300	289	589	220	359	579	213	208	421
60–69	275	253	528	143	230	373	205	201	406
Total	6,193	5,261	11,454	3,192	3,221	6,413	2,254	2,165	4,419

specific criteria for age, gender, or face size may not provide a comprehensive evaluation of face seal leakage for the Korean population. As a result, it becomes challenging to determine whether the test results obtained are truly representative of Koreans and effectively prevent face seal leakage.

The development of headforms is important for non-human-based TIL testing of FFRs because they offer several advantages over human-based evaluation methods in terms of safety, convenience, and cost-effectiveness. Human-based TIL test methods are limited due to safety and ethical concerns, such as testing for pediatric populations, long-term duration, high aerosol concentrations, and toxic aerosols (e.g., combustion aerosol or biological pathogens) [3–8]. Moreover, non-human-based methods are more convenient as they require fewer physical human resources, simplifying the requirements such as approval from an institutional review board, scheduling of experiments, recruitment of participants, and administration of experiments [8–12]. Lastly, the use of human participants is expensive and time-demanding [12,13].

Various types of headforms have been developed for the TIL testing of FFRs, considering the head characteristics and movement patterns of FFR users. For instance, Zhuang et al [14] developed five digital headforms (small, medium, large, short & wide, and long & narrow) representing the US workforce using the principal component analysis (PCA) method. These headforms are also included in ISO 16900-5 [15] and ISO 16976-2 [16]. The National Institute for Occupational Safety and Health (NIOSH) in the US developed the Static Advanced Headform (StAH), which is based on the medium-sized headform and is covered with silicon polymer skin defined by local tissue thickness [8,9]. A TIL test method using the StAH headform was validated instead of human-based TIL test methods for FFRs by an experimental setup with a Breathing Recording System (Koken Ltd., Tokyo, Japan) [3,9]. Furthermore, NIOSH developed a human-like robotic headform based on the StAH to achieve lifelike movements (speaking, turning head side to side, and moving head up and down) by articulated structures [8], although the TIL testing experiment protocol using this robotic headform has not been established yet [8]. Lastly, five 3D headforms were developed to represent Chinese workers based on 350 3D scanned participants to conduct TIL tests for the Chinese population [17,18].

Headforms representing Korean head characteristics need to be developed to improve the validity of FFR TIL tests. The NIOSH headforms based on western head measurement may result in issues affecting the validity of TIL tests [7]. Seo et al [7] developed three headforms (small, medium, and large) based on 44 head measurements of 4,583 Korean individuals aged 7 to 69 using the *K*-means clustering method. However, Seo et al [7] used the quota matrix of the 6th Size Korea project, which allocated a larger proportion of the population to children compared to the actual Korean residential population.

The objective of this research is to develop representative headforms for conducting TIL tests on FFRs for the Korean population aged 9 to 69 years. A PCA panel is constructed, considering various age groups and genders, in accordance with the age and gender ratios of the Korean resident demographics and international standards for headform development. The headform development process involved utilizing anthropometric measurements collected from Korean individuals to create headforms that represent each cell of the PCA panel, using both direct measurements and 3D measurements of Korean heads.

2. Development procedure

2.1. Materials

2.1.1. Head measurements

To analyze the representative shape of Korean heads for TIL tests on FFRs, the present study utilized both direct measurements and 3D measurements collected during the 6th and 7th Size Korea surveys [19,20]. Anthropometric data were sourced from a diverse range of individuals aged 9 to 69 years old, with 17,867 participants providing direct measurements and 4,419 participants providing 3D measurements as shown in Table 1. 3D measurements were extracted from 3D scans using an in-house program developed by the Size Korea survey team. The 6th and 7th Size Korea surveys collected direct measurements in 2010 and 2015, respectively, while only the 6th Size Korea survey gathered 3D measurements from 2010 to 2014 for participants at different age groups. It's important to note that direct measurements and 3D

Table 2
A sampled dataset stratified by gender and age groups based on Korean resident demographics

Age	Direct measurements			3D measurements		
	Male	Female	Total	Male	Female	Total
9	30	28	58	12	12	24
10–19	294	275	569	117	110	227
20–29	424	384	808	170	153	323
30–39	418	392	810	167	157	324
40–49	500	484	984	200	194	394
50–59	522	510	1,032	209	204	413
60–69	416	433	849	166	173	339
Total	2,604	2,506	5,110	1,041	1,003	2,044

