
Use of Speech Transmission Index (STI) for Voice Intelligibility Testing of Respiratory Protection Devices and Proposed Measurement Method

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ABSTRACT

Voice intelligibility of respiratory protection devices is a key metric of communication effectiveness. The Modified Rhyme Test is the current standard for measuring this key metric; the method is known to be cumbersome, time consuming, and subjective. The study being described evaluates the Speech Transmission Index method for use in measuring voice intelligibility of respiratory protection. The Speech Transmission Index is used in multiple industries to determine intelligibility and has been standardized by the International Electrotechnical Commission. In contrast to the Modified Rhyme Test, it is an objective test with a significantly reduced setup and test time. The study uses the Speech Transmission Index method developed by the National Fire Protection Agency for their 1981:2013 standard. Using three of Scott Safety's AV3000 facepieces, 313 data points were generated. The test operator and equipment remained the same throughout the testing. The operator was familiar with both Speech Transmission Index and donning respiratory protection facepieces. The repeatability and reproducibility of the National Fire Protection Agency method was evaluated by comparing the measurements gathered within and between test runs. It was found that within each test run an average of 70% of the measurements were equivalent with respect to the test system error. Between test runs it found that 90% of the sample populations were equivalent with respect to the test system error. Thus the method was found to be a robust way of objectively assessing voice intelligibility of the facepieces tested. However, it was noted that the National Fire Protection Agency method only assessed intelligibility directly in front of the user. To address practical usage scenarios a method is proposed using the Speech Transmission Index to assess voice intelligibility in 360 degrees around the user.

Keywords: Voice Intelligibility, Speech Transmission Index, Modified Rhyme Test

INTRODUCTION

Voice intelligibility is the degree to which a speech utterance, from a talker, can be correctly repeated by a listener. The measurement of this quality is desirable in many fields as it correlates to how well someone who is speaking can be understood by someone who is listening. This parameter is especially important in the field of respiratory protection as orders or directions are typically verbalized from one user to another. Thus agencies such as the National Institute for Occupational Safety and Health (NIOSH) and the National Fire Protection Agency (NFPA) have created standards to define voice intelligibility while wearing respiratory protection. Both NIOSH and NFPA have standardized on a Modified Rhyme Test (MRT). The former is standardized under 42 CFR part 84, subpart G, Section 84.63(a)(c)(d) and tested

per TEB-CBRN-APR-STP-0313 and the latter is standardized under NFPA 1981:2007 Edition Part 7.17 and tested per NFPA 1981:2007 Edition Part 8.25.

Rhyme tests were under development by the US military in the 1930's and 40's. Subsequent research by Fairbanks (1958) was published in the Journal of Acoustical Society of America. This research was ultimately used as a basis for formation of a standard under ANSI S3.2-1960, Method for Measurement of Monosyllabic Word Intelligibility. The Modified Rhyme Test is currently standardized under part 8.3 of ANSI S3.2-1960. The MRT is a basic word level test using monosyllabic words typically of the consonant-vowel-consonant (CVC) sequence. It is human subject based, requiring a speaker/talker and a group of listener subjects. The speaker/talker verbalizes the test word to the listener group. The Listener group is to either choose the correct response from a list or write/type their response dependant on which test standard is being administered. The test words may be spoken live, with the speaker/talker present or from a previously recorded audio track. The method is usually carried out in a quiet room with a defined level of background noise present.

Though there has been much study and refinement of rhyme tests, the various methods do have several drawbacks. The most significant detraction is the subjective nature of the test. Since the method uses human subjects, they must be carefully chosen such that their speech and/or hearing characteristics do not significantly influence the outcome of the test. The ANSI standard requires that all listener subjects have audiometrically normal hearing and that speakers/talkers must not have any regional accents and be verbalizing in their native language. Furthermore, to ensure consistency of the speaker/talker, training may be required to ensure that speech levels, interstimulus intervals, and cadence remain constant as well as ensuring that enunciation is proper. Listeners should be tested to ensure that their hearing is normal and in compliance with ANSI S3.2 section 5.3, before being accepted as a test subject. Besides limiting the subject pool, ensuring these pre-testing measures are met is time consuming. This adds to the resources that are required to properly complete this type of testing. With Modified Rhyme Testing, each test can take up to 15 minutes to complete. Completing a test cycle with enough data to make statistically significant conclusions can take several days. Another potential drawback is the limited diagnostic ability of the MRT. The data gathered from the test does not provide any information as to why the test was a pass or fail. This makes it hard for respiratory protection equipment designers to make improvements. As such, other potential test methods might be more desirable for the evaluation of voice intelligibility of respiratory protection devices.

