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Measuring fat mass in body equivalent materials using an RF resonant cavity

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Abstract:

Purpose: Provide a proof of concept for the potential of using a novel RF resonant cavity device for accurately and repeatedly measuring fat and fat free masses in phantom infants.

Materials & Methods: Design, construct, and characterize an RF resonant cavity with dimensions compatible to holding an infant. The cavity was characterized using spherical phantoms of 0%fat, 50% fat, and 100% fat to empirically calibrate shifts in resonant frequency. The phantoms were constructed using emulsions of bovine lard, water, and dish soap inside spherical containers which do not interact with the electric field. The calibration phantoms were compared with a phantom of a test sample to assess the ability of the resonant cavity perturbation technique for measuring body composition.

Results: Phantoms of distinct %fat (0%, 50%, and 100%) were used to calibrate the resonant cavity for measuring body composition. The calibration phantoms were used to create calibration lines of unique %fat and were compared to a 475mL sample of unknown %fat as a measure of how accurate the resonant cavity technique is for measuring body composition.

Conclusion: A 475 mL test sample was used to examine the robustness of the RCP technique. The sample was 25% fat and had a fat mass of (116.67 ± 0.96) g. The measured fat mass from the RCP technique was 114.30 ± 0.98 g, or a 2% difference. The resonant cavity perturbation technique provides an accurate and repeatable measurement of fat mass in spherical phantoms and suggests the technology might be an effective obesity research tool for infants. Future studies will focus on extending the work to more complex anthropomorphic shapes.

Key Words: radio frequency, resonant cavity, body composition, fat mass, fat free mass, pediatrics, BMI

Introduction:

Growth assessment of BMI (body mass index) in infants and young children has found a strong connection between high BMI at a young age and developing obesity in adolescence[1,2]. Growth assessment during this period is largely based on BMI with insufficient attention to relative partitioning of weight into lean mass or fat mass[3–5]. Infant body composition is indicative of lifelong metabolic health; thus, being able to accurately and reliably measure body composition is imperative for assessing infant health status. Reliable measurements of body composition in infancy and early life represent a technically challenging area[6]. The research presented in this paper shows resonant cavity perturbation (RCP) as a plausible method for accurately and repeatedly measuring body composition for tracking growth throughout infancy and childhood. Current methods of measuring body composition in infancy and early childhood include dual-energy X-ray absorptiometry (DXA), air displacement plethysmography (PEA POD and BOD POD), bio-impedance analysis (BIA), and total body water (TBW) deuterium dilution. Wells et al. did a comprehensive review of measuring body composition in infants, children and adolescents, which determined that DXA was the best individual measurement for determining soft tissue composition[7,8].

DXA is the current gold standard for infant body composition measurements; however, it utilizes ionizing radiation and cannot be measured frequently. PEA POD and BOD POD are closed units which calculate body composition using accurate measures of total body mass and total body volume using air displacement for infants-2yrs of age and 5yrs of age and older respectively. PEA POD and BOD POD do not use ionizing radiation and are not sensitive to motion artifacts. The devices are expensive, and there is a significant measurement gap between 6 months old and two years when kids outgrow PEA POD but are not yet large enough for BOD POD through which the technique cannot be used to monitor changes in body composition[9,10]. Bioimpedance analysis (BIA) provides a technique which can be used frequently, but it provides the least accurate results[11,12]. TBW measurements through deuterium dilution provide reproducible and accurate results, but is cumbersome to do frequently and expensive to conduct due to the requirement to collect biological samples which must be processed in a laboratory. The current technologies used for measuring infant body composition each have their merits and drawbacks.

A new method for measuring infant body composition utilizing a resonant cavity perturbation (RCP) technique is proposed in this research. The RCP technique is extremely sensitive to sample shape and mass distribution; both factors were carefully controlled while assessing the feasibility of RCP for accurate measurements of %fat. This paper specifically focuses on measuring fat mass in spherical phantoms using a radiofrequency resonant cavity to characterize the method for measuring %fat.

