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SOME ASPECTS OF RECENT FINDINGS PERTAINING TO THE BODY COMPOSITION OF ATHLETES, OBESE INDIVIDUALS AND PATIENTS

Research and Development Technical Report USNRDL-TR-339

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Biology and Medicine

Technical Objective
AW-6

Biological and Medical Science Division
Captain A. R. Behnke (MC) USN, Acting Head

Scientific Director
P. C. Tompkins

Commanding Officer and Director
Captain J. H. McQuilkin, USN

U. S. NAVAL RADIOLOGICAL DEFENSE LABORATORY
San Francisco 24, California

SUMMARY

1. Whole body density determinations are reported for a small group of athletes (weight lifters) and an analysis is presented of data derived from several investigations in which similar techniques were employed to measure total body water and the total exchangeable sodium, chloride (bromine space), and potassium in the body.

2. The mean value for body density (1.080) obtained on the athletes was similar to that obtained previously on professional football players and much higher than the mean value usually obtained on young men (~1.060).

3. In addition to the low body fat content characteristic of the athletes, the ratio of exchangeable K_e to Cl_e was higher in these men than in men of average physique. In turn, the values for K_e/Cl_e were even lower in obese individuals and in patients.

4. In healthy individuals, the sum ($K_e + Cl_e$) is highly correlated ($r = 0.99$) with total body water, and this finding provides an independent estimate of lean body weight.

5. In patients afflicted with certain types of chronic diseases, particularly those associated with the edematous state, the exchangeable Na_e to K_e ratio is strikingly higher than it is in healthy individuals.

6. Estimates of the amount of transudate in edematous patients may be made from analyses of total body water, and total exchangeable Na_e and K_e. Additional determinations, such as whole body density and red cell mass, are required to assess accurately the size of the lean body mass in these patients. Normal adult lean body size prior to illness may be estimated from "skeletal" measurements.

ADMINISTRATIVE INFORMATION

This work was accomplished under the Bureau of Medicine and Surgery Task Number NM 42 [illegible] Subtask 13, Technical Objective AW-6, as described in the U.S. Naval Radiological Defense Laboratory Annual Report to the Bureau of Medicine and Surgery (BS Form [illegible]) of 31 December 1958, and is listed in the U. S. Naval Radiological Defense Laboratory Fiscal Year 1959 Technical Program under Program A, Problem 1. This study was supported through funds provided by the Bureau of Medicine and Surgery and the Office of Civilian and Defense Mobilization.

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The authors are indebted to Dr. William E. Siri of the Donner Laboratory of Medical Physics for the determinations of whole body density by means of the helium dilution chamber technique.

It is to Dr. Francis D. Moore of the Departments of Surgery of Harvard Medical School and Peter Bent Brigham Hospital, Boston, that recognition should be given for the inauguration of a new era in the study of body composition in health and disease. The techniques utilized by Edelman, McMurrey, and Boling to determine exchangeable Na, Cl (Br), K, and total body water were perfected in his laboratory during the past decade. More than any other investigator, he has demonstrated the feasibility and importance of measurements of total quantities of body components as a basis for the rational care of surgical patients. The authors especially desire to express appreciation to Drs. Boling, McMurrey, Edelman and their co-workers for the extensive use made of the original data. The authors alone are responsible for any compilation or interpretation of data, not incorporated in the original papers.

INTRODUCTION

The analysis of the gross composition of the body of the living individual during the past 20 years constitutes an important advance in physiology and medicine. The procedures utilized include determinations of whole body density and notably the employment of dilution techniques involving the use of radioisotopes. As a result of these advances it is possible to partition the body into chemical entities or anatomical components such as total body fat and water, lean body mass, blood volume, red cell mass, cellular water, including muscle mass (potassium space), and extracellular water (chloride, sodium spaces). Of special importance are the ratios of sodium or chloride (the principal extracellular cation and anion respectively) to potassium present chiefly in the cells. The ability to measure in pathologic conditions significant departures from normal in these parameters makes possible a quantitative evaluation of the disease state, and this in turn serves as a basis for rational therapy.