In its most recent standards development cycle, the NFPA sought to improve the voice communications portion of NFPA 1981, Standard on Open-Circuit Self-Contained Breathing Apparatus (SCBA) for Emergency Services. The NFPA 1981 committee and communications task group sought to improve the quality of intelligibility of certified devices and develop a more repeatable, reproducible, and objective method with which to test the apparatus. As a result, in the 2013 Edition of NFPA 1981, respiratory protective full facepieces will now be subjected to Speech Transmission Index (STI) Testing in place of Modified Rhyme Testing required under the 2007 Edition.

The Speech Transmission Index (STI) method was developed by The Netherlands Organization (TNO) in the early 1970's with research performed by Houtgast & Steeneken (1971). This initial work eventually led to the formation of a standard for Speech Transmission Index testing by the International Electrotechnical Commission in 1988 under IEC 60268-16 Objective Rating of Speech Intelligibility by Speech Transmission Index. The STI method is an objective rating of the degradation of intelligibility of speech. The method is not subject-based, but instead, employs the use of a modulated speech-like test signal, microphone, and analysis system to evaluate the change in the test signal as it is delivered to the microphone. The design of the test signal is based on the concept that fluctuations in speech signals carry the most relevant information in speech intelligibility. The signal is comprised of seven octave bands from 125 Hz to 8 kHz. Each carrier is modulated with one or more modulation frequency at one-third octave intervals from 0.63 Hz to 12.5 Hz. Using the STI method, a modulation transfer function of the signal at the microphone's position describes the change in signal by the transmission path. From these

modulation transfer functions an STI score is calculated. The STI score is a relative measure of intelligibility ranging from 0 to 1, with 0 being completely unintelligible and 1 being completely intelligible. The STI method has been validated based on subject testing in several studies including those performed by Houtgast & Steeneken (1984) and later Anderson & Kalb (1987).

The STI method provides an objective method for testing speech intelligibility with several distinct advantages over MRT methods. The first advantage, by eliminating the need for a human subject pool, the STI method removes subjectivity introduced by these human factors. Secondly, because it eliminates the need for any human subject, all testing to ensure proper hearing and training of the speaker/talker is no longer required. Subsequently, this eliminates time required for the proper pre-screening of subjects as well as the resource required to employ the subjects for the duration of testing. Thus, the time savings using the STI method can be significant. The STI method used by the NFPA, the Speech Transmission Index Public Address (STIPA) variant, requires only 15 seconds per test. Since the test time is significantly shortened, it allows for an increase in test replicates, which in turn, allows for statistical evaluation of the results. The STI test results are more directly comparable and repeatable; STI eliminates factors such as variation in listener ability, speaker and/or speaker training that can, in turn, introduce significant error into the MRT method. These human factors can make direct comparison of testing performed with different listeners and speaker/talkers difficult. As a final advantage, the STI method allows for apparatus diagnosis based on the test results. A skilled technician can examine the modulation transfer indices and octave band sound pressure levels to make determinations as to why the apparatus under test achieved its score. This allows for recommendations to be made to improve the intelligibility of the apparatus under test through careful experimentation and design revision.

METHODS

The current study utilized the method developed for the NFPA 1981 Standard, 2013 Edition. The method uses the Speech Transmission Index Public Address (STIPA) variant which is simplified by omitting uncorrelated modulations required for interpretation of non-linear distortions. These types of non-linear distortion abnormalities are highly unlikely to be found in respiratory protection testing. The STIPA variant uses only two modulation frequencies, for a total of 14 modulation functions, as opposed to the full STI test that uses 14 modulation frequencies resulting in 98 modulation functions. This allows for a reduced measurement time of 15 seconds while only marginally increasing the error of the test system from 0.02 (using the full STI method) to 0.03 (using the STIPA variant).

