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Appendix B. Statement of Work

Purpose of Contract:

The purpose of this contract is to identify features of facial and/or respirator variation that influence respirator effectiveness using modern methods of biological shape analysis (morphometrics). Compare identified features to those obtained from traditional measurement protocols, and identify, if possible, simple and efficient derived measurements relevant to respirator fitting/efficacy.

Background and Needs:

Given an array of respirator styles and sizes, it is important to determine their fit and efficacy with respect to their intended user population and to quantify those facial features relevant to these parameters. Previous studies have focused on the association between linear and curvilinear facial dimensions and measures of respirator comfort and performance. In the field of anthropometrics, from which the facial measurements were borrowed, there has been considerable recent innovation in the quantification and statistical analysis of shapes based on the study of the Cartesian coordinates of the landmarks that usually serve as the basis for traditional measurement definitions. These new methods have proven more powerful and efficient than traditional approaches in many cases, and it is worthwhile to determine the extent to which they can advance the goal of respirator assessment. Such studies, in turn, could feed back into respirator design to achieve safer, more efficient product style and sizing.

DATA SOURCES: Existing data from which the proposed study is based include:

- respirator fit data for 12 respirators (four models in three sizes) for 30 subjects
- basic anthropometric data for subjects (sex, race/ethnicity, age, height, weight)
- traditional anthropometric measurements of facial form for subjects
- 3D laser scans for subjects' faces
- coordinates of anatomical landmarks for each subject
- an archive of laser surface scans for 1000 individuals with associated anthropometric data

RESEARCH: The assessment of respirator efficacy is fairly straightforward through the use of equipment such as the Portacount (TSI, INC.) device that measures the ratio of small particles inside and outside of a mask during operation. More challenging is identifying those aspects of morphological variation that are associated with the performance of a given array of respirators. The standard approach has been through the analysis of the correlation of traditional anthropometric measurements such as facial length, breadth, etc., with measures of respirator fit. In recent years, however, more powerful and efficient morphometric methods have been developed that are based on the analysis of superimposed sets of anatomical landmarks. The

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Cartesian coordinates of such data concisely encode all of the information from any traditional measurements that could be defined with respect to the same set of anatomical points. In theory, the use of these coordinate-based methods should provide the most comprehensive and powerful approach to relating variation in facial morphology to respirator performance, yet the assessment of these methods for this purpose has only just begun. The following is an outline of questions that are needed to be addressed to determine the overall utility of the landmark-based approach for the quantification of facial variation and its relationship to respirator performance.

I. Assessment of overall facial variability in the relevant population using the new methodology

II. Assessment of the relationship between traditional measurements and landmark-based results

III. Analysis of the association between respirator fit measures and landmark-based analysis

IV. Development of protocols for the identification of optimal landmark sampling strategies for the purpose of assessing morphological variation

V. Identification of areas of focus for respirator improvement based on results of IV

VI. Assessment of geometric features of respirator most relevant to performance in a given a target population

VII. The design of fitting protocols to achieve maximum respirator efficiency and comfort

VIII. Final report

Scope of Work:

The following paragraphs give more detail as to the requisite research.

I. Overall Facial Variability. To understand the important features of facial variability relevant to respirator performance it is first necessary to quantify and understand the patterns of variability in the targeted population. The traditional approach to this problem would be the multivariate analysis of limited sets linear and curvilinear distances, ratios, and/or angles. Such analysis has some significant limitations. For instance, a selected set of distances may not completely fix the relevant geometry of all of the anatomical features in question. If one focuses on, say, three anatomical points, then collecting distances between two pairs of these points fails to fix the angle at the common point or the distance between the two others. This is easily remedied when dealing with only three points (measure the third distance or the missing angle), but becomes prohibitively difficult as the number of points increases. New methods based on landmark coordinate analysis address this problem since all linear distances or angles that could be defined from that set of landmarks are encoded in the coordinates and can be recovered through simple trigonometry.

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The potential loss of information in traditional measurements is not necessarily random. For instance, facial length and breadth have been cited as important measures in determining respirator fit, yet different human populations differ significantly in facial projection (ortho/prognathism) that relates to differences in a dimension largely orthogonal to length and breadth. Failing to capture variation in this direction could be omitting important information.

It is therefore useful to undertake a comprehensive analysis of patterns of facial variation in the population relevant to respirator fit analysis. This would initially be done using the 30 subjects for which landmark data is currently available, but after preliminary analysis, would have to be extended to the entire population for which coordinate data could be obtained (the 1000 scans). Of particular importance in this extension is the full inclusion of different, relevant groups to assess important features of group differences. Females, for instance, have been shown to have significant sex-specific features of the facial skeleton that should translation into soft-tissue differences, as well. Similarly, different racial/ethnic groups are known to differ skeletally, and there are documented changes in facial morphology with age that could be relevant. Europeans, for instance, have a varied and unique nasal morphology, that could affect respirator fit, Dr. Slice and his coworkers have documented potentially serious limitations in the common designation "Hispanic" that fails to recognize the different biological backgrounds of Spanish-speaking populations – modern Cubans tend to be morphologically more similar to Europeans and Africans, while Mexicans have a strong physical resemblance to American Indian populations.