Materials and Methods:

Resonant cavities are closed, conducting structures which confine electromagnetic fields. Electromagnetic waves propagate back and forth between the walls of the cavity. Some of these frequencies will destructively interfere and vanish while others will constructively interfere and reinforce each other to form standing waves with frequencies corresponding to the geometry of the system. Shifts to the resonant properties can be made by inserting objects that change the average dielectric properties of the cavity[13–15]. This research focuses on the modes of a rectangular resonant cavity for which $\vec{E}$ is vertical (i.e. $\vec{E}$ has only a z-component, see Figure 2). These modes are conventionally called the transverse electric (TE_{mnp}) modes. These vertical TE_{mnp} modes are further defined by the indices m, n, and p which correspond to the number of half-wavelengths which can fit in each dimension. Each TE_{mnp} mode has a resonant frequency f_{nmp}, as shown below in **Equation (1).**

$$f_{mnp} = \frac{c}{2}\sqrt{\left(\frac{m}{w}\right)^2 + \left(\frac{n}{l}\right)^2 + \left(\frac{p}{h}\right)^2} \qquad \textbf{(1)}$$

Where w, l and h are the dimensions of the enclosure and c the speed of light. We will focus on the simplest vertical mode for which $\vec{E}$ is independent of the z-coordinate. Thus, we set $p = 0$, which corresponds to the TE_{mn0} modes, the lowest-frequency mode being the TE_{110}.

Following the treatment by Robinson *et al* (2003), the shifts in frequency and Q-factor can be described in terms of the complex *relative* permittivity ε* = ε' – iε" where ε' is the *relative* dielectric constant and ε" is the *relative* loss factor[15]. Note that the *absolute* dielectric constant and loss factor are given by $\epsilon'\epsilon_0$ and $\epsilon''\epsilon_0$, respectively.

$$-\frac{\Delta f}{f_0}+\frac{1}{2}i\Delta(Q^{-1})=2K_{sh}(\epsilon^*-1)\frac{V_s}{V_c} \quad \textbf{(2)}$$

Equation (2) can be broken into its real and imaginary parts, resulting in **Equation (3)** and **Equation (4)** respectively.

$$\Delta f=-2f_0K_{sh}(\epsilon'-1)\frac{V_s}{V_c} \quad \textbf{(3)}$$

$$\Delta(Q^{-1})=4K_{sh}\epsilon''\frac{V_s}{V_c} \quad \textbf{(4)}$$

The changes Δf and $\Delta(Q^{-1})$ are relative to the empty cavity, f_0 is the resonant frequency of the empty cavity, V_s is the volume of the sample, and V_c is the volume of the cavity. The shape factor, K_{sh}, is a dimensionless quantity which possesses important information about the geometry and distribution of materials inside of a given volume [35, 39]. In clinical applications total body volume (BV) can be difficult and expensive to assess. Current standards for measuring total BV are Air Displacement Plethysmography (ADP)[10,16] and 3D optical scans[16]. Total mass is a simpler, more cost-effective measurement. Using physical densities for the two compartments the total volume can be converted into a total mass. Applying the principle of superposition to equation **(3)** yields the result

$$\Delta f=-2f_0K_{sh}\frac{1}{V_c}\left[V_{fat}(\epsilon'_{fat}-1)+V_{lean}(\epsilon'_{lean}-1)\right]$$

A simple two compartment model divides the total body mass into lean mass (m_{lean}) and fat mass (m_{fat}); using the physical densities (ρ_{fat} and ρ_{lean}) of the two compartments the volume can be readjusted as a measurement of the total mass ($m = m_{fat} + m_{lean}$), resulting in **(5)**.

$$m_{fat} = \rho_{fat}\left[\frac{\frac{(\Delta f)V_c}{2f_0K_{sh}}\rho_{lean} + m\,(\epsilon'_{lean}-1)}{\left(\rho_{fat}(\epsilon'_{lean}-1)-\rho_{lean}(\epsilon'_{fat}-1)\right)}\right] \quad \textbf{(5)}$$

An RF resonant cavity was designed and constructed to have a practical size for scanning infants. Baseline properties, resonant frequency and Q-factor of the resonant cavity were established. The cavity was characterized to measure fat mass in spherical phantoms by observing shifts in frequency due to composition.