The testing is performed in a hemi-anechoic chamber with the test equipment arranged as shown in the schematic, Figure 1, and picture, Figure 2. The method uses a Knowles Electronic Manikin for Acoustic Research (KEMAR) with a mouth simulator manufactured by G.R.A.S. Facepieces are donned on the mannequin in the orientation they would be worn by a user. The STIPA signal is emitted through the mouth simulator port of the mannequin. The signal passes through the transmission path, in this case consisting of the facepiece apparatus and air, to the microphone position. Background noise is introduced from a speaker directly beneath the microphone in the form of pink noise which further degrades the signal as it is transmitted to the microphone position. The background noise creates an artificial noise floor as the STI method inherently assumes a non-infinite signal to noise ratio and may overestimate intelligibility as the signal to noise ratio becomes increasingly large. The signal collected by the microphone is used to calculate the modulation transfer functions of each modulated frequency. From the modulation functions an STI score for the facepiece under test can be determined. A full list of equipment used for testing can be found in Appendix B.

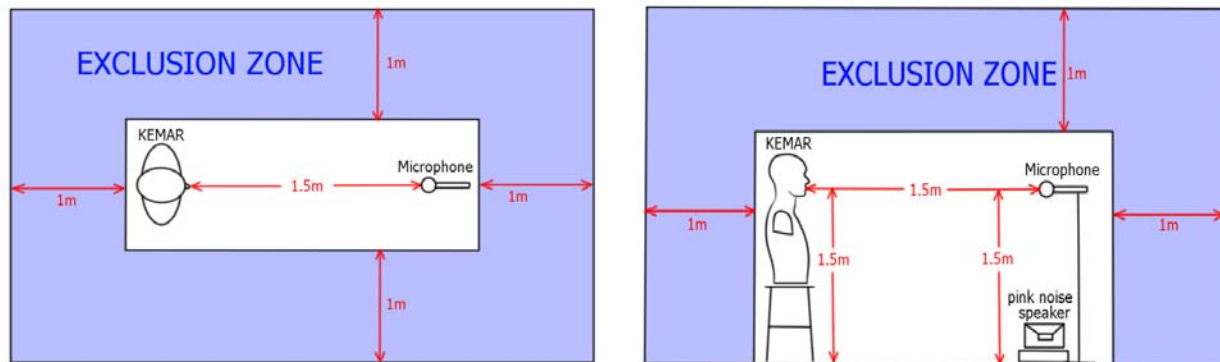


Figure 1. STI Setup Schematic Ref NFPA 1981 (Source: National Fire Protection Agency (NFPA). Standard 1981. Standard on Open-Circuit Self-Contained Breathing Apparatus (SCBA) for Emergency Services. 2013 Edition).



Figure 2. STI Setup (Photograph).

The NFPA requires that a total of three facepieces of the same model be tested. Testing is performed on the 'medium' facepiece which is donned on the mannequin five times, with three measurements taken during each donning. This results in a total of 45 measurements for each model under test.

The setup as described by the NFPA standard allows for little variation, thus the setup is nearly independent of operator. However, the effect of donning the facepiece on the manikin by the operator could add variation. This variation could significantly affect the repeatability and reproducibility of the test results. As such, for this study, only one operator experienced in donning respiratory protection facepieces was used throughout all test runs.

Testing for the current study was performed on Scott Safety's AV-3000 Full Facepiece with SureSeal (model 805773-85) equipped with the E-Z Flo Regulator (model 084370-02) and an EPIC voice amplifier (model 200260-01). Three individual facepieces labeled 1A, 2A, and 3A were used for testing while the second stage regulator and communication device were the same for all tests. The facepieces were tested to the Non-Electronic Communications Performance Test of the NFPA 1981 Draft Standard, Edition 2013 per part 8.10. The amplifier was mounted on the facepiece but in the 'off' condition. Seven

different test runs were conducted. Between each test run the system setup was completely dismantled and reassembled, with the exception of test runs 2 and 3 where the setup was only partially disassembled. This extensive testing collected 313 individual test measurements. These measurements allowed for assessing the repeatability and reproducibility of the NFPA standard. It also allowed for assessment using STIPA for respiratory protection voice intelligibility in general.

RESULTS AND DISCUSSION

Analysis of NFPA method results were performed using Minitab 16 statistical analysis software. It should also be noted that two data points were missing, one from facepiece 2A test run 5 and one from facepiece 3A test run 5. To complete and balance the data set these two measurements were filled by randomly sampling the data from facepiece 2A test run 5 and facepiece 3A test run 5 respectively.