In this paper whole body density determinations are reported for a small group of weight lifters whose body configuration was depicted quantitatively by Taylor and Behnke (1). The same subjects were also included in the series of Boling, et al. (2), who measured total body water, and the exchangeable sodium (Na_e), chloride (Cl_e), and potassium (K_e) content

of the body. Two other investigations (McMurrey et al. (3), and Edelman et al. (4)) have provided remarkably consistent data with respect to body water and electrolyte content, both in healthy men and women, and in patients. Additional analyses of the data of these investigators are presented herein to emphasize the striking differences existing between the Na_e/K_e ratios in patients and in healthy persons. Moreover, there is a significant difference between the ratios of Cl_e/k_e (2) and Na_e/K_e (3), not only for men and women, but for athletes and the obese. The largest individual weighed 170.4 kg (~375 lb) and the smallest 36.4 kg (80 lb). Since these ratios otherwise show little variation in healthy individuals, it is possible to use them to approximate the amount of transudate in patients.

The outstanding feature in this review is the employment of meticulous procedures by investigators who recieved their training in the laboratories of Dr. Francis Moore. Thus, it is possible to analyze data based on uniform methods applied in the study of heterogeneous subjects residing in widely separated areas. The techniques employed (2, 3, 4) were similar, if not identical, with the exception that Boling used H^3 as tritiated water, and McMurrey and Edelman deuterium oxide for the measurement of total body water. Br^{82} was employed to estimate exchangeable chloride.

FORMULAS FOR ESTIMATION OF BODY FAT

Estimates of Fat-free and Lean Body Weight from Whole Body Density and Total Body Water Determinations (TBW)

Hydrostatic or helium dilution chamber techniques make possible the determination of the net volume of the body and in turn an estimate of its density, $\frac{W}{V}$. If the body is divided into a fat (d, 0.90) and a fat-free component (d, 1.100), then the fat fraction F(f) may be calculated from the basic formulation of Morales et al. (5), and from experiments of Pace and Rathbun (6).

$$F(f) = \frac{\frac{1}{D(\text{body})} - \frac{1}{D(\text{lean mass})}}{\frac{1}{D(\text{fat})} - \frac{1}{D(\text{lean mass})}}$$

The fat-free body, however, is an in vitro entity. With reference to the living individual, it is more appropriate to refer to a lean body mass (LBM) which includes ~from 2 to 5 per cent essential lipids in bone marrow, central nervous system, and other organs.

The value for the specific gravity (~1.100) or density (~1.095) of the LBM has been derived from weight-volume relationships that pertain to extremely lean individuals examined during the past two decades and from analyses of carcasses of lower animals. Two sets of equations are used in this report for estimates of fat-free (7) and lean body weights.

Fat-free Weight (Body Weight - F(f) x B.W.), Siri's formulas

1/ From density alone, $F(f) = \frac{4.950}{D} - 4.500$

2/ From density and TBW, $F(f) = \frac{2.118}{D} - 78\ W(f) - 1.354$.

In 2/, W(f) is the water fraction of the body. The constants represent a slight change from those in Siri's original formula, (7). The constants in 1/ and 2/ are based upon the following density values, fat (0.90), fat-free mass (1.100), dry, fat-free mass (1.565), water fraction, fat-free mass (0.733).

Lean Body Weight (Body weight - "excess" F(f) x B.W.)

3/ From density alone, "excess" $F(f) = \frac{5.053}{D} - 4.614$.

4/ From density and TBW based upon Siri's formula,

$$\text{"excess" } F(f) = \frac{2.250}{D} - 0.77\ W(f) - 1.500.$$

The constants in 3/ and 4/ are based on the following density values, fat (0.90), lean body mass (1.095), dry, lean body mass (1.600), water fraction, lean body mass (0.72). The unique advantages of formulas 2/ and 4/ applied to individuals whose hydration is abnormal is shown by the substitution of the density value (0.993) for D, representing a hypothetical 100% aqueous body, such that $F(f) = \frac{2.250}{0.993} - 77 - 1.500$. From 4/, F(f) is essentially zero, whereas the substitution of 0.993 for D in 3/ gives an erroneous value for F(f) of ~47.5 per cent.