Designing the resonant cavity

Resonant cavities are closed, metallic structures which can contain electromagnetic fields which have eigenmodes that correspond to the physical dimensions of the cavity. Further, the RCP technique is valid for measuring TBW (i.e. fat mass) only if the following three conditions are met[14]:

1. Sample volume is small compared to the cavity volume, ideally less than 0.001 ratio
2. Penetration depth within the sample should be large compared to the thickness of the sample.
3. Dielectric properties correlate with body composition

An RF resonant cavity was designed with these three conditions in mind to accurately measure fat mass in babies up to 3 L in volume and using modes with frequencies which have a penetration depth which well exceeds the width of the sample.

We modeled the infant as phantoms made of only two compartments: fat mass and fat free mass. RCP utilizes the difference in water content between the fat and lean tissue dielectric properties to determine composition. The penetration depth is directly related to the dielectric properties of a given material. The dielectric property of human tissues have been investigated over a large range of frequencies, and their permittivities are correlated to the water content in UHF and microwave frequencies[13].

Given the above design criteria, a resonant cavity was designed to have dimensions 1.5 m × 1.0 m × 0.4 m, and the largest sample size has a volume of 0.035 m^3 having a volume ratio of 0.005. Although the largest volume ratio used in these experiments is larger than the recommended volume ratio of 0.001, it is still very small and was determined to be small enough to be consistent with the initial assumptions. These cavity dimensions were chosen to have a fundamental resonant frequency of 180.15 MHz, a frequency at which the plane wave penetration depth is about 1 m for muscle as shown in Figure 3[14(fig3),17]. Phantoms were constructed from plastic (radiotransparent) spherical containers and filled with pure water (0%fat), a water-fat emulsion (50%fat), or pure fat (100%fat). The largest samples were chosen to use 15.24cm diameter Alfie Pet Kerry Run-About Small Animal Exercise ball with 3.5mm thick walls and a 17.76 cm diameter Kaytee Run-About 7" Hamster Exercise Ball with 4mm thick walls. Silicone-based aquarium glue was used to seal holes in the spheres and contain the samples in the phantoms, while Michael's brand Christmas baubles were used for the smaller samples, as shown below in **Figure 3**.

Building the resonant cavity

A schematic of the infant RCP system is shown in Figure 1. Predicted baseline resonant properties were estimated to compare to the measured relative shifts in frequency and Q-factor when phantoms are placed inside the cavity. The VNA-UHF made by Array Solutions (Sunnyvale, Tx) produced a broad-spectrum reference signa that is most accurate (±5%) when measuring signals between 60 MHz and 180 MHz[18]. The software for the VNA-UHF was downloaded for from the Array Solutions website. The cavity was designed to operate in the 1 m and 10 m wavelength range, where there is good dielectric distinction between lean and fat masses as shown in Figure .

A resonant cavity was constructed from wooden frames with copper mesh (McMaster-Carr, copper wire cloth 9224T398) pulled tightly over the interior of each frame. The mesh had a hole diameter of 0.006", seen in Figure 2, but was equivalent to a solid sheet at the wavelengths used in this study[13,19,20] . The seams joining the frames together were sealed using conductive adhesive copper tape (76555A726, McMaster-Carr), and a protective baseboard was placed interior to the cavity. A grid was drawn onto the baseboard to allow for consistent sample placement. An access door was installed in order to place and remove samples into the resonant cavity. Conductive gaskets (parts were readily available for the project, unknown manufacturer) were attached to the edges of the interior face and latches were attached to the sides of the access door such that it could be easily removed and replaced while maintaining an electromagnetically sealed cavity. A pair of 17-cm monopole antennae (MFJ-1811, MFJ enterprises) were mounted in the top face 50 cm from each side and 50 cm from each end. A baseline measurement of the surrounding room was obtained using the VNA and compared to the measurement of the inside of the sealed cavity; the cavity proved to be electromagnetically isolated, and baseline resonant properties of the cavity were determined. It was determined that ambient humidity, temperature, and barometric pressure did not significantly affect the baseline resonant properties.

