

*Presented by:*

**Darren Ashley Stone**

- Applied Electromagnetics and EMC Group,
- Department of Electronics,
- University of York.

# Total Body Water Content Observations using Resonant- Perturbation Methods

*“A new direction in human-body  
water content determination...”*

- I. A Technique has been developed to Measure total body water content.
- II. Its Operation relies on the Resonant Cavity Perturbation method
- III. The perturbation technique is a well-established approach for identifying dielectric properties of materials at R.F and microwave frequencies
- IV. It utilises the relationship that the Dielectric properties are Correlated with the Water Content of materials
- V. We propose that this method Can be adapted in order to detect moisture levels within the human body

## Overview

- Clinical Utility of Total Body Water  
Content Techniques
- Current “State-of-Affairs”
- Theory
- Experimental Developments
- Future Directions
- Questions

## Clinical Utility

- Water accounts for over 50% of body
- Changes in Hydration Levels can indicate various conditions
- New technique will:
  - » Detect *changes* in body water content
  - » Detect *total* body water content
  - » Help detect fluid overloading (e.g. water retention), obesity, monitor dialysis treatment

I. Water accounts for over 50% of the human body's constituent elements, however, at present, there is no readily available means to determine this quantity.

II. This would be opportune because perturbations in hydration levels can act as an index to various diseases.

III. Accumulation of water fluids, e.g, *hypertension, renal or kidney failure, liver failure cancer.*

IV. Water Content Determination (TWCD) will:

- a. identify abnormal hydration levels in patients
- b. assess efficiency and monitor progress of dialysis treatment. Patients often required to undergo Dialysis in order to remove excess fluid.

## Current “State-of-Affairs”

- Established Techniques
- Dilution Technique (Deuterated Water)
- Electrical Approaches
- Dual Energy X-ray Absorptiometry (DXA)
- Limitations

I. *Dilution Technique*: Known quantity of solute is mixed with the Fluid-Under-Analysis. A division of volume and concentration quantities is made. For humans: a tracer is administered, from which a Saliva or Urine Sample is extracted. There is an equilibration period.

Limitation: Prolonged calibration time (equilibrium period)  
Apparatus Not Widely Available

II. Electrical Techniques: BIA - Electrodes attached to body, and a low current passed through - this determines body impedance. Using relationship that  $Z_{\text{body}} \propto \text{Total body water content, TBW}$  can be obtained.

Limitations are its invasive nature and that errors are caused by the contact impedance of electrodes;

Magnetic Field Analysis - Subject placed within a magnetic field, it measures the change in Conductivity. Limitations are high errors and that measurement is a function of body surface area water, rather than Total Body Water.

III. DXA:

Gold Standard. Patient subjected to “X-Ray” Radiation. Very accurate

Limitations: Expensive and Ionising

## Advantages of Proposed Technique

- Non-invasive
- Fast
- Simple
- Accurate
- Non-ionising
- Inexpensive
- Widely Available

## Resonant Cavity Perturbation Approach

- Screened Room acts as Cavity Resonator
- Cavity parameters are
  - » Resonant Frequency,  $f_{\text{res}}$
  - » Quality Factor,  $Q$
- Subject is placed into Room
- Subject will cause the Cavity parameters to undergo a negative shift
- Cavity parameters are measured

I. We have the use of a Large Rectangular Electrically Screened Enclosure.

This is in fact, a resonant cavity. A Hollow Enclosure, which Confines Electromagnetic Energy to its Interior. When a field is established, it is found to resonate at certain frequencies, depending on the Cavity Dimensions and its Dielectric Properties (complex permittivity).

II. Its principle resonance is assigned the abbreviation  $f_{\text{res}}$ . The resonant frequency will have a spread of energy, or quality factor, which can also be viewed as a measure of sharpness of the resonance, and is caused by material losses within the Cavity.

III. Samples of dielectric material can be placed in a resonant cavity, and significant effects can be observed. In this case, a human subject is placed within the Cavity.

IV. The introduction of a perturbing object, i.e. a human volunteer, will force the cavity parameters to undergo a negative shift. The  $Q$  will broaden out (due to losses incurred in the subject) and  $f_{\text{res}}$  will reduce (due to the change in permittivity).

V. Parameters are measured WITHOUT subject, then WITH subject.

## Resonant Cavity Perturbation Approach

- The change in  $Q$  and  $f_{\text{res}}$  are a function of the subject's Dielectric Properties
- Dielectric Properties correlate with the Water Content of subject
- Changes in Total Body Water Content relate to Perturbations of  $Q$  and  $f_{\text{res}}$
- *Result:* a powerful tool for quantifying the Water Content of a human subject.