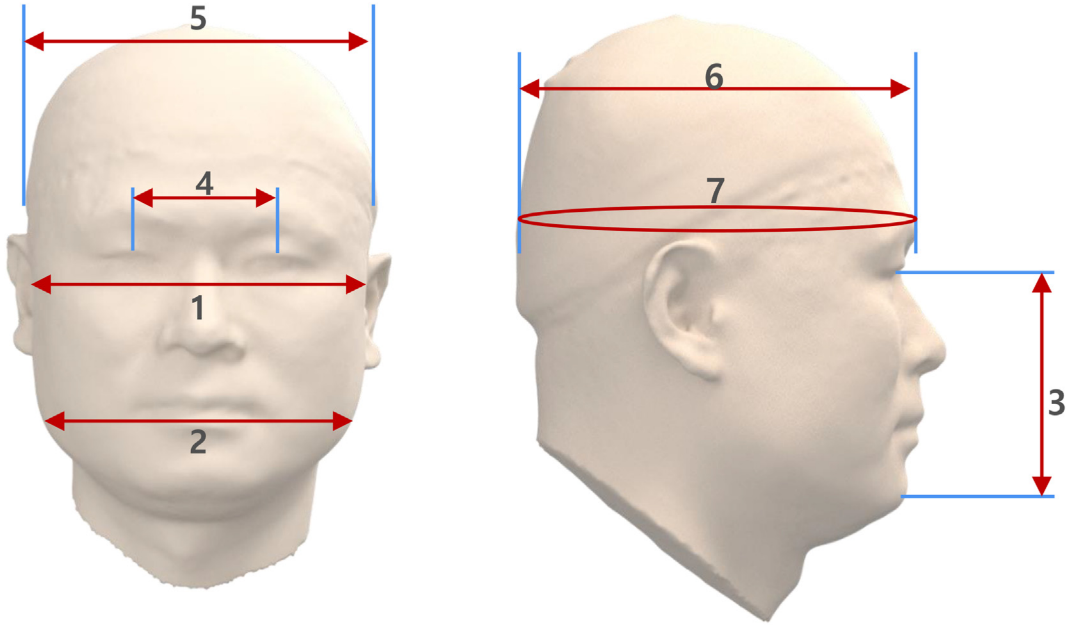

Fig. 1. Head dimensions selected for representative headform establishment: (1) face breadth (maximum horizontal breadth between the zygomatic arches); (2) bigonial breadth (maximum horizontal breadth between left and right gonions); (3) face length (vertical length between sellion and menton); (4) interpupillary breadth (horizontal breadth between the center of right and left pupil); (5) head breadth (horizontal breadth between right and left euryon); (6) head length (horizontal distance at the sagittal plane between glabella and occiput); (7) head circumference (maximum circumference of the head just above the glabella and occiput).

measurements, while both conducted during the 6th Size Korea survey, were targeted at different participant groups.

To ensure that the collected data from Size Korea surveys properly represent the recent population distribution of Koreans, we sampled the direct and 3D measurement data of individuals aged 9 to 69 years old based on the gender population by age, as per Korean resident demographics at the end of August 2021. This meticulous process resulted in 5,110 direct measurements and 2,044 3D measurements, creating a new data set that properly reflects the population distribution characteristics of Koreans (see Table 2). This dataset is suitable for deriving statistically representative head shapes for individuals of various sizes within the Korean population.

2.1.2. Head dimensions for headform grouping

The analysis of Korean head characteristics involved seven key head dimensions: face breadth, bigonial breadth, face length, interpupillary breadth, head breadth, head length, and head circumference (Fig. 1). The inclusion of these seven head dimensions was based on the following criteria: (1) the alignment with the dimensions in ISO 16976-2 [16]; (2) the availability of Size Korea measurements; and (3) the relevance to assessing the fit performance of FFRs.

Table 4
PCA results with seven head dimensions

No.	Dimensions	PC1	PC2
1	Face Breadth	0.412	−0.439
2	Bigonial Breadth	0.323	−0.597
3	Face Length	0.326	0.309
4	Interpupillary Breadth	0.298	0.498
5	Head Breadth	0.409	−0.051
6	Head Length	0.385	0.317
7	Head Circumference	0.464	0.052
Eigen value		3.591	1.138
Cumulative proportion		0.513	0.676

The Size Korea surveys provided a total of 14 direct measurements and 48 3D measurements related to head dimensions. In the present study, the selection of relevant head dimensions to address the fit performance of FFRs involved a thorough review conducted by three clothing science experts and two ergonomics experts, and then the results of this review were subsequently cross-checked by two FFR fit-test experts to ensure the appropriateness of the chosen dimensions. In comparing the seven head

Table 3
Regression equations for face breadth and bigonial breadth

Dimension	Gender	Equation	R^2
Face Breadth	Male	43.90 + 0.1605 × weight + 0.1990 × head circumference − 0.2662 × head length + 0.1208 × head breadth	0.28
	Female	47.20 + 0.2294 × weight − 0.09311 × bitragion arc + 0.10304 × sagittal arc + 0.4776 × head breadth	0.41
Bigonial Breadth	Male	80.48 - 0.02744 × stature + 0.2832 × weight + 0.1777 × interpupillary breadth + 0.2948 × head breadth	0.26
	Female	47.43 + 0.2945 × weight − 0.14736 × bitragion arc + 0.12150 × sagittal arc + 0.3797 × head breadth	0.46

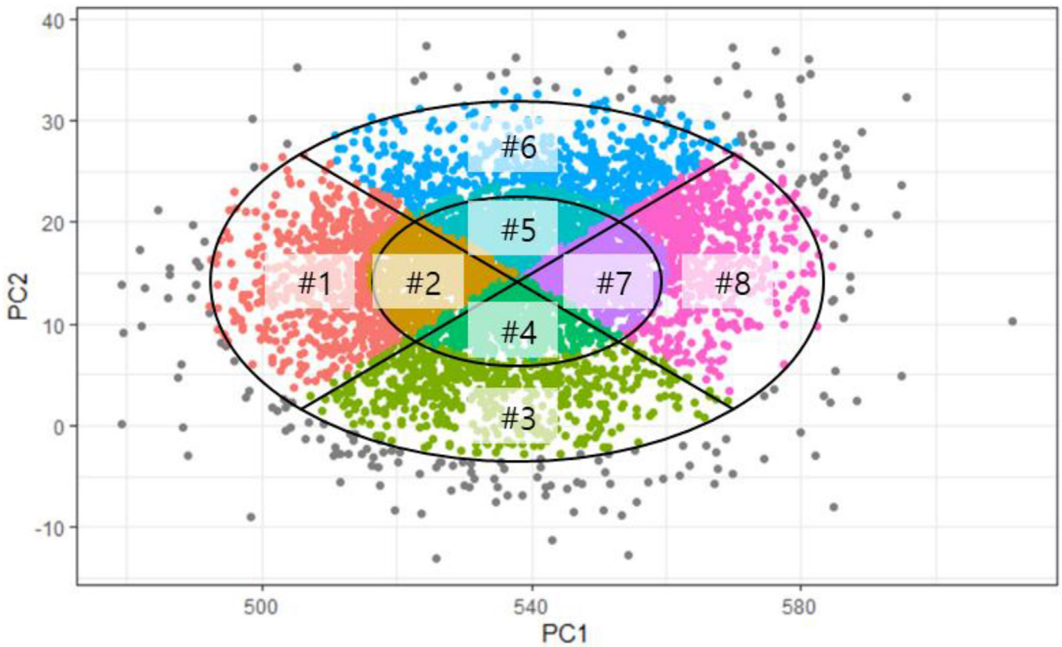

Fig. 2. PC score distribution of Korean direct measurements ($n = 5{,}110$).