Results

The baseline resonant frequency of the empty cavity was measured to be (173.73 ± 0.48) MHz and a Q-factor of (451.21±8.38). Differences in the measured and expected baseline properties could be due to the manufacturing tolerances when constructing the cavity or the use of 17-cm monopole antennas. These antenna are long enough in comparison to the size of the cavity, and the wavelength of the resonant frequency, to shift the baseline resonant frequency[13,21]. The RCP technique compares the difference between the baseline resonant frequency of the empty cavity and the resonant frequency of the cavity with a dielectric sample placed inside the cavity; the magnitude of the shift correlates to the composition of the phantom. The plastic phantom containers did not affect the observed resonant shift properties and observed shifts in the resonant frequency were due to the composition of each phantom. The 475mL size was chosen to test the RCP technique because the moderate size lends itself to accurate RCP measurements while simultaneously having a large enough distance between adjacent calibration curves.

As shown in **Equation (3)** the shape factor (K_{sh}) greatly affects observed shifts in resonant frequencies. Shape factor is a ratio of the perpendicular cross sections and was held constant by using spherical phantoms which have the same shape factor across all directions and sizes[13,15]. We used spherical containers of uniform composition to simplify the interpretation of our results.

Spheres of different uniform compositions of lard and water (0%fat, 50%fat, and 100%fat) and masses were created to cover a broad range of values, where %fat is measured as the ratio of fat mass to total mass. The 50% lard sample was formed as an emulsion with 5 drops of dish soap (Ajax, lemon) added as a surfactant. A three-composition calibration curve (0%fat, 50%fat, and 100%fat) was used as a method for measuring the %fat of a 475mL phantom test sample.

Figure shows the relationship between composition and shifts in frequency for spherical samples of various sizes. Composition calibration curves were empirically created using the test phantoms for 0%fat, 50%fat, and 100%fat. Using the characteristic **Equation (5)**, the fat mass for each of the phantoms was calibrated using the RCP technique for later use to measure %fat in an test sample. Bland-Altmann statistical analysis is used to show agreement between independent quantitative measures, as shown in Figure 6. The Bland-Altman analysis showed a positive bias towards larger samples, meaning the RCP technique was found to be less accurate for larger sample sizes. The absolute error for each phantom was determined to be more relevant. The absolute error increased with sample size but remained relatively small, thus the measurements are accurate.

A 475 mL phantom of 25%fat was compared to the calibration model to examine the robustness of the RCP technique. The cavity used in this research was designed to accurately measure the fat mass of a sample within 2% of known values ranging 150 mL to 1750 mL, which made the 475mL test sample ideal for testing the system. The sample had a fat mass of (116.67 ± 0.96) g or 25%fat, using the RCP technique the measured fat mass of the phantom was (114.30 ± 0.98) g or 23%fat. The RCP technique can accurately measure %fat in spherical phantoms, theoretically this outcome can be combined with more complex methods[15] indicates feasibility for measuring %fat in more complicated geometries using RCP.

Conclusions:

The RCP technique provides a precise, reproducible measurement of fat mass in spherical phantoms. The resonant cavity has a baseline resonant frequency of (173.73 ± 0.48) MHz and Q-factor of (451.21±8.38), relative shifts in resonant frequency were used to measure fat mass. Further, using the RCP technique the measured fat mass of the 25%fat test sample was (114.30 ± 0.98) g or 23%fat. Many of the variants, such as complex geometry and fat distribution, were experimentally removed from this study to gain a better insight of how the frequency shifts are affected by composition alone. The cavity shows good precision and can precisely measure the %fat of different compositions in radio-transparent containers of constant shape factor and various volumes.

Figure 6 shows the two methods used for statistical analysis: absolute error and Bland-Altmann. The absolute error measured in fat mass is simple error propagation following Taylor's methods[22], of the total mass of the sample and the measured frequency shifts. The test sample further was compared to the precision of weighing the fat mass on a scale during assembly to determine the robustness of RCP for %fat measurements. **Figure 6a** shows the absolute error in measured fat mass, this error increases with sample size; similarly **Figure 6b** shows the Bland-Altmann statistical analysis which has a positive bias towards larger samples. These analyses together imply that the technique is less accurate for larger sample sizes, which correlates to the initial assumption of using a sample with a small volume relative to the cavity ($\frac{V_s}{V_c} \ll 0.001$). The bias shown in ***Figure 6*** is determined to be acceptable, as the difference between the estimated fat mass and actual fat mass is small and the model continues to function as expected through the phantom size range. Current methods for body composition measurements are as accurate as 2% fat[23]; RCP is still in its infancy, which makes accuracy within 5%fat interesting and could be improved with further study.