I. The Resonant Frequency is dependant on the permittivity of the material (i.e. the *perturber*) placed within the cavity and  $Q$  is dependant on the losses incurred within the Cavity.

These quantities are the dielectric properties of the material perturber.

II. These properties are shown to correlate with Temperature, Mass, Density or Moisture content of the perturbing object, which in this case is the human volunteer

III. Therefore, changes in the cavity parameters can be related to the water content

## Perturbation Theory

- Dielectric Properties of the material are represented by *Complex Permittivity*

$$\epsilon^* = \epsilon_0 \cdot (\epsilon' - j\epsilon'') = (\epsilon - j[\sigma/\omega])$$

- The *real* component represents Permittivity
- The *imaginary* component represent the loss mechanism

I. These dielectric properties are represented by Complex Permittivity

II Epsilon Prime is relative permittivity of the perturber.

III. Epsilon double-prime is a function of loss within the cavity.

Loss is composed of

- i. Cavity Losses (walls, lid, antennas)
- ii. Material Losses (in the Dielectric/perturbing object)

## Perturbation Theory

- Complex Permittivity related to Measured cavity-parameters by:

$$\delta f = 2f_1.k.(ε' - 1).(v_s / v_c)$$

and

$$\delta Q = 4Q_1.k^2.ε''.(v_s / v_c)$$

- Perturbations in  $f_{res}$  and Q are now expressed as a function of the material's properties

I. These relationships were found by manipulating many of the cavity relationships around (please see end for a further reading list).

II. Changes in resonance and Q are determined by the

- i Volume of cavity and perturber (i.e. SUBJECT!)
- ii. Complex permittivity of material
- iii. SHAPE of material

## Why do the equations relate $f_{\text{res}}$ & $Q$ to complex permittivity?

- Resonant frequency dependent on permittivity ( $\epsilon'$ ) due to:

$$f_{\text{res}} = (1 / 2 \sqrt{\mu\epsilon}) \cdot [(m/a)^2 + (n/b)^2 + (p/d)^2]^{1/2}$$

- Quality factor dependent on material and cavity losses ( $\epsilon''$ ) due to:

$$Q = \omega(\text{Stored Energy} / \text{Power Lost})$$

I.  $f_{\text{res}}$  determined by cavity dimensions and permittivity of material filling it.

Introduce a dielectric and its permittivity will cause the wavelength to increase, since:  $v_s = c / \sqrt{\epsilon}$ , where velocity is a function of wavelength.

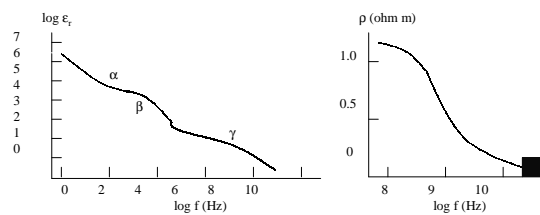
II. *Energy stored in Cavity* divided by *Energy lost per second in material and cavity*.

$Q$  is determined by losses arising in material and cavity itself, where:

$$1 / Q = 1 / Q_{\text{cavity}} + 1 / Q_{\text{material}}$$

## Water Content Determination

- Why is it that changes in  $f_{\text{res}}$  and  $Q$  are correlated with water?



- Dispersion regions

Complex permittivity is a function of complex frequency, therefore, the dielectric properties of the subject are dependent on the resonant frequency.

The resonant frequency, determined by the cavity dimensions, must be chosen to co-inside with WATER MOLECULE POLARISATION. The time-varying field (I.e. the resonant e-field) will induce electric polarisation of the dielectric's dipoles.

The Gamma Dispersion Region is where the water molecules will oscillate, and this is the region that we should operate in. Choose cavity dimensions appropriately.

## Experimental Developments

- Screened Room at York resonates at about 59 MHz.
- Perturbation equations requires that Cavity is much bigger than sample material
- Cavity to be relatively small to yield high  $f_{\text{res}}$ , for  $\gamma$ -dispersion (for water dependency)
- Trade-off

Cavity data:

$$f_{\text{res}} = 59.2388 \text{ MHz} \quad \lambda = 5.06 \text{ m}$$

Half wavelength of 2.53 m is reasonably uniform over someone of average height (172.5m).