ANALYSIS OF DATA

Group Comparisons of Athletes and Obese Individuals

The larger muscular mass and better physical development of the athletes compared with the obese is consistent with the relatively greater amount of K_e compared with Cl_e (Table 1). The significance of the higher Cl_e/K_e ratios in the obese compared with the athletes is made more meaningful by the remarkably small variation in $(Cl_e + K_e)$ per liter of body water in the two groups, i.e., 139 mEq for the athletes and 140 mEq for the obese. With respect to fat content, the athletes had an average of less than 9 kg of excess fat and the obese ~46 kg excess fat.

In normally hydrated individuals, total body water is 72 per cent of the lean body mass. It is seen (Table 1), that the group values for $(Cl_e + K_e)$ divided by 100 is nearly equal to the group values for lean body mass, i.e., TBW ÷ 1.072.

Individual Values and Density Determinations on Athletes

The body density values are high (Table 2) in the athletes as Welham et al. (8) observed in professional football players and much higher than the average value (~1.063) for young men (9). Despite appreciable inter-individual variation in the ratio, Cl_e/K_e, the $(K_e + Cl_e)$ per liter of TBW is remarkably constant for the athletes and subject 7. The low values of 130 and 129 in subjects 8 and 9 are minimal for the healthy men and women in the groups examined. Subject 8 is a sedentary individual who has had extensive gastric resections. Although of small size and lean in appearance, he has a moderate amount of fat. Subject 9, despite extreme leanness, is physically fit.

The close agreement between values of total $(K_e + Cl_e) \div 100$ and fat-free weight calculated from Siri's combined equation holds for all subjects except 9 and 10. If the $(K_e + Cl_e)$ to TBW ratios for these subjects were 140 instead of 130 and 129 respectively, then the values from $(K_e + Cl_e) - 100$ would be in close accord with their fat-free weights.

In four subjects especially, and for the group as a whole (Table 2), LBW calculated from density alone is much higher ($\bar{m}$ 71.3 kg) than LBW calculated from the ratio TBW $\div$ 0.72, ($\bar{m}$ 64.8 kg). The divisor, 0.72, in previous studies (9) has been accurate as a conversion factor for the estimation of LBW from TBW. In this small group, a divisor of ~0.67 would be required to bring the lean body weights into agreement with those derived from density. Appreciable error in the TBW determinations is ruled out by the small variation of $(K_e + Cl_e)$ per liter of TBW with the exception of the values for subjects 8 and 9. The data suggest either some degree of dehydration or that the value of 1.500 postulated for the density of the dry, lean body mass is too low.

Data on Healthy Men and Women. Stability and Importance of the Ratio, (K_e + Cl_e) to Total Body Water

Boling et al. (2) pointed out the high correlation (r = 0.96) between K_e and TBW (CV, 4.8%), and Cl_e and TBW (CV, 4.5%). However, the combined value (K_e + Cl_e) is more highly correlated with TBW (r = 0.99). The mean value for 29 male subjects of (K_e + Cl_e) per liter TBW was 138.6 mEq~4.09 (CV, 2.95%). The data of McMurrey et al. (3) on healthy men (Table 3) and healthy women (Table 4) further support the constancy of this ratio, although the mean value was somewhat higher, ~140 mEq ± 4.5 (CV, 3.2%). The greater Cl_e and smaller K_e values per liter of water for women compared with men is highly significant.

Estimates of fat-free weight (kg) may be made from TBW ÷ 0.733, and of lean body weight from TBW ÷ 0.72. It is fortuitous that the sum (K_e + Cl_e) ÷ 100 is nearly identical numerically with TBW ÷ 0.72. On the combined groups comprising 49 male and female subjects, $\bar{m}$ TBW ÷ 0.72 was equal to 57.5 kg ± 13.3 (CV, 23.1%), and $\bar{m}$ (K_e + Cl_e) was equal to 57.9 13.4 (CV, 23.2%). The correlation between values derived from TBW ÷ 0.72 and (K + Cl) ÷ 100 was 0.992, the standard error ± 1.71 kg, or 2.9% of the mean.

The Na_e/K_e and (Na_e + K_e)/TBW Ratios in Healthy Individuals and in Patients

The noteworthy finding was the greatly elevated Na_e/K_e ratio in patients compared with healthy individuals (Table 5). However, with respect to (Na_e + K_e)/TBW, the mean values for the patients (148.6 mEq (CV, 5.5%)) and healthy individuals (160.9 mEq (CV, 2.75%)) are significantly different but not too divergent. The presence of excess solutes such as urea and glucose in patients does not appear to lower the (Na_e + K_e)/TBW ratio. It is

beyond the scope of this paper to discuss the reasons for the discrepancy in the mean values of this ratio in patients and healthy individuals, except to point out that the correlation between serum Na and $(Na_e + K_e)/TBW$ in patients (4) is not sufficiently high ($r = 0.83$) to be useful in this analysis. The osmotically active or inactive substances affecting this correlation remain to be identified.