dimensions selected in this study to the 10 head dimensions specified in the NIOSH headforms [21], four dimensions (nose width, sellion breadth, nose length, nose protrusion, and minimum frontal breadth) were not included, as these were not included in the Size Korea measurements and two dimensions (head length and head circumference) were added to the present study. The exclusion of the dimensions related to nose shape could be justifiable, as FFRs available in the Republic of Korea are equipped with adjustable nose wires to accommodate various nose shapes. The dimension of minimum frontal breadth was omitted from the analysis because it was not measured in either the direct or 3D measurements, and it was not deemed essential given the coverage area of the FFRs. The inclusion of head length and head circumference as new dimensions for headform grouping was based on their good correlation with measurement values estimating ear position [22] and their provision of general information about head size, which is relevant to how well FFRs fit around the ears.

During the data collection process spanning multiple years, it was observed that measurements for face breadth and bigonial breadth were missing for particular age groups. To estimate these missing data, regression equations (see Table 3) were established using measurements from other age groups as a basis.

Table 5
Distribution of eight Korean PCA test panel cells

Cell	N			%		
	Male	Female	Total	Male	Female	Total
1	80	497	577	3.1	19.8	11.3
2	187	559	746	7.2	22.3	14.6
3	125	457	582	4.8	18.2	11.4
4	217	334	551	8.3	13.3	10.8
5	404	285	689	15.5	11.4	13.5
6	356	154	510	13.7	6.1	10.0
7	542	104	646	20.8	4.2	12.6
8	588	22	610	22.6	0.9	11.9
Total	2499	2412	4911	96.0	96.2	96.1

(Note) The sum of the percentages of cells 2, 4, 5, and 7 = 51.5%.

2.2. Principal component analysis (PCA) approach

To identify the primary factors that contribute to the typical shapes of Korean heads, we applied the PCA approach to the direct measurements of the seven head dimensions obtained from the stratified random sample of 5,110 individuals. This analysis resulted in the extraction of two principal components, which collectively accounted for 67.6% of the total variance as presented in Table 4. Notably, this variance was higher than the PCA result by NIOSH, which accounted for 58.5% of the variance. The first principal component (PC1) displayed significant positive loadings for head circumference, face breadth, head breadth, head length, face length, and bigonial breadth. This suggests that these dimensions strongly contribute to the variation captured by PC1. Consequently, PC1 can be interpreted as representing the overall size of the head, with higher scores indicating more pronounced head characteristics and lower scores indicating less prominent features. On the other hand, the second principal component (PC2) exhibited high negative loadings for bigonial breadth and face breadth, along with high positive loadings for interpupillary breadth, head length, and face length. PC2 is indicative of the height and sagittal length of the head. Larger scores on PC2 correspond to narrow and vertically elongated features when viewed from the front, as well as prominent features when viewed from the side. Conversely, smaller scores on PC2 indicate wider and shorter features from a frontal view, along with less prominent features from a sagittal view.

2.3. Scheme of Korean fit test panel

The PCA results were used to develop an eight-head-size fit test panel following the NIOSH algorithm [22]. This panel was determined based on the score of two primary components, PC1 and PC2, which were derived by calculating each individual's seven head dimensions as follows:

$$\text{PC1} = 0.412 \times \text{face breadth} + 0.323 \times \text{bigonial breadth} + 0.326 \times \text{face length} + 0.298 \times \text{interpupillary breadth} + 0.409 \times \text{head breadth} + 0.385 \times \text{head length} + 0.464 \times \text{head circumference}$$

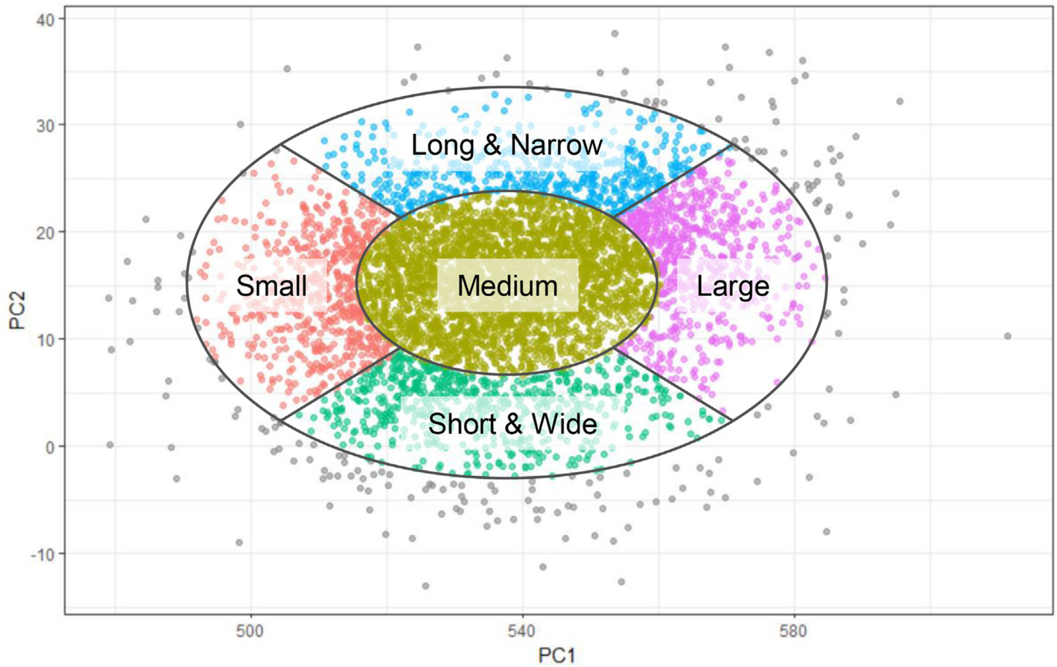

Fig. 3. PC score distribution of Korean direct measurements for five Korean headform size categories.