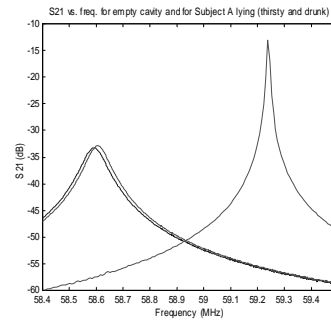
$$\text{Average Person} = 0.1 \text{ m}^3$$

$$\text{Screened Room} = 33.42 \text{ m}^3$$

Person is 0.3% of the room. 0.1 % is the recommended figure.. This is not as near as we would like, but a trade-off with competing dispersion-region considerations must be made. We could increase cavity, but this will reduce  $f_{\text{res}}$  even further, and move us further away from the gamma dispersion-region. We must settle with this trade-off.

## Experimental Results

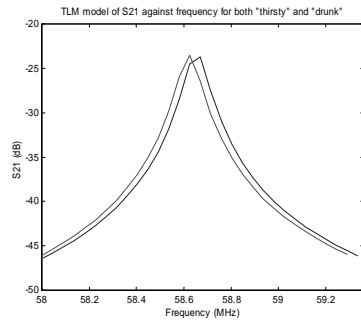
- Measured frequency - response of screened room
- Room empty and with volunteer present
- Red corresponds to empty room
- Green & blue correspond to the volunteer when 'thirsty' and after 1.25 litres of water, respectively



$F_{\text{res empty}} = 59.2375 \text{ MHz}$

$Q = 8400$

## Experimental Results



- Measured frequency response for volunteer when at differing hydration levels
- Blue corresponds to regular hydration
- Green corresponds to volunteer after consuming 1.25 litres of water

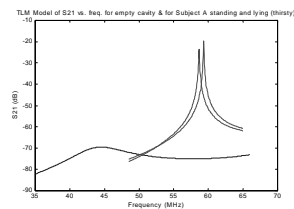
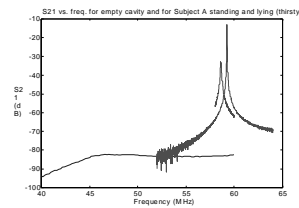
The resonant frequency (here) reduced from **59.2375MHz** to **58.6066MHz**, a **1.07%** reduction, i.e. a  **$\delta f$  of 630.9 KHz**.

The subject was then asked to consume **1.25 litres** of water, thus  **$f_{\text{res}} = 58.584$  MHz**; a further reduction of **22.6 KHz**.

**Q = 8400**, down to **Q = 740**

## Experimental Results

- Above: when room is empty and when volunteer is lying and standing at regular hydration (red, green and blue respectively)
- Below: Transmission Line Matrix (TLM) simulation



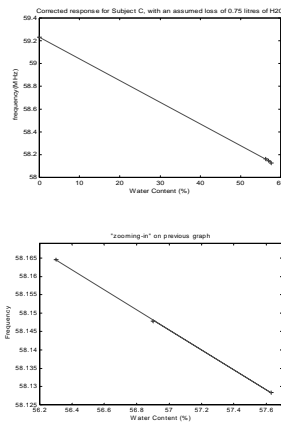
### Standing in Cavity:

When the volunteers were asked to stand, the losses were so high, that the resonant peak broadened too much, in other words, the profile of  $f_{\text{res}}$  was heavily damped.

This made it hard to detect the resonant peak when using the network analyser, and therefore the cavity and subject will need to be simulated using computer-modelling techniques, in order to help locate these points.

**Stood-up: 44.75 MHz (14.5 MHz reduction)**

## Experimental Results



- Moisture content calibration graphs
- Can be used with a calibration equation of the form  $y = mx + c$
- 4 points mapped into graph: Room empty, volunteer 'thirsty', after 1.5 litres of fluid and after voiding bladder

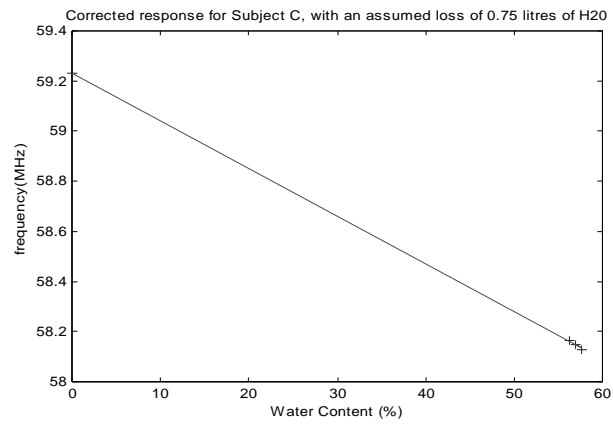
Notable changes in the room's resonant frequency and Q have been observed (see previous pages);  $f_{\text{res}}$  was subjected to a negative shift and Q was reduced. This decrease in  $f_{\text{res}}$  and Q indicates that changes in body water are correlated to these measured quantities.

