4-1-2023

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Keywords: Manikin, Real Ear Measurement, Simulation, Clinical Training, Task-Trainer

Abbreviations:

CARL	Clinical Assistant for Research and Learning
dB	Decibel
RECD	Real Ear to Coupler Difference
REUR	Real Ear Unaided Response
REM	Real Ear Measures
wRECD	Wideband Real Ear to Coupler Difference
SPL	Sound Pressure Level

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Word Count: 4276

Abstract

Objective: Simulation-based learning experiences provide low-risk opportunities for procedural training and practice in audiology. A series of real ear measurements (REM) were completed using Clinical Assistant for Research and Learning (CARL) manikins to determine expected responses and to compare to normative data.

Design: (1) Real-ear Unaided Response (REUR) curves were measured with one CARL and each of three ear styles. (2) Test/retest reliability was evaluated by repeating each REUR. (3) Real ear to coupler difference (RECD) values for foam-tip and custom earmolds were calculated. (4) The reliability across copies of the CARL heads was evaluated by comparing REUR measurement from one set of ears on 4 heads.

Study Sample: Four adult CARL manikins and thirty ears (5 sets of large, small, and bent).

Results: Within each ear category, the average difference across frequencies from one ear to the next was less than 2.5 dB with no significant individual difference more than 5.8 dB. Test/retest reliability was excellent. Typical REUR and RECD curves were created for each ear style and compared to published data on human ears.

Conclusions: REM using the adult CARL head are predictable and repeatable making this simulator a good tool for audiological training.

Introduction

Simulators are used to train audiology students and new clinicians on procedures that would otherwise require volunteers or patients. They are a viable means for low risk-of-harm independent procedural practice (Brown, 2017; Dudding et al., 2019; Koch et al., 2020) both systematic reviews and measures of student opinion and self-reported competency support the use of simulated learning in audiology education (Alanazi et al., 2020; Dzulkarnain et al., 2015; Wilson et al., 2020). One such simulator, the Clinical Assistant for Research and Learning (CARL) from AHead Simulations (Figure 1) was shown to increase novice clinician confidence and procedure accuracy for probe tube placement and foam tip insertion (Koch et al., 2020). In its original iteration, this manikin-based simulator, now commercially available as Camera-CARL, consisted of silicone ears from a 3D printed ear model with a software-based optical tracking system which attached to a 3D printed head. Recent enhancements to the CARL manikin include: (1) opaque ears in several skin tones and without a camera; and (2) several different interchangeable ear shapes and sizes that include adult small, adult large, and adult bent ear canal configurations. These options provide the opportunity for novice clinicians to use the CARL manikin as a task-trainer (Lioce et al., 2020, Dudding et al., 2019) and practice a variety of clinical skills including impression taking, cerumen management, hearing aid insertion and removal, and hearing aid verification with probe-tube microphone measures (AHead Simulations, 2021; Scollie & Koch, 2019).