PC2 = −0.439 × face breadth − 0.597 × bigonial breadth + 0.309 × face length + 0.498 × interpupillary breadth − 0.051 × head breadth + 0.317 × head length + 0.052 × head circumference

Fig. 2 shows the PCA test panel for Koreans, which is divided into eight cells. The outer ellipse is designed to accommodate more than 95% of the population, while the inner ellipse is tailored to include more than 50% of the population. As a result, a PCA test panel was developed, accommodating 96.1% of the population ($n = 5{,}110$) using the direct measurements, with each cell catering to at least 10% of the population (see Table 5).

2.4. Case selection for representative headforms

The Korean PCA test panel, initially consisting of eight cells, was reduced to five cells using NIOSH's headform size definition method [14,22]. Since PC1 on the X-axis of Fig. 2 describes the overall size of the head, and PC2 on the Y-axis describes the height and sagittal length of the head, head shapes in cell #1 were classified as small, those in cell #8 as large, those in cell #3 as short & wide, and those in cell #6 as long & narrow, with head shapes in cells #2, #4, #5, and #7 classified as medium since they fell within the central area of the ellipse (Figs. 2 and 3). Of the five headform size categories, medium was the most common, accounting for 51.5% of the population. There were relatively higher proportions of males in the long & narrow and large size categories and females in the short & wide and small size categories (see Table 6).

Table 6
Distribution of five Korean headform size categories

	Category	N			%		
		Male	Female	Total	Male	Female	Total
1	Long & Narrow	356	154	510	13.7	6.1	10.0
2	Large	588	22	610	22.6	0.9	11.9
3	Short & Wide	125	457	582	4.8	18.2	11.4
4	Small	80	497	577	3.1	19.8	11.3
5	Medium	1,350	1,282	2,632	51.8	51.2	51.5
Total		2,499	2,412	4,911	96.0	96.2	96.1

To generate representative three-dimensional headform shapes for the five Korean sizes (long & narrow, large, short & wide, small, and medium), the present study utilized the 3D shape information of 2,044 individuals measured at the 6th Size Korea survey. The 3D measurements were obtained without compressing the hair or head, resulting in slightly larger values compared to direct measurements. Although both direct measurements and 3D measurements were available in the present study, regression equations based on direct measurements to predict 3D measurements, as previously reported by [14], were not feasible due to the difference between the group-obtained direct measurements and those obtained from 3D measurements in the Size Korea surveys. Consequently, the 3D measurements were remapped to reflect the relative size of the manual measurements in the present study in the following manner. First, the sampled 3D measurements ($n = 2{,}044$) were standardized, and the PC1 and PC2 scores were calculated using factor loadings derived from direct measurements. Then, the classification algorithm was applied to the standardized PC score distribution of 3D measurements to identify five headform sizes. Lastly, a total of 25 representative 3D cases were selected from remapped 3D measurements. To select the representative cases of the five headform size categories, the centroid point was determined as the average of PC1 and PC2 scores of the standardized direct measurements for each headform size category. Then, for each headform size category, five 3D headform cases with the closest Euclidean distance to the corresponding centroid point were selected. All selected head shapes were within the range of ± 1 standard deviation of the average value of each headform size category (see Fig. 4).

2.5. Image processing of representative head forms

The average 3D headform shape in this study was generated by aligning a head template model developed by [23] with the shapes of five faces selected for each size category and adjusting the shape of the lips, ears, and neck. The procedure for generating the NIOSH

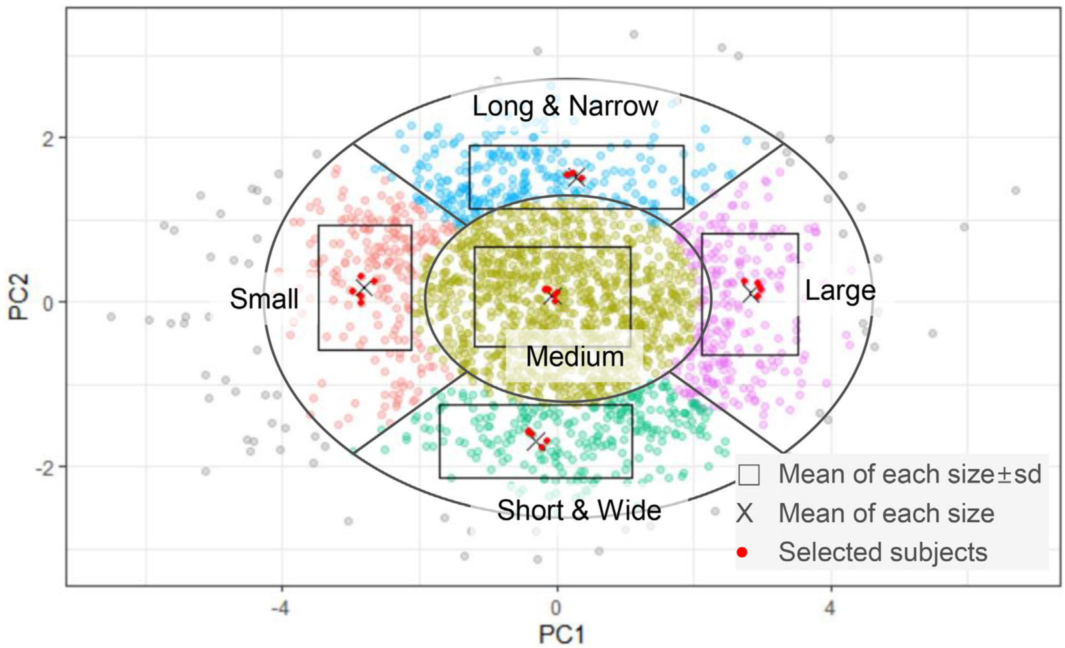

Fig. 4. PC score distribution of Korean 3D measurements (n = 2,044) using standardized scores of direct measurements of Korean headforms.