The Estimation of the Amount of Transudate and Lean Body Weights of Edematous Patients

The high correlation of $(Na_e + K_e)$ to TBW, and the constancy of the Na_e/K_e ratios in healthy men (0.828) and in women (0.975) serve as a basis to estimate the amount of transudate and the lean body weight in the patients of Edelman et al. (4). In healthy men, Na_e constitutes ~ 45 per cent of the combined $(Na_e + K_e)$, and this amounts to about 72 mEq per liter of body water in these individuals (i.e., 0.45×160). In male patients, the mean value of $(Na_e + K_e)/TBW$ was ~ 148 mEq/L. If this value is multiplied by 0.45, one obtains ~ 67 mEq of Na_e per liter of body water.

a. An approximation of the transudate (mean value) in the male patients follows: mean values, weight (67.6 kg), TBW (40.21), total Na_e (3666 mEq) and total K_e (2210 mEq). The product of TBW (40.2) and 67 = 2693 Na_e, and this may be assumed to be the normal Na_e for this quantity of body water. On the assumption that Na is the principal cation in transudate and that K is absent, the "excess" fluid is equal to 973 mEq ÷ 148 = 6.6 liters. A first approximation to estimated normal $\bar{m}$ TBW, 40.2 - 6.6 = 33.6 liters.

Lean body weight = 33.7 ÷ 0.72 = 46.8 kg.

LBW + transudate = 53.3 kg.

Body fat = 67.6 - 53.3 = 14.3 kg.

b. Calculation of transudate and LBW in a grossly edematous patient.

Weight (119.5 kg), TBW (69.6 L), Na_e (6983 mEq), K_e (3293 m Eq) and $(Na_e + K_e)$/TBW (~148 mEq).

Est. normal Na_e = 0.45 x 148 = 67 mEq, 69.6 x 67 = 4663 mEq.

Est. "excess" Na_e = 6983 - 4663 = 2320 mEq.

Amount of transudate 2320 ÷ 148 = 15.7 liters.

Lean body weight (69.6 - 15.7) ÷ 0.72 = 75.0 kg.

LBW + transudate = 75 + 15.7 = 90.7 kg.

Body fat = 119.5 - 90.7 = 28.8 kg.

c. Calculation of transudate and LBW from mean values of women patients (4).

Weight (55.1 kg), TBW (29.1 L), Na_e (2626 mEq), K_e (1706 mEq) and $(Na_e + K_e)$/TBW (150.3 mEq).

The ratio of Na_e to $(Na_e + K_e)$ in healthy women is ~0.49.

Estimated normal Na_e/TBW = 0.49 x 150 = 74 mEq per liter.

Est. normal Na_e = 29.1 x 74 = 2153 mEq.

Est. "excess" Na_e = 2626 - 2153 = 473 mEq.

Amount of transudate = 473 ÷ 150 = 3.15 liters.

Lean body weight = (29.1 - 3.15) ÷ 0.72 = 36 kg.

Lean body weight + transudate = 36 + 3.2 = 39.2 kg.

Body fat = 55.1 - 39.2 = 15.9 kg.

d. Calculation of LBW in a non-edematous female patient.

Weight (36.4 kg), TBW (18 L), Na_e (1228 mEq), K_e (1358 mEq) and $(Na_e + K_e)$/TBW (144 mEq).

Est. normal Na_e/TBW = 0.49 x 144 = 70.6 mEq per liter.

Normal Na_e = 70.6 x 18 = 1271 mEq.

d. (cont'd).

Total Na_e deficit = 1228 - 1271 = 43 mEq.

Since this deficit is within the limits of measurement error,

LBW = 18 ÷ 0.72 = 25 kg.

Excess fat = 36.4 - 25.0 = 11.4 kg.