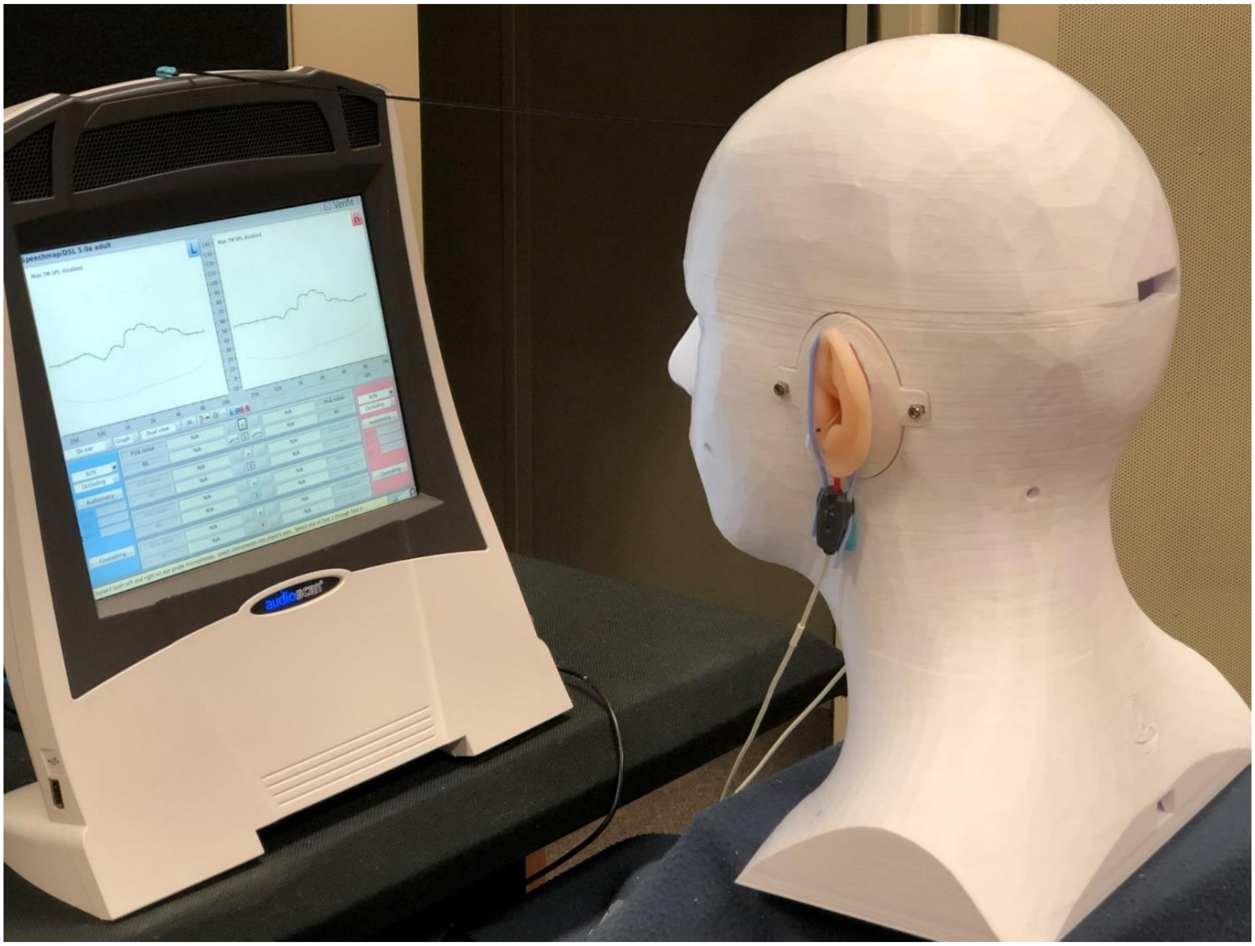

Figure 1: Instrumentation and set-up for the real ear measures with a CARL manikin

Preferred practice guidelines in the field of audiology recommended the use of probe-tube microphone measurement for the verification of gain and frequency response during hearing aid fitting (American Academy of Audiology, 2006; CASLPO, 2016). Despite this, clinical uptake of the procedure continues to be low (2-40%) (Leavitt et al., 2017; Mueller, 2015; Mueller & Picou, 2010), with possible higher uptake by pediatric audiologists (Moodie et al., 2016b) Factors related to low uptake of probe-tube microphone verification include cost of real ear equipment, appointment time constraints, over-confidence in manufacturers' derived first-fit, as well as lack of training and clinician confidence (Palmer, 2009; Zitelli et al., 2021). Training and clinician confidence can be addressed directly via task training with patient simulators.

Simulators are particularly useful for procedures that carry risk of harm/discomfort for volunteers or patients. They can be used to practice repeatedly until the necessary skill is acquired, particularly when a manikin form factor is used to provide a life-like representation of the relevant anatomy, and training activities break down the task into steps (Dudding et al., 2019). This may be particularly relevant to hearing aid verification, because high hearing aid output levels prevent practice with many hearing aid fittings with classmate volunteers who have normal hearing. This can limit the amount of experience an in-training clinician has with probe-tube microphone verification and on-ear fine tuning and troubleshooting before entering clinic. Simulation-based learning experiences that mimic real life allow students to hone key clinical skills, gain confidence, and learn from any mistakes made without any harm done to patients and clients (Alanazi et al., 2016; Andre et al., 2021; Brown, 2017; Dudding et al., 2019; Dzulkarnain et al., 2015). Due to Covid-19, with stricter infection control guidelines requiring students to follow social distancing measures, training programs must implement novel ways to provide quality clinical education (Whitelaw, 2020). Patient simulation tools, in combination with coursework and practica, are therefore set to play a more vital role in ensuring these essential hands-on skills are effectively mastered before graduation (Volkers, 2020) and can be used for “patient-free" comprehensive examinations and patient contact hours (Andre et al., 2021).