headforms shape by [14] served as a reference, and a five-step procedure (alignment of 3D heads, registration of the head template to the head scan, generation of an average head shape, modification of detailed eye, nose, and lip features, and generation of the final symmetric head) was followed to analyze the mean 3D headform shape. In the first step, 10 reference points on the faces were aligned to the global origin at the sellion, using the symmetry plane and Frankfurt plane to align the data of the five faces (Fig. 5-1). In the second step, the head template, consisting of 3,508 vertices and 6,974 faces, was aligned to each of the five selected face data for each size category using the Bounded Biharmonic Weights (BBW) algorithm [24] and the Iterative Closest Point (ICP) registration method [25]. The head template maintained the same mesh structure and was aligned to the face scan based on the position of the reference points on the face (Fig. 5-2). In the third step, the average shape of the aligned head template was obtained for each point on the individual face scan data (Fig. 5-3). In the fourth step, the smoothed shapes of the lips, nose, and eyes were adjusted to desired positions (e.g., vertex-lip height = 188 mm) and dimensions (e.g., lip width = 51 mm; menton-lip height = 41 mm) based on the size and shape of the face (Fig. 5-4). In the final step, the detailed shapes of the ears and neck were applied to the average headform shape, and the average face shape was symmetrically adjusted and corrected based on the median plane, resulting in a corrected headform shape overall (Fig. 5-5).

3. Results

Five 3D headforms (small, medium, large, long & narrow, and short & wide) representing Korean head shapes were created in the present study (Fig. 6). We measured the seven head dimensions of these five 3D headforms using the 3D software CLO (CLO Virtual Fashion, Republic of Korea), and compared them with the average 3D measurements of the Korean population. Table 7 presents a comparison of 3D head measurements for the five representative headforms and the average measurements of the corresponding PCA test panel groups.

Most of the measurements of the 3D headforms, except for head breadth in the long and narrow headform, fell within one standard deviation of the average value for each test panel group. These results indicate that the 3D headforms properly represent the characteristics of each Korean test group. Each headform exhibits distinct morphological characteristics. The small headform has a small head circumference, narrow head width, and short head length. The large headform has a large head circumference, wide head width, and long head length. The long & narrow headform has a medium head circumference, narrow head width, and long head length. The short & wide headform has a medium head circumference, wide head width, and short head length. Finally, the medium headform falls within the medium range for all the head dimensions.

4. Discussion

4.1. *Representativeness of Korean headforms*

This study is unique in that it included a wide age range of individuals, from 9 to 69 years old, and used data that reflected the population distribution ratios by gender and age of Koreans based on the Korean resident demographics [26] (see Table 8). Therefore, it is more representative of the Korean population compared to previous studies that may have only focused on specific age groups and/or regions. The previous headforms proposed by NIOSH were based on a dataset of adult workers aged 18 to 66 [22], which may have overrepresented male facial characteristics. In another headform development study targeting Koreans using the 6th Size Korea survey, which focused on Koreans aged 7 to 69 years old [7], there was an overrepresentation of the younger age group. The current study, however, used a dataset that reflects the gender and age distribution of Koreans, providing more representative data for the development of headforms for the Korean population.

We utilized the Size Korea dataset, covering the years from 2010 to 2015, to accumulate a significant volume of data. The measurement protocols of the Size Korea surveys align with corresponding ISO standards such as ISO 7250-1 [27], ISO 8559-1 [28], and ISO 20685-1 [29], guaranteeing both reliability and conformity to established measurement practices. However, despite its extensive scope and broad representativeness, the Size Korea dataset may