The results for the NFPA method were examined by first calculating basic statistics on the overall measurement sample. The repeatability of the measurements was assessed by comparing the standard deviations of the facepiece samples within each individual test run. By comparing the standard deviations of a particular facepiece within a test run to the accepted STIPA error of 0.03, the percentage of measurements that fell within the error tolerance of the STIPA test were determined. Measurements that fell within the STIPA error tolerance were accepted as equivalent data as there was no way to determine whether the deviation in measurements was caused by the test system error or some other factor. The reproducibility of the measurements was assessed by comparing individual facepiece means between all of the test runs using an analysis of variance (ANOVA). By comparing the facepiece data between test runs with respect to the sample mean, standard deviation, and test system error, the percentage of test runs that could be considered equivalent was determined. Sample means with 95% confidence intervals that fell within the accepted test error were accepted as equivalent samples as there is no way to determine whether the deviation in means was caused by the test system error or other factors.

The overall sample population results are shown in Figure 3 with respect to a standard normal distribution. The data is centrally peaked and evenly distributed on either side of the mean with a very slight skew of 0.066. The kurtosis of 0.80 indicates that the peak is sharper than a standard normal distribution. The sharper peak may be partly caused by the rounding of the STI score to two significant digits as required by the STI standard.

Next, the standard deviation within each test run was examined for each facepiece sample. As previously mentioned, each facepiece test run consisted of 45 total measurements. Table 1 shows the mean and standard deviation for each facepiece and test run combination. Using the standard error tolerance of the STIPA method per the IEC standard of 0.03 and assuming that the error tolerance could be applied in a normal distribution around the mean of the sample, the number standard deviations within the error tolerance was calculated. Also assuming that the sample populations follow a standard normal distribution, the percentage of measurements represented by the number of standard deviations within the error tolerance were calculated as well and are also shown in Table I. The percentage of measurements that fell within the error tolerance ranged from 47% to 88% with a pooled average of 73% for all facepiece samples between all seven test runs. Therefore, on average (pooled) 73% of the measurements within a test run were considered equivalent. It should also be noted that because the overall sample population was more sharply peaked than a standard normal distribution (kurtosis = 0.80) the actual percentages that fell within the error tolerance would be slightly higher. This assumes the samples would follow a similar distribution to the larger overall sample population. The distribution of measurements that did not fall within the error tolerance of the test setup could potentially be attributed to variations in donning of the facepiece (among other factors).

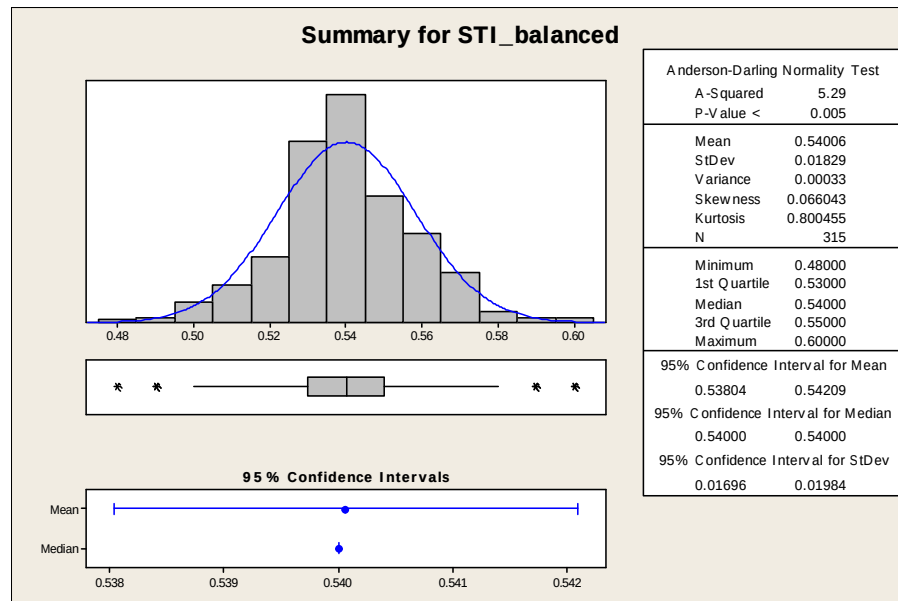


Figure 3. Overall Population Data Statistical Summary.