For a patient simulator to be an effective training tool, it should be evaluated to determine whether it provides consistent and useful simulation. The CARL manikin ears were created based on CT scans of actual human ears, and designed to mimic the physical shape and texture of external ears. The acoustic properties of the different ears, and the consistency of these properties, have not previously received formal evaluation. Potential variations created in the manufacturing process (3D printing tolerances, multiple molds per ear style, silicone lot variation, etc.) could lead to variations in ear canal acoustics between copies of the ears. The ears themselves can be moved between CARL manikin heads, and the acoustic variability between manikin copies is also unknown. Probe-tube microphone measurement can also be affected by user errors such as equipment set-up inaccuracies and shallow probe tube insertion depth, so knowing the consistency of acoustic properties of an ear simulator and manikin may aid instructors in knowing whether trainee measurement variability is the result of error or ear variation. This is particularly relevant for instructors who have multiple manikin stations set up in a classroom, and who therefore rely upon consistency across multiple ears and manikins of the same style. Similarly, knowledge of typical ear canal measures for simulated ears can help with planning instructional and/or evaluative course activities. With these needs in mind, the purposes of this study were to: (1) measure the Real Ear Unaided Response (REUR) across ear styles to determine average responses and equivalency within each style; (2) evaluate the test/retest reliability of REUR measures made on the CARL ears in comparison to typical test-retest performance on human ears; (3) evaluate between-head test-retest variability of REUR measures; (4) measure average REUR and both foam-tip and earmold Real Ear to Coupler Differences (RECDs) for each ear style; and (5) compare the measured REUR and RECD values to typical data from human ears.

***Methods and Materials**:*

CARL Heads and Ears

Four adult-sized CARL heads and thirty ears were used in this study. All were obtained from AHead Simulations (Cambridge, ON) and were made of opaque material. Three styles of ears are available for the adult CARL manikin - large, small, and bent, and may be installed and exchanged on the same head. Five pairs each of large, small, and bent ears were used in this study. The ear style was stamped or marked on the back of each ear by the manufacturer. Numbers were also written on the back of each ear to track repeated copies of the same ear. Neither the ear style nor number was visible during data collection, as they are concealed inside the manikin head once installed.

Participants: Real ear measurements were retrospectively extracted from participant records from previous studies. These included: (1) Individual REURs using pink noise at 65 dB SPL from twenty adult participants (10 male and 10 female, ages 25-81) (Folkeard et al., 2019); (2) Individual foam-tip RECDs from forty adult participants (22 male and 18 female, ages 24-78) (data not previously reported); and (3) Individual earmold RECDs from eighteen adult participants (13 males and 5 females, ages 37-85) and fourteen pediatric participants (7 males and 7 females, ages 24 to 127 months) (Moodie, et al., 2016a). All real ear measurements were completed using Audioscan Verifit equipment and followed the manufacturer's recommended procedures, including placing the end of the probe tube within 5 mm of the tympanic membrane using otoscopy and the visually assisted positioning method (ANSI 3.46,2013). ER3A foam inserts were used for the foam-tip RECDs and were inserted so that the outside edge of the foam eartip was flush with the entrance to the ear canal and was given time to expand to acoustically seal the ear to reduce low-frequency leakage. This technique is visually depicted in equipment user guides, practice guidelines (Patel, 2021) and textbook chapters (Dabrowski, 2015). All studies were conducted at the National Centre for Audiology with approval by the Human Research Ethics Board of Western University.

Procedures for Typical Values and Between-Ear Variability

Ear Canal Volume

Ear canal volume measurements were made for each of the five pairs of CARL ears to quantify differences in the volumes of each ear style. A GSI-Tympstar middle ear analyzer with a 13 mm blue disposable tip was used to provide this estimate of ear canal size between CARL ear styles. Because CARL ears are not designed to simulate the impedance of the middle ear system, other elements of immittance measurement were discarded. The impedance probe was inserted into the ear and the volume measure was recorded for each ear. The probe was then removed, and the procedure was repeated a second time.

Real Ear Unaided Response Measures

All probe-tube measurement testing with the CARL manikins were completed using an Audioscan VF2 (Software 4.18.1), which was located in a carpeted, quiet room and calibrated daily during the project. Instrumentation is pictured in Figure 1 and was held consistent across the project with the use of floor markings to indicate correct positioning. CARL rested on a table with a box which was covered with a felt blanket. CARL was placed 15 cm from the VF2 screen/loudspeaker and a plumbline was used to verify distance from the speaker. Putty was used to affix the probe modules to CARL’s neck. Each set of ears was tested using two new probe tubes which were marked at 30 mm for the small and the bent ears and 31 mm for the large ears. After inserting the probe tube so that the marker was located at CARL’s inter-tragal notch, the probe tube was not moved or adjusted until after the measurement was completed.

The REURs were measured using a 65 dB SPL pink noise. By operating the system with a wireless mouse, the tester stayed more than 1.25 metres from the sound field while the REUR measurements were taken. For retest measures, the probe was removed from the ear and the probe module was removed from the pinna, and re-installed in the ear. For between-ear measurements, the order of ears tested was counterbalanced across pairs. For between-head measurements, one set of ears was chosen at random (Bent 3). These ears were installed in four different CARL heads. The session files from the Audioscan VF2 were saved and the data were extracted for analysis.