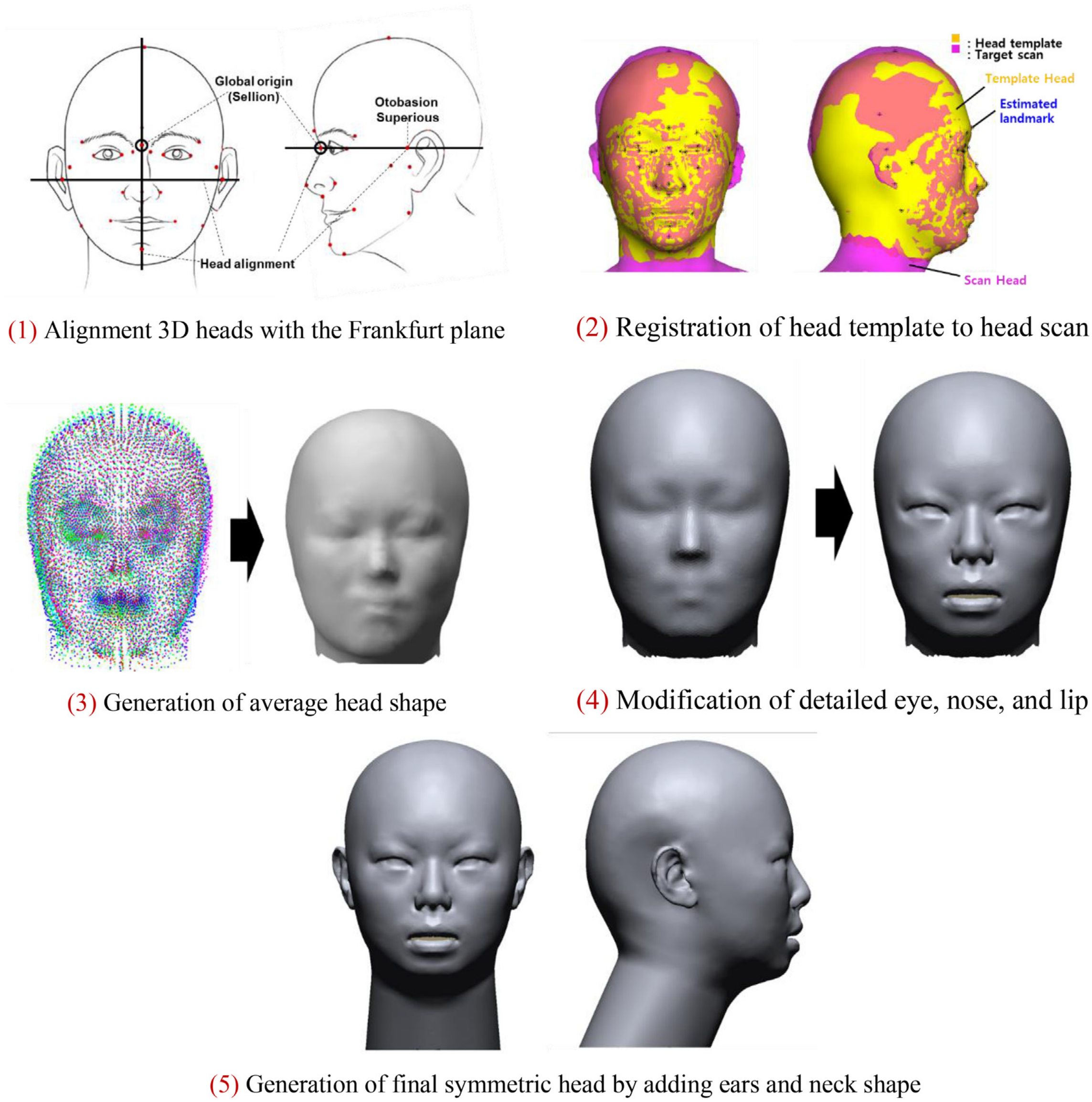

Fig. 5. Head shape generation process using a head template.

have inherent limitations, notably stemming from disparities among measurement devices and the skill levels of measurers.

When comparing the face width and face length of headforms from previous studies in the US, China, and Republic of Korea, the face width of the present study's population was found to be small and the face length was smaller than that of the US and slightly larger than that of China for the medium size category (Table 9). In comparison to the results of Seo et al [7] on Koreans, the face length of the headform of the present study was larger, while the face width was smaller, which may be due to the fact that the face width dimension data used in Seo et al [7] was based on 3D measurements and did not reflect the compression of the skin during measurement. Seo et al [7] study had a relatively high proportion of 7–19-year-olds in the study population, resulting in a very small face length for the small size category. Compared to the Chinese medium headform [17], the face length was slightly larger and the face width was smaller. When the Korean medium headform and the NIOSH medium headform for the US workforce were overlapped based on glabella (Fig. 7), the Korean headform appeared to have a larger face width and more prominent cheeks and cheekbones, but a flatter forehead, nose, and chin, suggesting that it reflects the flat facial characteristics of Koreans well compared to the NIOSH medium headform.

4.2. Headform sizes without alienating any specific age or gender group of Koreans

The headforms developed in this study are important for testing the TIL of FFRs on individuals of all ages, including children and adolescents who may be more vulnerable to infectious diseases. These headforms represent the population distribution of Koreans by gender and age and are especially suitable for testing FFRs on children under the age of 18 and female groups. This ensures that FFR TIL testing can be performed without excluding any specific group of Koreans.

The study found that among Koreans under the age of 18, 32.5% were in the small headform size, with a higher proportion of females (20.7%) than males (11.9%) (Fig. 8). This suggests that the small headform size is particularly important for representing the Korean population across all age and gender groups.

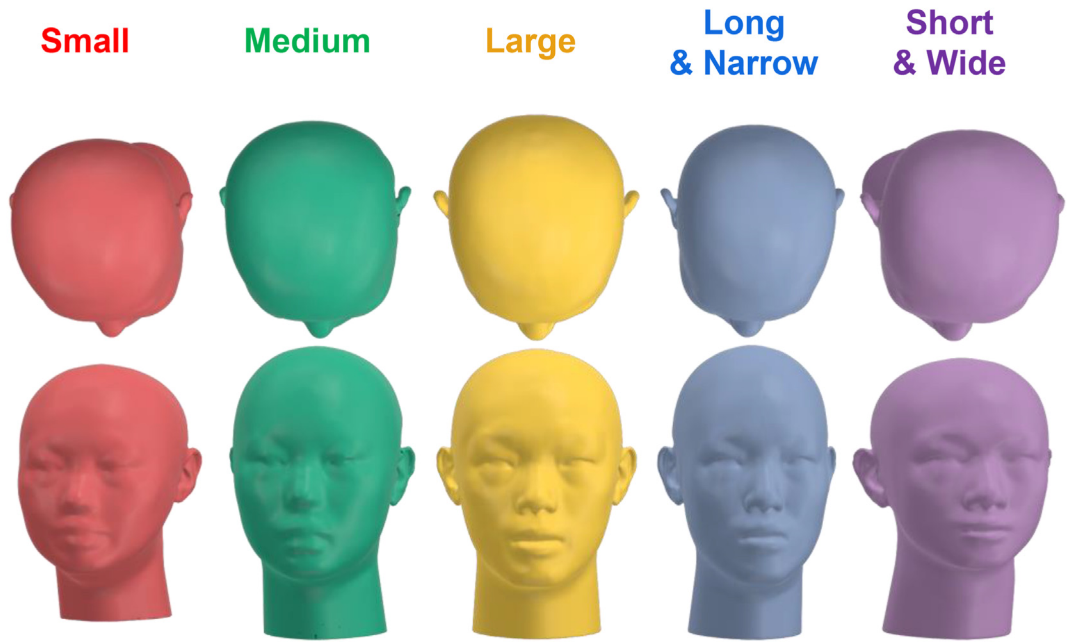

Fig. 6. Five 3D headforms representing five head size categories for Koreans aged 9 to 69 years.