The standard protocol for this would be a combination of principal components analysis and multivariate analysis of variance (MANOVA/regression). These analyses would include newly proposed methods for the inclusion of size information in a morphometric analysis – Procrustes size-shape space analysis.

II. Traditional measurements vs. landmark-based analysis. There is a substantial literature relating variation and respirator fit to traditional distance measurements. The landmark-based approach provides a more powerful and comprehensive mode of analysis, but the results of the two methods need to be compared and contrasted. This portion of the study would quantify the additional information obtained from the landmark-based analysis by computing the residuals of the shape-coordinates from a regression onto the proposed traditional measurements.

III. Respirator fit and landmark analysis. Given an adequate characterization of facial variation quantified in the above analyses, an assessment would be made of the components of that variation relevant to respirator fit. This would be done via regression of shape-coordinate and ancillary anthropometric data onto respirator fit measures. The result would be a statistical summary and visualization of the components of facial variation most associated with respirator effectiveness. Also, the residuals from the landmark-traditional comparison would be assessed for significant association with the respirator fit data. A significant result here would indicate important information capture by the coordinate analysis missed by the traditional measurements.

IV. Optimal landmark sampling. The above analyses would use a reasonable set of anatomical landmarks borrowed from the general anthropometric literature. An important extension of this would be the optimization of these data sets to streamline future investigations by identifying minimal subsets of landmarks relevant to facial variation and/or respirator fit. For traditional data, this would be accomplished via a stepwise procedure wherein measurements would be added or subtracted in order of most/least associated variance until some stopping criterion is reached (no significant improvements in fit for variable addition, significant reduction in explanatory power in the case of variable elimination). Coordinate-based data will require modification of the standard procedures since the results of the superimposition of a set of landmarks are dependent upon the specific landmarks in that set. That is, changing landmark sets could change results.

In this case, the contractor would begin with the results of the complete complement of landmarks and then repeat the complete analyses (PCA or regression of respirator fit onto superimposed landmarks) with each landmark excluded. That landmark with the least impact on the results would be removed from the data set. This would then be repeated leaving out each individual retained landmarks, etc. until a substantial change in the results is noted after all individual landmark removals. Such a case would indicate no further reduction in the set of landmarks would be possible. Assessing the impact of a landmark on the analysis could involve graphical analysis of the results, but the determination of the exact criterion would be part of the research. In any case, the entire analysis beginning with the superimposition step will have to be repeated with each landmark removal. This process will be automated by the creation of new, general morphometric routines to carry out the analysis in existing morphometric programs.

V. Areas of focus for respirator improvement. Similarly, the above procedure would be modified as a step-wise regression to identify that subset of landmarks most relevant to respirator fit. All possible sets of a small number of landmarks would be tested after separate superimposition to identity that set with the most explanatory power. Additional landmarks would then be added using the same criterion until a (hopefully) reduced set of landmarks is identified that would best explain respirator performance.

Despite the theoretical advantages of landmark-based shape analysis, there are certain aspects of the particular problem of respirator fit that might suggest modified or alternative approaches. In the above scenario, subsets of landmarks must be refit at each stage of the analysis. A different type of analysis would be to use the landmark coordinates to generate a comprehensive list of interlandmark distances (which are invariant to superimposition) and use stepwise procedures to assemble an optimal subset of those distances. This is actually different from the traditional approach of predefining an initial set of distances, and would involve the comprehensive analysis of all possible distances derivable from the landmarks.

In both cases, examination of the resulting landmarks or distances could help localize areas of facial variability most relevant to respirator performance and possibly direct fitting procedures and future design considerations.

VI. Respirator mask/seal features relevant to performance. The complimentary question of which aspects of facial variability most influence respirator efficacy is: Given a target population, what aspects of respirator form most influence fit and performance? Previous investigations have used elliptical Fourier analysis (EFA) and radii of curvature to characterize the shape of the respirator seals. The resulting parameters could then be statistically related to actual respirator performance measures. Fourier methods are powerful ways to parameterize overall curve shape and statistically analysis curve differences, but they have limited ability to localize features contributing to any detected differences. That is, local features driving mask/seal shape differences or responsible for associations of mask/seal shape with measures of mask performance will be distributed across a broad spectrum of Fourier coefficients and not easily associated with specific regions of the mask/seal. On the other hand, the parameterization of radii of curvature, like traditional measurements, requires the *a priori* specification of important mask/seal regions for subsequent study.