Table I. Percent of Measurements within Error Tolerance

Facepiece	Test Run	Mean	St Dev	% Within Error Tolerance
1A	1	0.538	0.014	72.5
1A	2	0.555	0.012	77.1
1A	3	0.535	0.012	77.1
1A	4	0.514	0.018	59.4
1A	5	0.553	0.017	61.7
1A	6	0.540	0.012	79.1
1A	7	0.531	0.014	72.1
2A	1	0.535	0.024	47.0
2A	2	0.567	0.014	71.7
2A	3	0.536	0.012	77.3
2A	4	0.519	0.013	75.9
2A	5	0.553	0.012	78.0
2A	6	0.544	0.016	65.3
2A	7	0.539	0.015	68.7
3A	1	0.547	0.018	60.8
3A	2	0.550	0.013	76.9
3A	3	0.537	0.010	84.8
3A	4	0.533	0.010	88.1
3A	5	0.549	0.012	79.4
3A	6	0.543	0.011	82.7
3A	7	0.525	0.011	84.3

An analysis of variance (ANOVA) at a 95% confidence level was performed between the test runs by facepiece sample. For each facepiece sample, the ANOVA indicated that there were statistically significant differences between each test run. The P value was 0.00 for all 1A, 2A, and 3A facepieces (full ANOVA analysis is found in Appendix A). However, the practical difference between the test runs was not as significant. If the 0.03 error of the STI method is considered, the difference between means becomes less significant. Figures 4A through 4C show the 95% confidence intervals for the means of the facepiece samples between all test runs. Marked on each plot is the pooled mean for the facepiece and the error tolerance of 0.03 for the STI method distributed evenly about the mean.

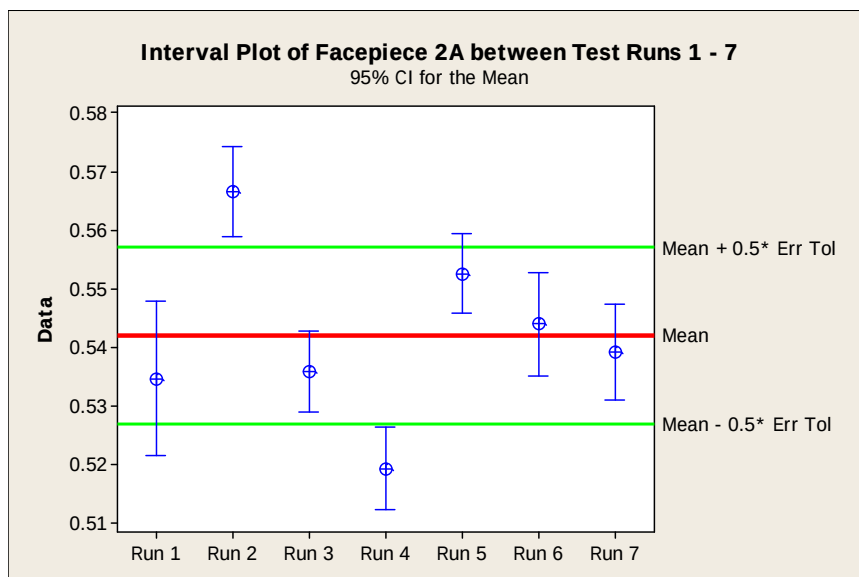


Figure 4A. 95% Confidence Interval for the Mean for Facepiece 1A.

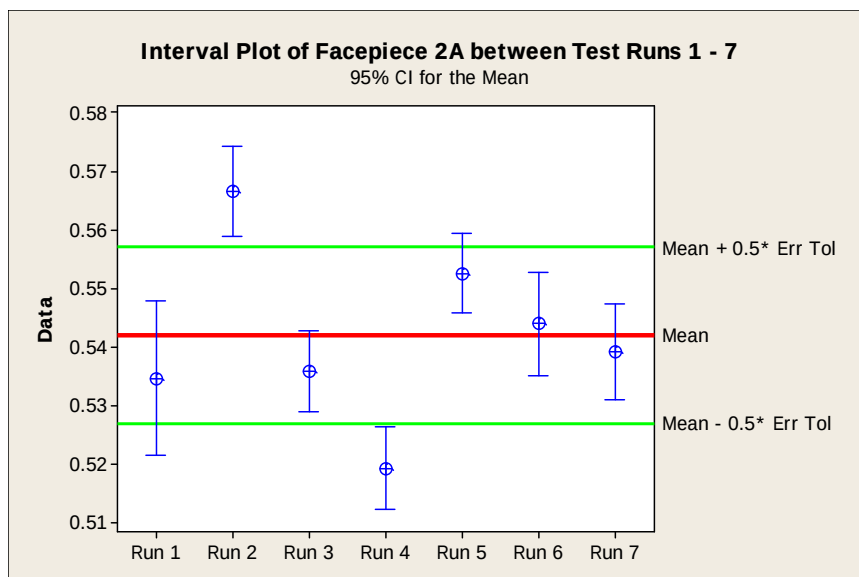


Figure 4B. 95% Confidence Interval for the Mean for Facepiece 2A.