Discussion:

An RF resonant cavity was proposed to accurately measure infant body composition, the research presented took a systemic approach to measuring fat mass using an RF resonant cavity. The RCP technique provides a precise, reproducible measurement of the baseline resonant frequency of (173.73 ± 0.48) MHz and Q-factor of (451.21±8.38). Further, using the RCP technique the measured fat mass of the 25%fat phantom test sample was (114.30 ± 0.98) g or 23%fat. This research focused on a pre-clinical method of measuring phantom body composition and has confirmed RCP as a plausible method of determining fat mass in phantoms with simple geometry.

RCP is sensitive to the shape factor, composition, and distribution of materials in the phantom. In its current form, the RCP technique is limited in sample size, shape, and fat distribution. This research focused on spherical phantoms of uniform composition; however, to more generally extend this method the RCP technique must be extended to complex geometries and non-uniform distributions. The cavity presented in this research was characterized to accurately measure fat mass; however, the technique can be applied to any dielectric material mainly comprised of water content. It is recommended that the cavity size be increased for future research of *in vivo* infant body composition, as many infants are larger than 3 L in volume.

In conclusion, the RCP technique can measure the fat mass of a 475mL spherical phantom within 2% of the actual composition. A comparison of the estimated fat mass to the actual fat mass demonstrated the RCP method to be accurate for smaller sample sizes, and overestimates fat mass for larger sample sizes. The RCP technique is feasible for accurately measuring body composition; however, the technique is restricted to simple geometries and small samples. Many of the variants, such as complex geometry and fat distribution, were experimentally removed from this study to gain a better insight of how the frequency shifts are affected by composition alone. The cavity shows good precision and can precisely measure the %fat of different compositions in radio-transparent containers of constant shape factor and various volumes. A larger cavity and more complex geometries would need to be explored to extend RCP to clinical application.

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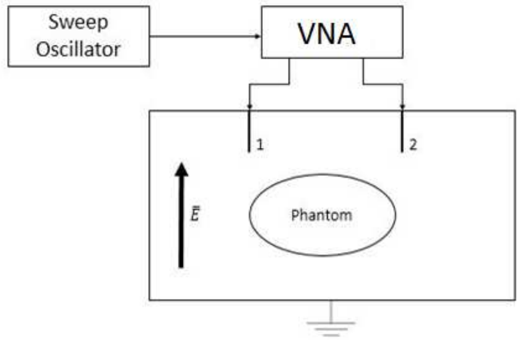


Figure 1: Method for measuring shifts in resonant properties utilizing a resonant cavity with a VNA and two quarter-wavelength ground plane antennae.

Figure 2: Interior view of the resonant cavity through access door. The base board was marked with a measured grid to allow for better sample placement. Monopole antennae can be seen protruding from the top face of the cavity.

Figure 3: A photograph of the different phantom containers filled with 100%lard. From left to right the containers are a 150mL Christmas bauble, 275mL Christmas bauble, 500mL snow globe, 1000mL snow globe, 1600mL hamster ball, and a 1800mL hamster ball.