Real Ear to Coupler Difference measures

In conjunction with the REUR measurements, wideband Real Ear to Coupler Differences (wRECD) were also measured, once with ER3A foam-tip (yellow adult) and using custom earmolds. A new foam-tip was used at the beginning of each ear-type measurement. Custom earmolds were fabricated for each ear-type using an ear impression taken from just one copy of each ear style. The large and bent earmolds were made of soft materials in a full shell with no vent. The small earmold was an acrylic skeleton earmold with the vent plugged medially. The variation in the style, material, and venting of the earmolds used represents some degree of the variation seen within clinical populations where RECDs would be measured, and no attempt was made to standardize the earmolds across ear-types. Similarly, there were small variations (< 2mm difference) in canal lengths between the left and right ear within each ear-type (left 16 mm, right 18 mm; bent left 19 mm, right 21 mm; large left 20 mm, right 21 mm).

Troubleshooting for the wRECD was completed in a manner consistent with clinical practice recommendations (Bagatto, 2001). While making the wRECD measures, the foam-tip was adjusted to remove leakage if observed, and the probe was reinserted if the marker moved or was pinched during insertion of either the foam-tip or earmold. The session files from the Audioscan VF2 were saved and the data were extracted for analysis and the wRECDs were converted to use an HA-1 coupler reference (ANSI S3.46, 2013).

Results

Ear Canal Volume

For each of the three ear styles (large, small, bent), the test and retest measurements were recorded and the mean and standard deviation per style and side were calculated (mL): large right (M=2.5, sd=.17); large left (M=2.4, sd=.21); small right (M=1.1, sd=.12); small left (M=1.1 sd=.19); bent right (M=2.4, sd=.12); bent left (M=2.3, sd=.16). Left and right ear combined per style results were also calculated: large (M=2.5, sd .19); small (M=1.1, sd=.16); bent (M=2.4, sd=.14).

Acoustic Ear Equivalence per Ear Type

For each of the three ear styles (large, small, bent), the mean and standard deviation REUR values per audiometric frequency from 250-10,000 Hz were calculated from one measure of each of the 5 pairs within each of the ear-styles and are presented in Table 1.

<Insert Table 1>

To evaluate the REURs between styles, a repeated-measures ANOVA was completed using SPSS v24 (IBM Corporation, Chicago, IL). The analysis used *frequency* as the within-subjects variable and *style* and *ear* as between-subject variables. A Greenhouse-Geisser epsilon was used to adjust the degrees of freedom for non-sphericity in the data. Post-hoc analyses were completed using Bonferroni corrections for multiple comparisons. As expected, there was an overall effect of frequency because the REUR varies with test frequency as shown in Figure 2 [F (5.346, 128.301) = 2076.174, p <.001, η^2 = .989]. There was a significant difference between ears (F (1, 24) = 121.112, p <.001, η^2 = .835) and by ear style [F (2, 24) = 12.850, p <.001, η^2 = .517]. There were also significant interactions between *frequency* and *ear* [F (5.346, 128.301) = 10.879, p <.001, η^2 = .312], *frequency* and *style* [F (10.692, 128.301) = 109.749, p <.001, η^2 = .989], as well as a three-way interaction between *frequency, ear* and *style* [F (10.692, 128.301) = 3.601, p <.001, η^2 = .231]. For each of the three styles, there was a significant overall difference between the left and the right ears (p = <.001). Because per frequency differences are important in audiological measurements, additional post hoc paired comparisons of the left and right ears were completed with Bonferroni corrections. Results showed significant left/right ear differences in output at 62 of 73 frequencies with 6 of those frequencies having a difference exceeding 3 dB. Pairwise comparisons between styles per frequency were also completed. When comparing the large and the small ears, 21 frequencies between 2120 and 11,800 Hz were more than 3 dB different with a maximum difference of 6.54 dB at 3550 Hz. When comparing the large and the bent ears, 17 frequencies had a difference >3 dB in the range of 1400-4000 Hz with maximum difference of 10.5 dB at 2240 Hz. When comparing the small and the bent ears, 24 frequencies had differences exceeding 3 dB with a maximum difference of 14.6 dB at 2380 Hz.

The differences in REUR response between ear styles can be seen in Figure 2. For comparison, a mean adult REUR (n=40 ears) measured using the same stimulus, room, and measurement equipment (Folkeard et al., 2019) is also plotted. The shaded area represents the 95% confidence interval for these data. Results show that the significant differences reported above are associated with unique peak frequencies for the REURs per style. For example, the small ear exhibited the highest peak frequency. However, all ear styles had mean REURs that fell within the adult REUR 95% confidence interval at most frequencies. The observed CARL REURs are less smooth than the mean REUR, but exhibit REUR-like properties including a peak resonant frequency in the 2000 to 4000 Hz range that varies across ear styles.