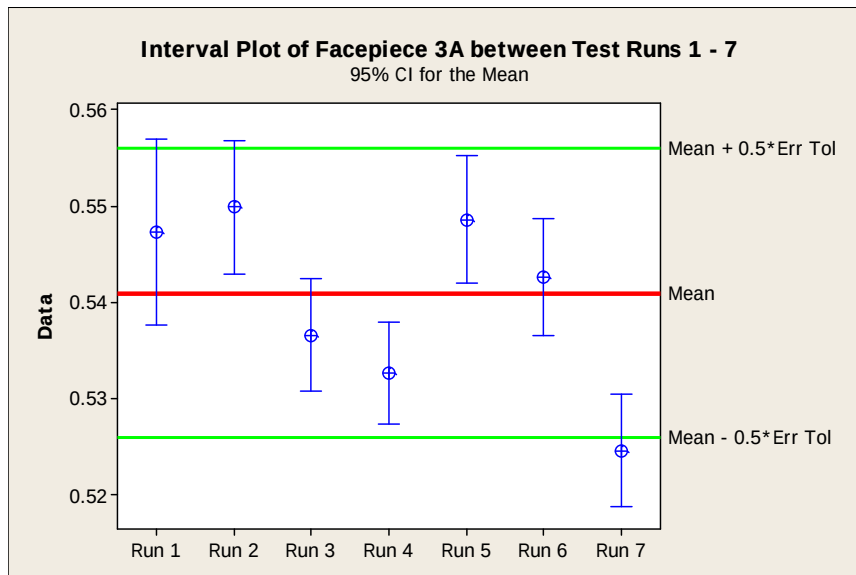


Figure 4C. 95% Confidence Interval for the Mean for Facepiece 3A.

From Figures 4A through 4C, it is seen that the 95% confidence intervals for the means of each test run for facepiece 1A fell within the error tolerance of the STI test. Similarly for facepiece 3A, all confidence intervals fell within the error tolerance. Facepiece 2A had two test run sample populations that fell outside of the error tolerance, test runs 2 and 4 respectively. Therefore, test runs 2 and 4 for facepiece 2A were considered practically different from other test runs. Out of 21 test runs, only 2 sample populations effectively differed from the others with respect to the test system error. As such, just over 90% of the test runs per facepiece were considered equivalent.

Proposed Measurement Method: Voice Intelligibility Profile

The standard test procedure developed by the NFPA using the STIPA provides a robust method for testing voice intelligibility of respiratory protective devices. However, this method only addresses intelligibility directly in front of the speaker on the sagittal plane of the body. In practical usage it is a likely scenario that a speaker or respiratory protective device user would address a large group which cannot all be directly in front of him or her. Also, it is not uncommon to speak to someone without directly facing them, for example, walking side by side. Furthermore, there may be situations where it is not possible or probable to directly face someone when addressing them such as in a confined space scenario. Thus, it may be desirable to measure intelligibility from multiple locations around the speaker to understand how intelligibility is affected by orientation. A potential method for testing this is further described using the STI method as a basis. The data presented in this section is used only to illustrate the proposed method; no conclusions are drawn from the data.

The proposed method builds on the NFPA standard and creates a common methodology for categorizing the voice intelligibility of respiratory protection devices, in general, by building an intelligibility profile around the speaker. This was achieved by rotating the test manikin about the sagittal-coronal axis in 45 degree increments as shown in Figure 5. The data generated could be displayed on a radar graph as shown in Figure 6 so that the user can visualize the results. The facepieces shown in the graph labeled Mask A, B, and C respectively and represent distinctly different facepiece designs to be compared for intelligibility profile.