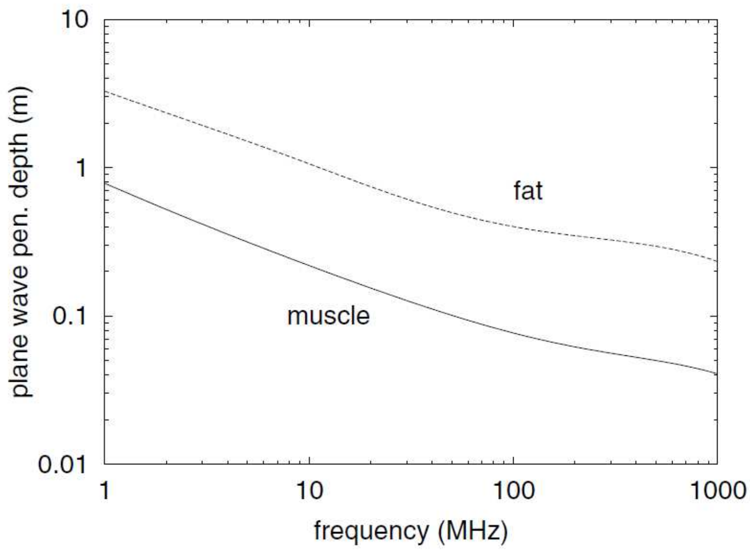


Figure 4: Logarithmic variation of the plane-wave penetration depth with frequency for fat and muscle [35]. There are distinct penetration depths for muscle mass and fat mass, which allows for a unique distinction between the two dielectric materials