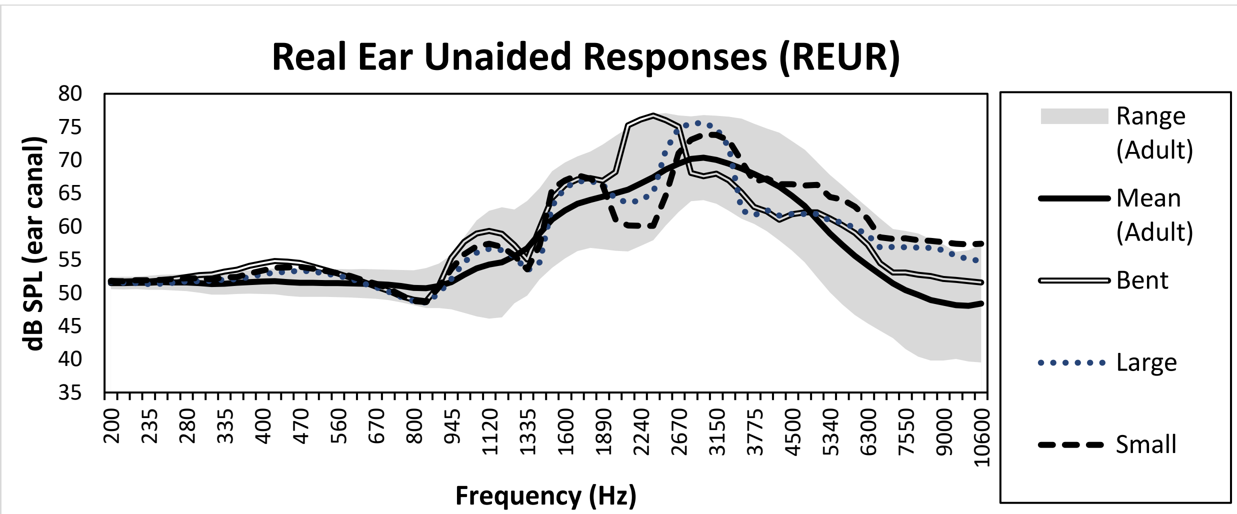

Figure 2: Average REURs obtained for each of the 3 styles of CARL ears (large, small, bent) and the mean and 95% confidence interval for the REUR from 40 adult ears using the same stimulus, level and equipment (Audioscan VF2).

To evaluate the consistency of the acoustic properties of ears within the same style, each ear (left or right) for each style (large, small, or bent) were compared with the other four ear copies within that side/style. The measured REURs across frequency, test-retest, and ear copy were submitted to reliability analysis using the Intraclass Correlation Coefficient (ICC) with a two-way mixed model, and absolute agreement form for single measures, following published recommendations (Koo & Li, 2016). *Retest* and *frequency* were set as raters, while *ear copy* was set as items within this analysis. The results indicate that copies of each ear provide excellent

(>0.90) acoustic agreement with one another across multiple ear copies and test repetitions as shown in Table 2.

<Insert Table 2>

Acoustic Equivalence across Heads

To examine the acoustic effects of using different CARL heads, one ear set was chosen at random (Bent 3) and installed on four different adult CARL heads, each made of the same material. The REURs were measured for the left and right ear on each head. For each frequency measured, the maximum difference between the REUR between CARL heads was calculated and results showed differences of ≤ 4.7 dB from 2800 and 3150 Hz and ≤ 2.7 dB at all other frequencies. The measured REURs across frequency, ear, and head were submitted to reliability analysis using the ICC method described above. *Ear* and *frequency* were set as raters, while *head copies* were items within this analysis. Results indicated excellent agreement between measures taken on different head copies (Cronbach's alpha - .998, ICC = 0.99, p<.001, range = 0.25 dB).

RECD

In order to evaluate the typical acoustic properties of the CARL ears in the occluded condition, RECDs using both foam-tip and custom earmold couplings were completed for each ear. The average RECD per side and style are shown in Table 3. Foam RECD values range between zero and 18 dB between the test frequencies of 500 and 4000 Hz, with between-ear style variation of up to 10 dB per frequency in this range. Between-coupling variation was also observed, with earmold RECDs more often exhibiting characteristically lower values in the 2000to 4000 Hz region that is related to the longer tubing associated with earmolds (Moodie et al., 2016a).