Table 7
Summary of 3D head measurements for five representative headforms and average of corresponding group (n = 2,044; unit: mm)

Dimensions	Long & Narrow			Large			Short & Wide			Small			Medium		
	Head-form	Measurements		Head-form	Measurements		Head-form	Measurements		Head-form	Measurements		Head-form	Measurements	
		Mean	SD		Mean	SD		Mean	SD		Mean	SD		Mean	SD
Face Breadth	125.3	122.6	4.5	136.3	139.4	4.8	137.7	136.8	8.0	117.3	116.9	128.8	125.6	128.8	7.2
Bigonial Breadth	117.1	109.6	6.3	128.2	133.7	8.3	125.5	131.6	8.5	119.1	111.8	123.7	128.9	123.7	8.9
Face Length	117.1	114.8	5.6	115.4	118.5	6.8	100.9	106.6	8.2	100.1	104.9	112.4	109.4	112.4	7.6
Interpupillary Breadth	67.7	71.1	3.0	71.8	70.9	5.1	64.4	62.3	3.8	64.7	64.5	67.3	65.8	67.3	4.1
Head Breadth	149.0	155.0	5.8	165.6	169.2	6.5	163.7	162.9	6.8	155.0	149.1	159.6	161.6	159.6	7.2
Head Length	186.3	191.0	3.8	197.7	197.0	6.9	182.9	184.4	6.9	175.5	179.9	188.3	191.8	188.3	6.4
Head Circumference	545.2	558.7	2.9	593.5	584.2	15.4	563.8	572.2	20.9	534.1	537.0	558.9	573.1	558.9	14.7

Table 8
Comparison of population distributions by age category

The present study				NIOSH (2020)				Seo et al (2020)			
Age (year)	Male	Female	Total	Age (year)	Male	Female	Total	Age (year)	Male	Female	Total
9	0.6%	0.6%	1.1%					7–13	13.3%	13.6%	26.9%
10–19	5.7%	5.4%	11.1%					14–19	14.8%	13.4%	28.2%
20–29	8.3%	7.5%	15.8%	18–29	13.1%	12.1%	25.2%	20–39	9.3%	8.8%	18.1%
30–39	8.2%	7.7%	15.9%	30–44	26.1%	12.1%	38.2%				
40–49	9.8%	9.5%	19.3%					40–69	13.5%	13.3%	26.8%
50–59	10.2%	10.0%	20.2%	45–66	21.4%	15.2%	36.6%				
60–69	8.1%	8.5%	16.6%								
Total	50.9%	49.1%	100.0%	Total	60.6%	39.4%	100.0%	Total	50.8%	49.2%	100.0%

4.3. Overcoming the limitations of Size Korea data

In this study, the researchers employed a novel approach to choose representative individuals using 3D measurements, especially when the direct measurement group and the 3D measurement group differed. Facial tissue is pliable and can be distorted during direct measurement, often resulting in smaller measurements compared to 3D measurements. Zhuang et al [14] addressed this discrepancy by using regression equations to estimate direct measurements based on 3D measurements. However, this technique cannot be employed when the direct measurement group and the 3D measurement group are not the same. To overcome these limitations, the present study standardized and remapped the direct measurements and 3D measurements. Due to variations in measurement techniques, discrepancies existed in the measurement results between direct measurements and 3D measurements collected in the Korean surveys. Nevertheless, they standardized and aligned the statistical units of these two types of measurements, allowing the groups derived from direct measurements to be equally applied to 3D measurements.

Table 9
Comparison of face length and face width by headform size (unit: mm)

	Study	The present study	NIOSH (2015)	Seo et al (2020)	Yu et al (2012)
	Population (age range)	Korean citizens (9 to 69)	US workers (18 to 66)	Korean citizens (7 to 69)	Chinese workers (18 to 66)
Face Length	Small	108.3	110.0	90.6	108.0
	Medium	115.1	119.0	104.0	113.0
	Large	122.2	127.0	120.2	119.0
	Long & Narrow	119.6	127.0	—	122.0
	Short & Wide	109.3	112.0	—	107.0
Face Width	Small	128.3	128.0	127.1	135.0
	Medium	135.6	140.0	143.2	143.0
	Large	142.9	151.0	149.1	152.0
	Long & Narrow	132.1	140.0	—	143.0
	Short & Wide	139.8	141.0	—	145.0