As can be seen on this slide, calibration graphs and basic calibration equations are being developed from these results, to show how the measured quantities are dependent on body water content, thus providing a prototype tool in which TBW can be unequivocally obtained.

Total human body water was determined by estimating the amount in the body when thirsty using experimental equations given in our peer paper, as developed by Duck. When extra water was drunk, the estimated water content was increased linearly. These estimated values of the body water content were plotted against the measured resonant frequency and Q values. It is hoped that after measuring a further 20 volunteers, that a general pattern can be recognized, such that real values of water content can be gauged. These values will be calibrated against values determined by the gold standard (DXA) method.

$$\text{TBW(litres)} = W/100.(79.45 - 0.24W - 0.15A)$$

# Experimental Results



## Future Directions

- Investigate shape
- Try perturbation formulae ratios
- Double Measurement Technique
- Devise a technique to determine whole body water
- Investigate position information

I. Delta  $f_{\text{res}}$  and delta Q are also dependent on k, or shape.

There are solutions for spheres, ellipsoids and cylinders tangential and perpendicular to the the field direction.

Shape factors can be determined experimentally for human subjects.

II. By dividing the perturbation formulae by each other, it will force certain parameters “Cancel-Out”, thus rendering the ratio of measured cavity parameters independent of volume or shape.

III. Takes an average of the cavity parameters when the Sample is RE-ORIENTATED by  $90^{\circ}$ .

This means the shape will “cancel-out”.

IV. Improve present techniques with more people.

V. Look at higher modes.

## Perturbation Formulae Ratios

- Enables shape or volume independence:

$$X = \delta f / \delta Q$$

$$= [2f_1.k.(ε' - 1).(v_s / v_c)] / [4Q_1.k^2.ε''.(v_s / v_c)]$$

- Allows  $(v_s / v_c)$  terms to 'cancel-out', and:

$$R = \delta f / \sqrt{\delta Q}$$

$$= [2f_1.k.(ε' - 1).(v_s / v_c)] / [4Q_1.k.ε''.(v_s / v_c)]$$

- Allows  $k$  terms to 'cancel-out'

## Positional Information

- $TE_{101}$ ,  $TE_{102}$ ,  $TE_{103}$  and  $TE_{104}$  are currently under investigation
- $\delta f$  is proportional to amount of water in dielectric
- Different modes correspond to various locations in body
- Compare location of body to  $\delta f$

## “Question Time”



- For Further Information:
- Refer to our paper in January’s “Physics in Medicine & Biology” (Robinson et al.)
- Refer to March’s edition of “Physics World” for a special feature
- or try me !!

Further reading:

H. M. Altschuler, *Handbook of Microwave Measurements Vol. II*, 3rd ed, M. Sucher and J. Fox, Eds. Brooklyn, NY: Polytech. Press, 1963, ch. 9, Dielectric Constant.

G. B. Forbes, *Human Body Composition*, NY: Springer-Verlag, 1987, ch. 2.

R. F. Harrington, *Time Harmonic Electromagnetic Fields*, NY: McGraw-Hill, 1961, ch. 7. M.

F. Horner, T. A. Taylor, R. Dunsmuir, J. Lamb and W. Jackson, “Resonance methods of dielectric measurement at centimetre wavelengths,” *Jour. IEE*, vol 93 III, pp. 53 – 68, 1946.

A. W. Kraszewski and S. O. Nelson, “Observations on resonant cavity perturbation by dielectric objects,” *IEEE Trans. Microwave Theory Tech.*, vol. 40, pp. 151–155, Jan. 1992.

D. V. Land and A. M. Campbell, “A quick and accurate method for measuring the microwave dielectric properties of small tissue samples,” *Phys. Med. Biol.*, vol. 37, pp. 183 – 192, 1992.

P. Robinson, J. Clegg and D. A. Stone, “A novel method of studying total body water using a resonant cavity: Experiments & Numerical simulation,” *Phys. Med. Biol.*, vol.48, pp. 113 – 125, 2003.