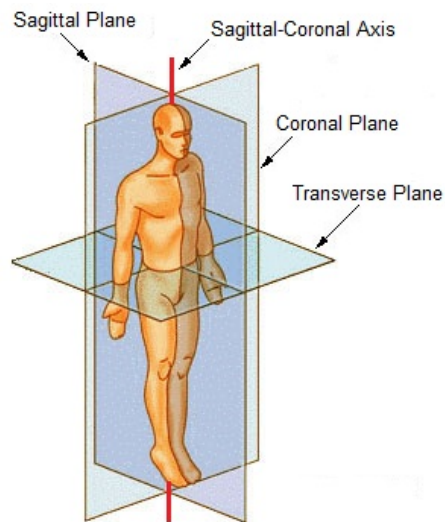


Figure 5 – Body Planes.

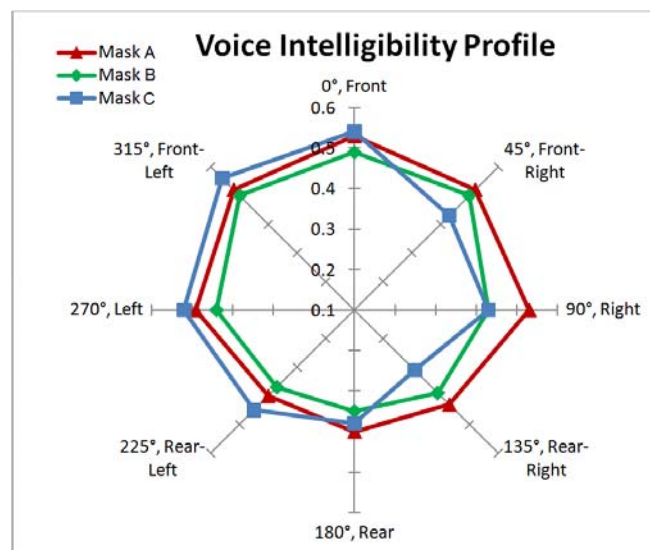


Figure 6 – Voice Intelligibility Profile Radar Graph.

Using only the radar graph visual the different facepiece designs can be difficult to compare. This makes it difficult to ascertain which facepiece provides the 'best' intelligibility profile. To determine which facepiece provides the 'best' intelligibility profile a weighted average can be calculated for easier comparison. To calculate a weighted average, weighting factors are assigned to each angular direction and a single Voice Intelligibility Profile (VIP) score is calculated as in Equation 1. The VIP score can be used in combination with the radar graph visual to fully describe the voice intelligibility of the facepiece. For purposes of direct comparison between facepieces, the VIP score can be used to determine a 'best in class' rating in terms of overall voice intelligibility.

$$V.I.P. = \frac{1}{n} \sum_{\alpha=1}^n STI_{\alpha} * WF_{\alpha} \quad (1)$$

Where:

STI_{α} is the average STI score at the given Angle / Direction

WF_{α} is the weighting factor assigned to the given Angle / Direction

Note that the STI_{α} parameter should be an average of at least three subsequent STI measurements of any angle/direction. A minimum of three measurements should be taken due to the systematic error of the STI method. If it is desired to perform multiple donnings of the facepiece for each direction, it would be necessary to take the compiled average of all measurements and donnings for that angle/direction.

The weighting factor, WF_{α} , would be determined based on the usage case of the facepiece. For example, in industries where the user has ease of mobility, it might make sense to place more emphasis on the frontal/anterior direction as it would be easier for the user to face those they are addressing. In such an industry, higher weighting factors would be assigned to the frontal/anterior direction or simply use only a frontal measurement. In industries where users do not have as much mobility (are required to be in various positions, address large groups, not able to address someone directly), it might be advantageous to more evenly distribute the weighting factors about the angles/directions.

CONCLUSIONS

The STIPA method developed under NFPA Standard 1981:2013 Edition provides some significant advantages over the previous MRT method. The STI method significantly reduces the time needed to complete each individual test. It also reduces the test setup time by eliminating the need to qualify a human subject pool. By reducing the test and setup time the method allows for less burdensome collection of data that is sufficient for statistical analysis. It also provides respiratory protection designers with some useful data regarding the performance of the test that can be used to improve future designs. Furthermore, the method provides highly repeatable measurements as assessed by comparing the measurement distributions to the error tolerance of the test method. This study found, on average, greater than 70% of the measurements using the same facepiece donned by the same operator within a test run were equivalent as they fell within the error tolerance of the test method. The NFPA STI method also provides a highly reproducible test setup across multiple test runs when using the same test equipment and operator. This study found that greater than 90% of the sample populations were equivalent between test runs as indicated by the means falling with the STI method error tolerance. The NFPA voice intelligibility standard could be further improved by testing intelligibility in a profile around the wearer as opposed to only the frontal direction. The VIP method described provides a basis for measuring intelligibility in 360 degrees around the user, however further research is required to refine the method.