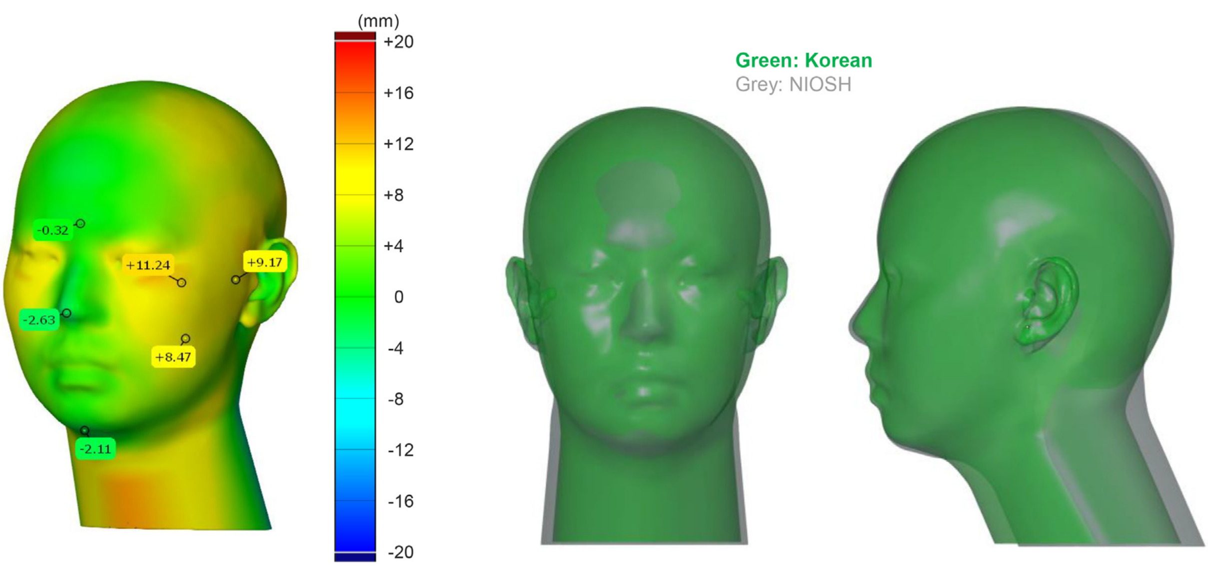

Fig. 7. Comparison of the NIOSH medium headform and Korean medium headform with the glabella in alignment.

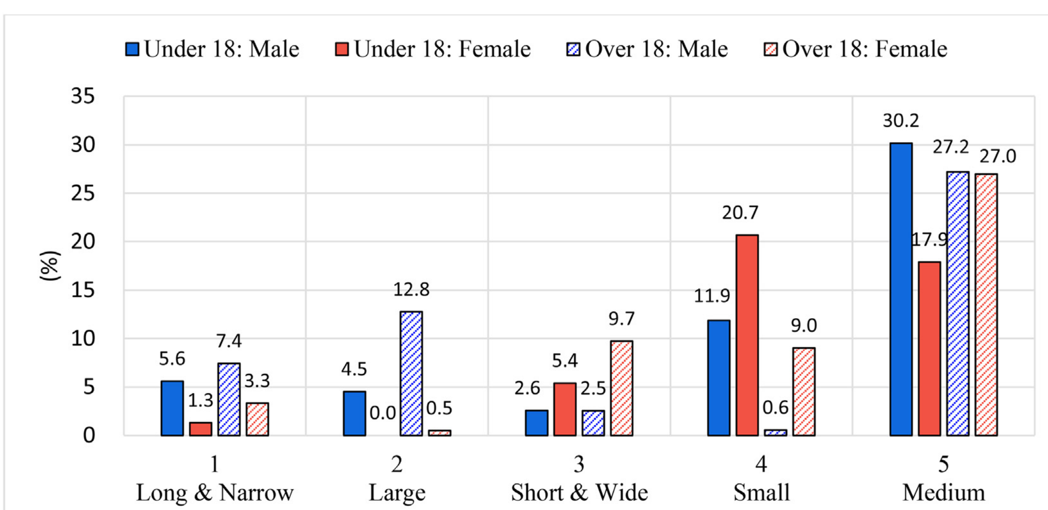

Fig. 8. Distribution of gender and age by headform size (n of under 18 = 464; n of over 18 = 4,447).

The direct measurements collected during the Size Korea surveys, which were used to establish the headform test panel, were limited in terms of the comprehensiveness of the head dimensions measured. Specifically, only five head dimensions (face breadth, bigonial breadth, face length, interpupillary breadth, and head breadth) out of the ten dimensions used in the NIOSH PCA test panel were measured. To overcome this limitation, two ergonomics experts and three apparel experts conducted a review and redefined the set of head dimensions, incorporating the five head dimensions used by NIOSH, and adding head length and head circumference. This set of seven head dimensions was considered appropriate for characterizing Korean head shapes for the purpose of TIL tests on FFRs.

5. Conclusion

In this study, a set of five representative headforms, reflecting the characteristics of Korean heads, was developed to test the performance of FFRs. The present study utilized analysis data from the Size Korea surveys, including direct measurements from 5,110 individuals and 3D measurements from 2,044 individuals, sampled based on the age and gender ratios of the Korean resident demographics, aged between 9 and 69 years. The seven head dimensions for the Korean PCA test panel were selected by considering the alignment with the dimensions in ISO 16976-2 [16], the availability of Size Korea measurements, and the relevance to the fit performance of FFRs. A PCA analysis with the head dimensions identified two primary factors explaining the variability of the head characteristics. The two principal components of the direct measurements were standardized and remapped to the 3D measurements to establish five size groups representing Korean head shapes: medium, small, large, short & wide, and long & narrow. Representative 3D head shapes were defined by averaging five cases for each size category. The significance of this study lies in its identification of the factors defining Korean head characteristics, the development of five representative head shapes that faithfully reflect these characteristics, and the inclusion of population ratios for children, adolescents, and females, which were often underestimated in the generation of headforms. The present study also introduces a novel methodology for using Size Korea data, despite its limitations in head dimensions and differences between direct and 3D measurements, in a scientific and pragmatic manner. The set of five representative Korean headforms developed in this research can be used to develop robotic headforms for TIL tests on FFRs. If the reliability and validity of the headform test can be confirmed by comparing the FFR wearing evaluation of the robotic headform to the actual human test panel evaluation results for the corresponding size, it will enable safer, more accurate, and more efficient testing in the future.

Conflicts of interest

All authors certify that they have NO affiliations with or involvement in any organization or entity with any financial interest (such as honoraria; educational grants; participation in speakers' bureaus; membership, employment, consultancies, stock ownership, or other equity interest; and expert testimony or patent-licensing arrangements), or non-financial interest (such as personal or professional relationships, affiliations, knowledge or beliefs) in the subject matter or materials discussed in this manuscript.

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