<Insert Table 3>

To compare the result of each of the CARL ears to the range of expected RECD values from human ears, the RECDs were plotted against the range of RECDs obtained from the adult and pediatric human ear data described above. The results indicate that the CARL RECDs generally fall within the expected range of adult RECDs (Figure 3). The small ear exhibited the largest RECD values for both earmold and foam-tip coupling, which is consistent with the known effects of ear volume on this measurement, as well as with the observed ear canal volume measures reported above. It appears that the small ear, which has the smallest measured ear canal volume, can be characterized as somewhat outside the range of adult RECDs, particularly in the frequencies above 4000 Hz with the earmold RECDs but does fall within the expected range for children's RECDs.

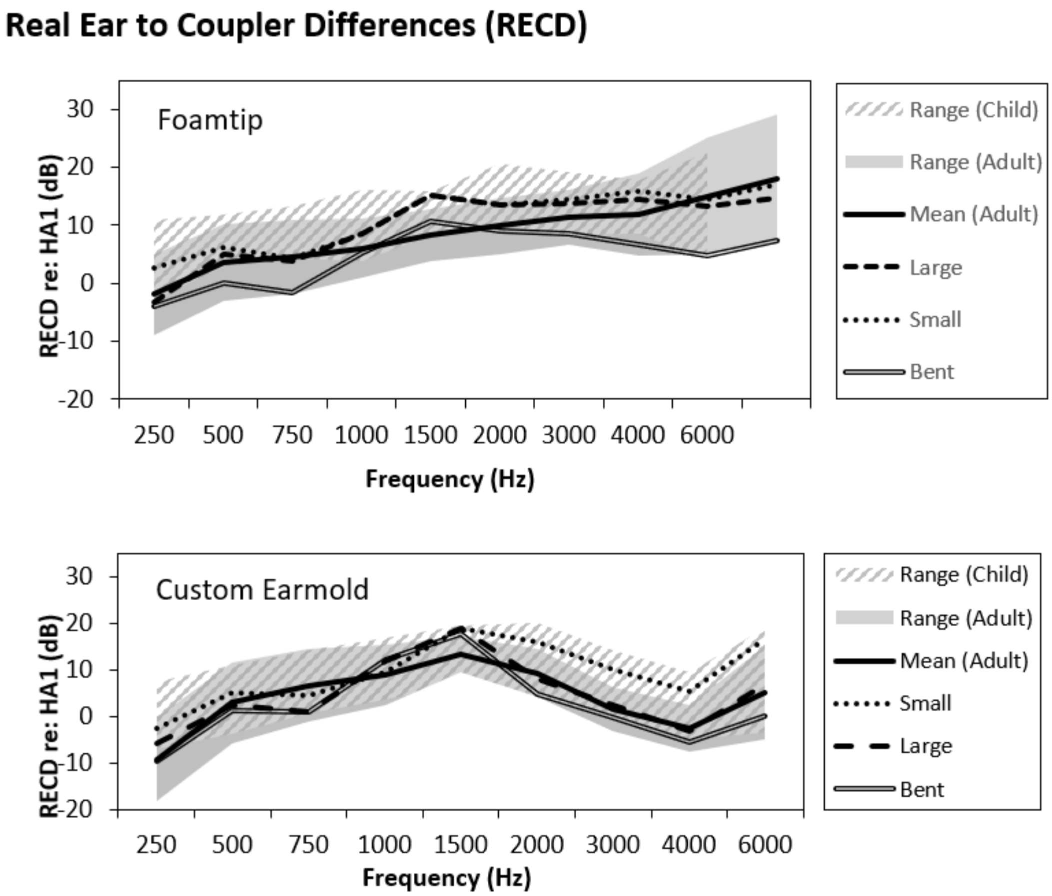

Figure 3: Average RECD for each of the ear styles using both (a) a foam-tip and (b) a custom earmold (left and right ear of each style averaged). Mean RECDs from a sample of adults and the 95% confidence interval from a sample of adults and a sample of children (ranges) are also indicated.

Discussion

Measurement of the canal volumes with the three CARL ear styles was feasible with a clinical immittance system. These values were collected as a means to characterize between-style ear canal volume differences, mainly to assist interpretation of between-ear acoustic differences. Ear canal volume results of the CARL large style (2.5 mL) and bent style ears (2.4 mL) fell only slightly above the normative range of 1.0-2.2 mL for males (>10 years and adults) reported by Hunter (2013). The volume of the small ears (1.1 mL) also fell within that range, as well as within the range of 0.8-1.9 mL for females (>10 years and adults) and within the range for children >18 months (0.6-1.22 mL). As such, the observed variability in ear canal volume between CARL ear styles spans a realistic range of between-patient ear canal volumes observed in clinical samples.