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Appendix A. Minitab 16 ANOVA Analysis

One-way ANOVA: Run 1_1A, Run 2_1A, Run 3_1A, Run 4_1A, Run 5_1A, Run 6_1A, ...

Source	DF	SS	MS	F	P
Factor	6	0.017307	0.002884	13.87	0.000
Error	98	0.020373	0.000208		
Total	104	0.037680			

S = 0.01442 R-Sq = 45.93% R-Sq(adj) = 42.62%

Individual 95% CIs For Mean Based on Pooled StDev

Level	N	Mean	StDev
Run 1_1A	15	0.53800	0.01373
Run 2_1A	15	0.55467	0.01246
Run 3_1A	15	0.53533	0.01246
Run 4_1A	15	0.51400	0.01805
Run 5_1A	15	0.55333	0.01718
Run 6_1A	15	0.54000	0.01195
Run 7_1A	15	0.53067	0.01387

0.510 0.525 0.540 0.555

Pooled StDev = 0.01442

One-way ANOVA: Run 1_2A, Run 2_2A, Run 3_2A, Run 4_2A, Run 5_2A, Run 6_2A, ...

Source	DF	SS	MS	F	P
Factor	6	0.020050	0.003342	13.70	0.000
Error	98	0.023907	0.000244		
Total	104	0.043956			

S = 0.01562 R-Sq = 45.61% R-Sq(adj) = 42.28%

Level	N	Mean	StDev
Run 1_2A	15	0.53467	0.02386
Run 2_2A	15	0.56667	0.01397
Run 3_2A	15	0.53600	0.01242
Run 4_2A	15	0.51933	0.01280
Run 5_2A	15	0.55267	0.01223
Run 6_2A	15	0.54400	0.01595
Run 7_2A	15	0.53933	0.01486

Individual 95% CIs For Mean Based on Pooled StDev

Level	N	Mean	StDev
Run 1_2A	15	0.53467	0.02386
Run 2_2A	15	0.56667	0.01397
Run 3_2A	15	0.53600	0.01242
Run 4_2A	15	0.51933	0.01280
Run 5_2A	15	0.55267	0.01223
Run 6_2A	15	0.54400	0.01595
Run 7_2A	15	0.53933	0.01486

0.512 0.528 0.544 0.560

Pooled StDev = 0.01562

Source	DF	SS	MS	F	P
Factor	6	0.008025	0.001337	9.00	0.000
Error	98	0.014560	0.000149		
Total	104	0.022585			

Level	N	Mean	StDev	Individual 95% CIs For Mean Based on Pooled StDev
Run 1_3A	15	0.54733	0.01751	(-----*-----)
Run 2_3A	15	0.55000	0.01254	(-----*-----)
Run 3_3A	15	0.53667	0.01047	(-----*-----)
Run 4_3A	15	0.53267	0.00961	(-----*-----)
Run 5_3A	15	0.54867	0.01187	(-----*-----)
Run 6_3A	15	0.54267	0.01100	(-----*-----)
Run 7_3A	15	0.52467	0.01060	(-----*-----)

Pooled StDev = 0.01219

APPENDIX B. Test Equipment List

Description: Sound Analyzer

Manufacturer: NTI Audio AG – Schaan, Liechtenstein

Model: Acoustilyzer AL1 600 000 080

Description: Pink Noise Generator

Manufacturer: NTI Audio AG – Schaan, Liechtenstein

Model: Minirator MR-PRO 600 000 310

Description: Microphone

Manufacturer: NTI Audio AG – Schaan, Liechtenstein

Model: MiniSPL 600 000 022

Description: Test Manikin

Manufacturer: GRAS – Holte, Denmark

Model: K.E.M.A.R. 45BM

Description: Graphic Equalizer

Manufacturer: Behringer – Willich, Germany

Model: DEQ2496

Description: Pink Noise Speaker

Manufacturer: Fostex – Gardena California

Model: 6301B