COMMENTS

The Na_e/K_e ratios are elevated in the patients even after a correction has been made for transudate. This may be attributed to an insufficient correction for transudate or to abnormal loss of K_e in the patients due to wasting disease and the compensatory increase of exchangeable sodium. If the correction for transudate were made on the basis of restoring the normal Na_e to K_e ratio, then the lean body weights of the patients would be far below the mean values for healthy individuals. Even so, without any subtraction of transudate from total body water, the mean body water content of 40.2 liters (men) and 29.1 liters (women) are remarkably low in view of the large number of edematous patients included in the series (4).

The above calculated lean body weights may apply to the pre-edematous condition of the patients. The lean body weights accompanying the edema state may be more closely related to the potassium levels. Two additional measurements would be invaluable in removing uncertainties and speculation, namely, determinations of whole body density (7, 9) and the total red cell mass (10). Under conditions of weight loss following partial starvation and certainly in the healthy state, the total red cell mass is highly correlated with lean body mass. Total body density in conjunction with the measurement of total body water unequivocably defines the size of the "active protoplasmic mass." Finally, an estimate of the normal, adult size of the lean body mass prior to illness may be obtained from "skeletal" anthropometric measurements which presumably are not altered by the types of chronic disease under consideration.

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Approved by:

A.R. BEHNKE
Captain (MC) USN
Acting Head, Biological and
Medical Sciences Division

For the Scientific Director

TABLE 1

Mean Values for Total Body Water Exchangeable Chloride and Potassium Determinations on Healthy Men in Relation to Body Fat Content and Muscular Development (Analysis of Data from Boling et al.)

	% TBW/Weight	Cl_e/K_e	M Eq/L water Cl_e	M Eq/L water K_e	LBW: TBW ÷ 72 kg	LBW: M Eq (Cl_e+K_e) ÷ 100	Weight kg	% Fat
Group 1 Obese N = 8	45.2 (41 - 49)	0.63	54	86	75.9	76.3	122.2	37.7
Group 2 N = 7	53.4 (52 - 55)	0.60	52	87	62.3	61.6	83.5	25.4
Group 3 N = 10	57.7 (55 - 60)	0.60	51	86	58.1	58.6	73.5	20.9
Group 4 Athletes N = 7	63.8 (62 - 67)	0.55	49	90	66.3	66.1	74.7	11.2
Total N = 32	56	0.603	51.2	87.3	65.9	65.8	88.4	24
Range	(41 - 67)	(.50 - .68)	(46 - 54)	(80-96)	(43 - 97)	(40 - 96)	(52 - 170)	(5 - 41)
σ		0.043	2.3	4.2		11.0	19.3	
C.V.		7.0	4.5	4.8		16.7	27.2	

TABLE 2

WHOLE BODY DENSITY, WATER, EXCHANGEABLE K AND Cl, FAT-FREE BODY WEIGHT AND LEAN BODY WEIGHT OF MEN, CHIEFLY WEIGHT LIFTERS.

Subject	Age	Stature cm	Weight kg	Density	TBW kg	M Eq/L Water K_e	Cl_e	$K_e + Cl_e$	Total $K_e + Cl_e$ % 100	Fat-free Weight from Density and TBW	Lean Body Weight From Density	TBW/0.72	Density and TBW
1*	35	161.[illegible]	74.8	1.085	46.5	92	50	142	65.9	[illegible]	71.5	64.6	67.7
2*	25	160.[illegible]	70.9	1.078	45.5	94	49	143	65.0	[illegible]	65.7	63.2	64.3
3*	24	181.[illegible]	94.6	1.075	57.5	90	50	140	80.9	[illegible]	86.4	80.0	82.8
4*	26	176.2	79.3	1.069	49.7	93	46	139	69.1	[illegible]	70.3	68.0	69.6
5*	30	174.0	78.6	1.078	53.0	87	53	140	74.3	[illegible]	72.9	73.6	73.3
6*	22	177.0	83.4	1.094	51.6	96	48	144	74.2	[illegible]	83.0	71.7	76.7
7**	56	178.8	93.6	1.045	48.5	88	53	141	68.3	68.4	72.8	67.3	69.8
8	43	159.0	52.4	1.059	30.6	80	50	130	39.7	42.4	44.2	42.5	43.2
9	37	175.2	58.2	1.084	38.0	80	49	129	48.8	52.9	55.4	52.8	53.9

*Athletes (Calistenics, Weight lifting)

**Former athlete

TABLE 3

Total Body Water, Exchangeable Sodium, Chloride, and Potassium Determinations on Healthy Men

(Analysis of data of McMurrey et al.)