Real ear measurement of both the REUR and the RECD was also feasible with all three CARL ear styles and resulted in interpretable responses for both measurement types. Test/retest reliability was excellent (<2.5 dB averaged across 1/3 octave band centre frequencies from 250 through 8,000 Hz for the REUR) across both repeated measurements and multiple copies of the same ear and head. This observed reliability is similar to previously-reported reliability of similar measurements made in humans (Vaisberg et al., 2018, Vaisberg et al., 2016, Bestwood & Bamford 1992, Valente et al., 1991) and indicates that the CARL system provides repeatable results across multiple CARL manikins provided that the same ear style is used.

The REUR was measured across ear styles. Results indicated that measures differed by style, meaning that the small, large, and bent ear styles provide simulation of different patient ear acoustics for the purposes of real ear measurement. This result indicates that instructors using the CARL manikin for simulation can install multiple equivalent workstations for trainees that are equivalent in terms of ear acoustics by using multiple copies of the same ear, or workstations that vary in ear acoustics by using different ear styles, as desired.

The REURs for three CARL ear styles were descriptively compared to the REURs obtained from a group of adults with normal middle ear status (Folkeard et al., 2019) collected using the same

REM measurement equipment. The average CARL REUR fell within the 95% confidence range of adult REURs at most frequencies, varied with ear style, and generally exhibited an REUR-like prominent resonant peak in the mid- to high-frequencies. The CARL REUR was noted to have a less smooth response than is typical of human REURs, but nonetheless varies with ear anatomy and approximates the REUR characteristics of a human ear. Although the REUR differed somewhat from the average human REUR, each ear style provides a different REUR measurement as does each ear side, giving distinct cases that differ from one another. For teaching purposes, having CARL ears that are human-like but with reliable differences allows for easy identification of expected results, allowing instructors to rapidly note deviations in trainees' results.

RECDs were also measured for each of the ear styles for both foam-tip and earmold couplings to the three ear styles. As with the REUR, the RECD values varied across ear style, by up to approximately 10 dB across ear styles. They also varied with foam-tip versus earmold coupling to the ear, with specific variation that was consistent with the expected differences for these two coupling types. This variation between the ear styles provides representation of clinical variation between ear anatomies across ages and ear sizes. Specifically, the large and bent ear styles provide simulation of typical adult ear acoustics, while the small ear style approximates a child's ear acoustics, or perhaps that of a small adult ear given the overlap between human RECD ranges observed in adults and children. Although not evaluated in this project, an infant-sized manikin (BabyCARL) uses much smaller ear sizes within the infant range, and may therefore provide a fourth relevant anatomy. With these between-ear and between-coupling differences, the measured RECDs differ sufficiently that the ear styles may be used to represent different patients, both typical and atypical, for the purposes of training simulation. The feasibility of manufacturing custom earmolds for the CARL manikin ears is also relevant to the use of the manikin in simulation of hearing aid fittings.

REUR and RECD values can be measured with accuracy and consistency across ears within the different ear styles and should be taking into consideration when using this simulator for more advanced real ear measurement protocols such as hearing aid fittings. There are many advantages of patient simulators which allow for in-training clinicians to practice without risk of harm, repeat procedures until comfortable and become proficient at the skills required clinical practice (Brown, 2017). Manikin-based simulation provides many opportunities for the delivery of audiology education and, along with tele-practice and computerized platforms for virtual audiology, can be instrumental for competency training. Simulation has provided important opportunities for skill practice during disruptions to hands-on training because of Covid-19 (Volkers, 2020; Whitelaw, 2020) and will continue to do so to support the growing needs of audiology graduate programs (Dubbing et al., 2019).

Conclusion

The purpose of this study was to evaluate the measurement consistency and repeatability within each of the three types of ears that are available for the adult CARL, to determine the average foam-tip and earmold wRECD for each ear and to determine if measures completed on different CARL heads from the same generation were consistent. With this knowledge, instructors and trainees should be able to replicate the measurements for REUR and RECD, and have confidence in setting up multiple equivalent task trainers when teaching competencies in real ear measurement. Further, CARL ears of different types produced unique ear canal acoustics that may facilitate implementation of different test cases for use in simulation education.

Limitations

The authors acknowledge that all testing was completed in one lab with one real ear measurement system. There is a potential for variation, especially in open ear measures such as the REUR depending on room acoustics and nearby reflective surfaces.

Funding.

Funding for this project was provided through a grant from the Ontario Centres of Excellence. The authors take responsibility for the content and writing of this paper.