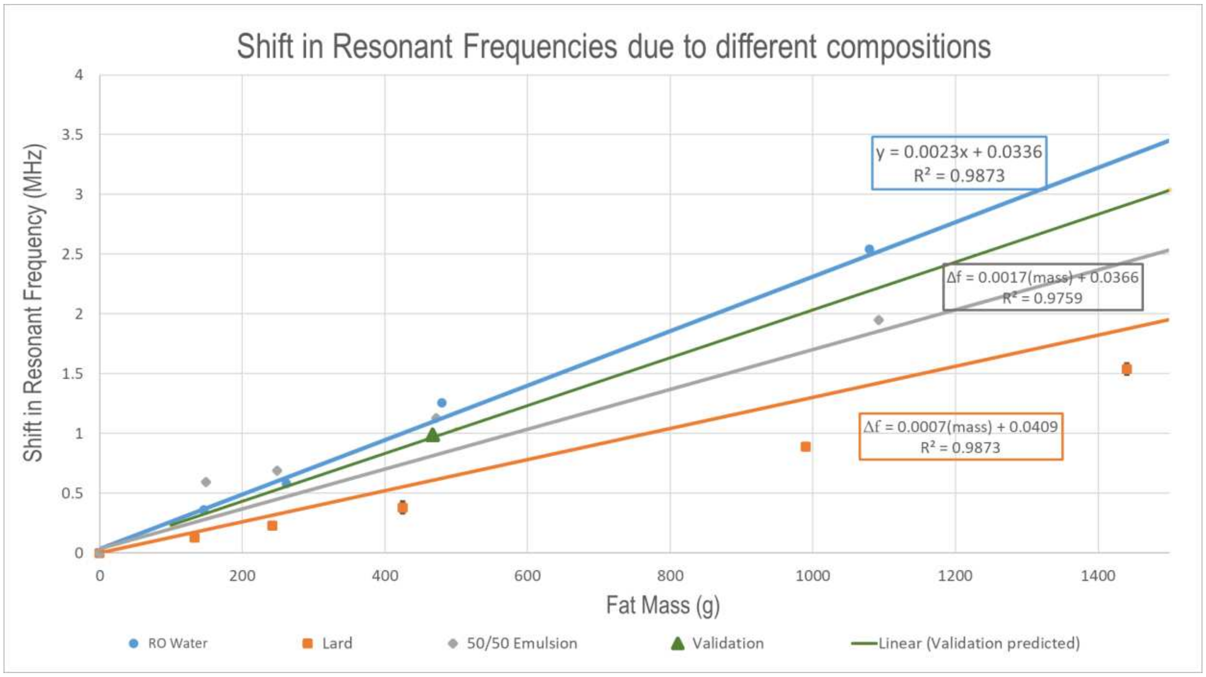
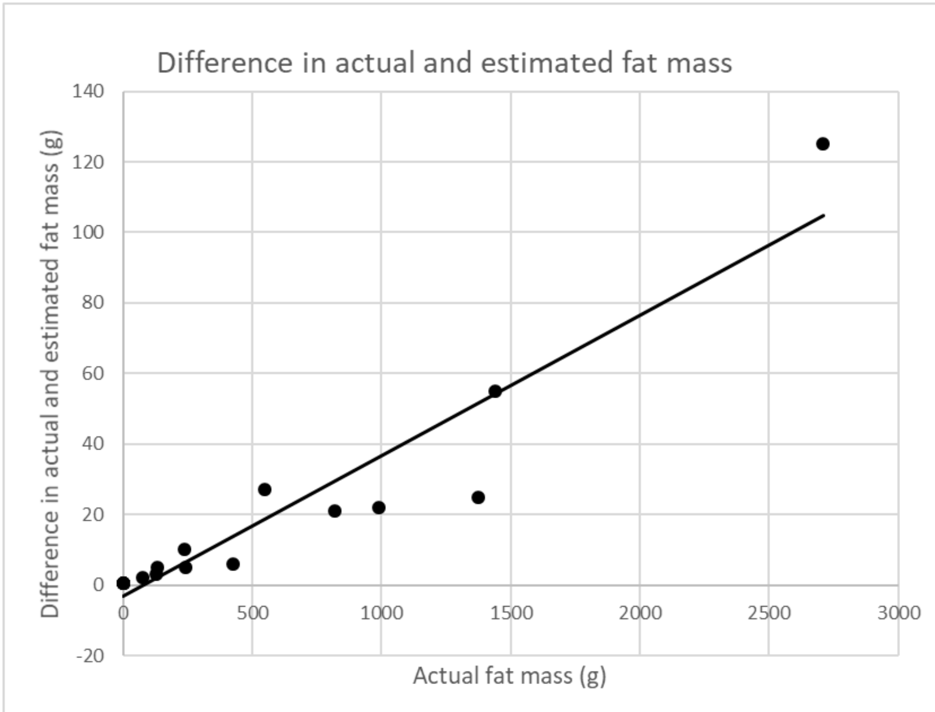
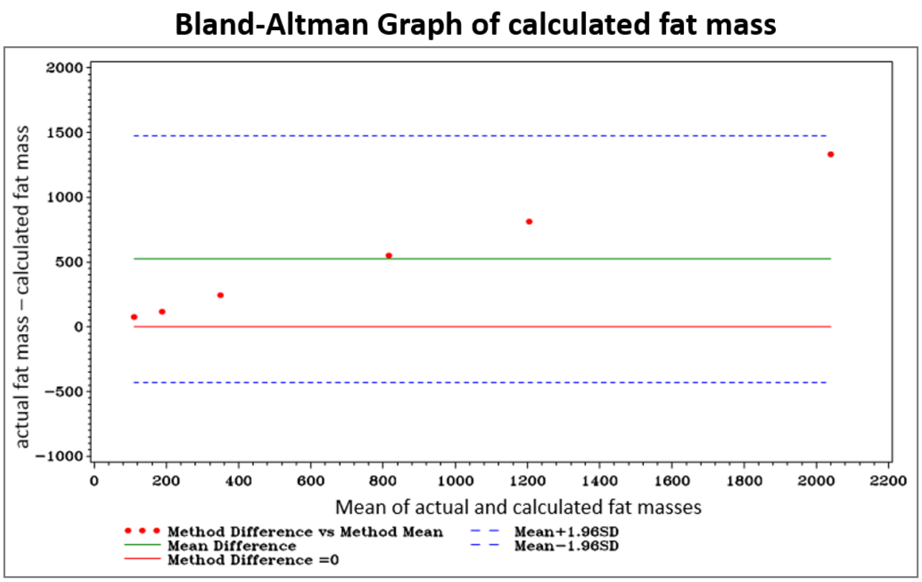


Figure 5: Shifts in resonant frequency due to distinct compositions (0%fat, 50%fat, and 100%fat) to calibrate the cavity. A 475mL test sample of 25%fat was used to see how well the RCP method is able to determine body composition.



a)



b)

Figure 6: **a)** Difference of absolute error in estimated fat mass as sample size increases. b) Bland-Altman analysis of sample sizes. There is a positive bias in the measurement of larger sample sizes. All estimated fat masses are within 5% of the actual fat mass. The error bars in both graphs are smaller than the resolution of the dot sizes, the trend cannot be observed simultaneously with the error bars.