This project would take advantage of the relatively new methods of sliding-landmark analysis to identify regions of the respirator seal where attention could be focused either in fitting procedures or enhanced design considerations. The basic idea is to initially position landmarks around the mask/seal curve according to some simple rule that minimizes the need for functionally homologous relationships across masks. That is, one may specify the first landmark to be at the superiormost point of the mask/seal midline, then record the coordinates of 10 or 100 subsequent points on each mask/seal positioned at intervals of 10 or 1% the length of the mask/seal curve. During the superimposition procedure, the landmarks (other than the first or any others designated as "fixed" or "non-sliding") will have their positions adjusted along the tangent of the curve to minimize one of several criteria suggested in the literature for sliding landmarks. In this way, the arbitrariness of the initial landmark positioning can be removed or reduced. The resulting coordinates can be regressed on respirator mask/seal performance measures and specific areas of the mask/seal that impact performance can be identified and the nature of the affecting variation (magnitude and direction) visualized. Of the two criteria suggested so far for landmark sliding optimization, Procrustes distance seems the most defensible since all other aspects of landmark superimposition are initially based on this criterion. The other criterion, Bending Energy (BE), is appropriate if the goal of the analysis is to generate interpretable thin-plate visualizations. Both methods will be compared and contrasted as part of this project, as will the number of landmarks required for analysis.

The basic methodology for this procedure is fairly well-known, but it has seen limited application in the analysis of 3D curves due to a scarcity of programs capable of such an analysis. Software currently under development by Dr. Slice will provide the first widely available software suitable for 3D sliding-landmark analysis and will be used in this project.

VII. Development of fitting and design protocols. Given a target population and range of respirator models, the above analyses will provide basic information on population variability in facial morphology and respirator design relevant to comfort and efficacy. In addition, though, these results could also be used to develop efficient fitting procedures and suggest design modifications that could enhance user comfort and safety.

The landmark/distance sets derived from Tasks 4 and 5 that optimally predict respirator function, comfort, or other relevant characteristics could suggest measurements on which to base a fitting procedure. That is to the extent possible given the study results, the contractor would provide explicit instructions of the form "Take measurement A and if it is in range R_a to R_b use mask model W in size Z" designed to maximize respirator effectiveness, but also comfort. The Contractor will summarize the relevant results and outline an appropriate fitting protocol if warranted by the outcome of this analysis.

Based on an assessment of these results and those of the analysis of respirator shape and deformation, the contractor would also provide recommendations on the regions and design aspects of the respirator to would most benefit from additional study and development. For instance, landmark analysis might suggest variation in the nasal region to be most important in respirator effectiveness (a likely result due to known human variation in this area). The manufacturer could then use this recommendation to redesign the respirator to more effectively accommodate population variation. Similarly, analysis of the mask morphology, itself, might reveal variation in efficacy associated with, say, the chin region, and this recommendation could be used by manufacturers to redesign the targeted area of the mask to reduce variability in this region. Note that these two results are not necessarily the same thing. Population variation could induce variation in mask performance even when mask morphology is static. Variation in mask morphology, as in the latter scenario, could also affect mask efficacy even in the face of no facial variation. Both aspects will be examined using the results of this study.

Most of the above procedures could be carried out using a combination of existing software tools. Others such as the identification of optimal landmark subsets and the analysis of respirator seals using sliding landmarks would require the development of new software tools. In some cases, the necessary tools are already under development for other purposes and could be brought to bear in the current research. In others, the work would require the development of new routines to be added to existing packages, and, in general, the incorporation of many of the more standard procedures into dedicated morphometric software would be a great benefit to future research in this area. There are no current plans for data acquisition (digitizing surface landmarks) or surface blending or manipulation, but this Java-based software would include the basic landmark-based analytical routines described above and would be modified to provide enhanced routines specific to this project.

VIII. Final Report. At the end of each task, a progress report shall be prepared to document the analytical methods used, summarize and describe the results of each task. The results of all of the above investigations will be assembled into a final report assessing the utility and additional benefits for landmark-based shape analysis, the patterns of facial variability in the population, and the aspects of that variability that most impinge upon respirator performance. Specific results as to what aspects of facial morphology or respirator design are most associated with respirator function will be presented, and suggestions for any suggested design changes and fitting protocols will be discussed.

PROJECT TIME TABLE

Tasks

I. Facial variability

II. Traditional (distances/angles) vs. Geometric (landmark coordinates) Morphometrics (GM)

III. Respirator fit = f(face shape) GM analysis

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IV. Optimal landmarks subsets

V. Analysis of all interlandmark distances

VI. Fit = f(respirator morphology)

VII. Fitting protocol based on above

VIII. Final report

	Month	I	II	III	IV	V	VI	VII	VIII	Progress Report
JUL	1	160								
AUG	2									1
SEP	3		80							
OCT	4			120						2/3
NOV	5	[redacted]								
DEC	6									
JAN	7				200					
FEB	8					120				4
MAR	9						160			5
APR	10									6
MAY	11							80		7
JUN	12								40	8