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Evaluation of CARL manikin for REM

REUR

	250 Hz	500 Hz	750 Hz	1000 Hz	1500 Hz	2000 Hz	3000 Hz	4000 Hz	6000 Hz	8000 Hz	10,000 Hz
Large Ears											
Left mean	51.8	53.8	49.6	55.7	63.7	64.9	76.9	63.7	59.5	56.7	56.1
Left SD	0.3	0.6	1.2	0.4	1.5	1.2	1.6	1.4	1.0	0.9	0.6
Right mean	50.9	52.7	49.2	53.6	62.5	63.4	74.3	61.2	60.1	57.0	54.1
Right SD	0.5	0.8	0.9	0.6	1.8	0.9	1.7	1.4	1.6	1.1	0.7
Small Ears											
Left mean	52.4	54.2	49.8	57.0	66.2	62.1	74.5	67.7	62.6	59.4	59.8
Left SD	0.2	0.3	0.3	0.3	1.2	1.1	1.3	0.9	1.3	0.6	1.0
Right mean	51.5	53.1	49.6	54.7	65.1	60.0	73.2	66.8	63.5	56.5	54.9
Right SD	0.2	0.4	0.2	0.6	1.2	1.0	1.5	1.2	1.5	0.8	1.2
Bent Ears											
Left mean	52.5	54.7	50.0	58.5	65.2	69.8	68.6	64.2	60.2	53.7	53.7
Left SD	0.3	0.6	0.5	0.8	0.3	0.7	0.9	0.5	1.2	1.0	1.0
Right mean	51.2	53.3	48.9	56.9	63.3	66.6	66.5	60.3	57.9	51.8	49.8
Right SD	0.3	0.6	0.6	0.3	1.0	1.2	0.4	0.8	0.8	1.6	1.0

Table 1: REUR values for the audiometric frequencies for the left and right ears in each of the three ear styles (large, small, bent). Values were calculated using one measure of each of the 5 pairs within each ear style.

Ear	Side	ICC	P	Cronbach's alpha	Range of between-ear differences (dB)
Large	Right	.982	<.001	.999	2.5
	Left	.984	<.001	.999	2.3
Small	Right	.987	<.001	.999	1.9
	Left	.990	<.001	.999	1.5
Bent	Right	.989	<.001	.999	1.3
	Left	.993	<.001	1.00	1.4

Table 2: Intraclass Correlation Coefficient analysis results for consistency of the acoustic properties of the three styles of CARL ears (large, small, bent), together with the range of between-ear differences, averaged across 1/3 octave band centre frequencies from 250 through 8000 Hz.

Evaluation of CARL manikin for REM

HA-1 RECD

Foam-tip

	250 Hz	500 Hz	750 Hz	1000 Hz	1500 Hz	2000 Hz	3000 Hz	4000 Hz	6000 Hz	8000 Hz
Large Ears										
Left mean	-3	5	4	7	15	14	14	14	13	13
Left SD	3.0	1.7	1.5	.4	1.1	.9	.6	.9	.5	2.2
Right mean	-5	4	4	7	15	14	14	14	15	16
Right SD	3.1	1.4	2.8	1.5	1.9	2.1	2.3	3.0	3.1	2.5
Small Ears										
Left mean	3	7	6	8	16	14	15	18	15	17
Left SD	1.5	1.1	1.2	.6	1.1	.3	.4	.4	.5	1.1
Right mean	1	5	4	7	15	14	14	16	15	16
Right SD	1.5	1.0	.8	1.1	1.0	1.0	.8	1.0	.8	1.4
Bent Ears										
Left mean	-3	1	-1	6	11	9	9	8	5	9
Left SD	1.8	.8	.6	.6	.9	.9	1.1	1.9	2.2	1.1
Right mean	-5	0	-2	5	11	9	8	6	5	6
Right SD	2.8	1.1	1.1	.8	1.5	1.5	1.7	2.8	2.7	1.1

HA-1 RECD

Earmold

Large Ears										
Left mean	-3	3	2	13	19	8	3	-1	7	18
Left SD	1.0	.3	.5	.5	.4	1.1	.8	1.0	2.1	2.9

Right mean	-9	2	0	11	18	8	2	-5	7	16
Right SD	3.7	1.8	.6	1.0	1.2	1.1	.9	1.2	1.3	1.9
Small Ears										
Left mean	0	5	5	9	19	18	12	7	19	22
Left SD	1.2	.5	.9	.4	.9	.9	.4	.8	1.0	1.8
Right mean	-5	5	5	10	19	14	9	4	14	18
Right SD	4.6	1.5	1.1	.6	.4	1.8	1.0	.3	.6	1.2
Bent Ears										
Left mean	-6	2	3	13	18	5	1	-3	1	9
Left SD	2.7	.5	.3	.4	.6	.5	.4	.4	.5	1.2
Right mean	-13	0	0	11	17	4	-1	-8	-1	9
Right SD	.8	.8	.3	.4	.2	.5	.5	1.5	2.5	3.9

Table 3: HA-1 RECD values (foam-tip and earmold) for the audiometric frequencies for the left and right ears in each of the three ear styles (large, small, bent).