% TBW/Weight	Cl_e/K_e	Na_e/K_e	M Eq/L Water Cl_e	M Eq/L Water K_e	M Eq/L Water Na_e	LBW TBW ÷ 72	M Eq (Cl_e + K_e) ÷ 100	Weight kg	% Fat	MEq/L Water Cl_e + K_e	MEq/L Water Na_e + K_e
46.0	.65	.86	59	90	77	56.5	60.5	88.5	36.1	149	167
49.4	.61	.81	55	90	73	52.1	54.3	76.0	31.4	145	163
50.2	.61	.86	51	85	73	54.1	53.1	77.7	30.3	136	158
54.7	.59	.77	52	88	68	60.4	60.9	79.5	24.0	140	156
55.0	.57	.85	51	90	76	52.3	53.2	68.5	23.6	141	166
56.0	.68	.96	57	85	81	70.4	72.0	90.5	22.2	142	166
56.3	.60	.77	53	89	68	57.2	58.4	73.2	21.8	142	157
56.6	.70	.84	59	85	72	41.5	43.1	52.7	21.2	144	157
59.2	.56	.76	50	90	68	52.2	52.7	63.5	17.7	140	158
59.5	.56	.80	52	93	74	45.0	46.9	54.5	17.4	145	167
M 54.3	.613	.828	53.9	88.5	73.0	54.2	55.5	72.5	24.6	142.4	161.5
σ	.049	.066									

Total Body Water, Exchangeable Sodium, Chloride, and Potassium Determinations on Healthy Women
(Analysis of Data of McMurrey et al.)

% TBW/Weight	Cl_e/K_e	Na_e/K_e	M Eq/L Water Cl_e	M Eq/L Water K_e	M Eq/L Water Na_e	LBW TBW ÷ 72	LBW M Eq $Cl_e + K$ ÷ 100	Weight kg	% Fat	mEq/L Water $Cl_e + K_e$	mEq/L Water $Na_e + K_e$
40.7	.72	.95	59	82	78	41.5	42.0	73.4	43.4	141	160
41.6	.78	1.06	63	81	86	42.2	43.8	73.0	42.1	144	167
48.3	.70	.91	60	86	78	41.9	44.2	62.5	32.9	146	164
48.5	.73	.94	57	79	75	43.6	42.7	64.8	32.7	136	154
48.5	.70	.94	59	84	79	40.0	40.8	59.1	32.3	143	163
48.9	.79	1.06	61	76	81	33.0	32.6	48.6	32.0	137	157
49.0	.75	1.01	56	75	77	33.6	31.9	49.5	30.1	131	152
50.6	.80	1.04	64	80	83	41.8	43.4	59.5	29.7	144	163
53.8	.67	.91	56	84	76	43.3	43.5	58.0	25.3	132	160
55.9	.66	.93	56	84	79	34.6	34.9	44.5	22.2	140	163
M 48.6	.740	.975	59.1	81.1	79.1	39.7	40.0	59.3	32.3	139.4	160.3
σ	.044	.068									

TABLE 5

The Exchangeable Sodium/Potassium Ratios in Various Diseases and in the Healthy State

	Na/K
Disease State (from Edelman et al.)	
Male:	
Heart disease (N = 22)	1.77 ± 0.195 (.91 - 3.09)
Liver disease (N = 21)	1.73 ± 0.167 (.92 - 2.78)
Kidney disease (N = 4)	1.72 (1.42 - 1.99)
Lung disease (N = 4)	1.48 (1.07 - 1.90)
Gastro-intestinal disease (N = 3)	1.38 (0.97 - 2.15)
Neurological disease (N = 2)	1.44 (1.35, 1.54)
Miscellaneous disease (N = 8)	1.23 (0.96 - 1.51)
Female:	
Heart disease (N = 10)	1.59 (1.00 - 2.55)
Liver disease (N = 6)	1.74 (1.20 - 2.48)
Healthy State (from McMurrey et al.)	
Male (N = 10)	0.828 ± .066
Female (N = 10)	0.975 ± .068