Image from data that apeared in Electronics Letters in 1983

the Table that it should be possible to produce an image of electrical resistivity which distinguishes tissue.

Reconstructed images using resistivity have been obtained so far only from computer simulation or on laboratory phantoms,[3,4] and not from *in-vivo* measurements. A practical difficulty of *in-vivo* measurements arises from the contact resistance between the electrode and the skin of the patient. This resistance is in series with the resistance to be measured, and is of the same order of magnitude as the resistance to be measured. The method to be described circumvents this difficulty.

Applied potential tomography (APT): Fig. 1 shows a two-dimensional circular object the resistivity distribution of which is to be determined, and to the surface of which 16 electrodes have been connected. Suppose current is passed between two of these electrodes (say numbers 8 and 16), and the electrical potential at the other electrodes measured. The values of these potentials must reflect the distribution of current within the object, and hence the distribution of resistance. In measuring the potential on the electrode the effect of contact resistance of the electrode is avoided by using a voltmeter of sufficiently high input impedance.

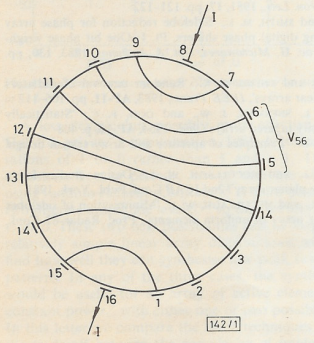


Fig. 1 *Electrode positions and equipotentials for a circular region of uniform resistivity*

In this Figure a voltage is applied between electrodes 8 and 16. V_{5-6} is the voltage difference between electrodes 5 and 6 while current is flowing

The potential can be measured at the electrodes for all possible pairs of electrodes through which current is applied. However, these measurements are not all independent; using N electrodes it is only possible to produce $N-1$ independent current distributions. The voltage differences between adjacent electrodes are measured, but if one of these electrodes is a current electrode the measured voltage difference is discarded because of the voltage drop across the contact resistance. For N electrodes, $N-3$ measurements of voltage difference can be obtained for each pair of adjacent current electrodes. There is also reciprocity between the electrode pairs of current application and of voltage measurement, and hence it can be shown that the number of independent measurements is $N(N-3)/2$.

In the results to be presented 16 electrodes were used (giving 104 independent measurements), and voltage difference measurements were taken for all possible pairs of current application in order to average the data and so improve the signal/noise ratio. The electronic system for obtaining the measurements will not be described.

Image reconstruction: The voltage measurements were used to construct an image of the resistivity distribution using an adaptation of the method of backprojection used in computed tomography (CT).[2] Essentially the image is formed from the profiles of the measurements made on the periphery of the region to be imaged. For each profile, the simplest image is formed which could have produced this profile. All these images, one for each profile, are then added together. In the case of CT, filtering of this image produces the desired image.

In the present reconstruction method, the peripheral profiles are the measured voltage differences between adjacent electrodes for each pair of current electrodes. Fig. 1 shows these lines of constant potential (here called unipotentials) which end on electrodes for this particular electrode configuration, and for a medium of uniform resistivity. Consider the voltage difference between electrodes 5 and 6. If the measured voltage difference is different from the calculated difference, then the resistivity in all of the region between the unipotentials which end on electrodes 5 and 6 is altered to a value such as to produce the measured potential difference. For a constant current between the drive electrodes, the resistivity will be altered in proportion to the voltage difference. The resulting image formed by backprojecting the profile measurements, normalised to the case of uniform resistivity, into the regions between the unipotential lines is the simplest image consistent with this profile of measurements. The images so produced by each current configuration are then summed. This summed image is then filtered, by analogy with CT imaging,[2] to reduce the blurring inherent in backprojection.

Results: The above description is essentially two-dimensional, and results have been obtained by this method for two-dimensional distributions of resistivity. In practice the distributions of resistivity of clinical interest are three-dimensional, and this poses some extra problems for the reconstruction, because current will flow out of the plane of the electrodes. In order to demonstrate that *in-vivo* data can be collected and used to produce an image, measurements were made on a human forearm and the data processed using the two-dimensional algorithm described above. The image will be contaminated by structures above and below the plane

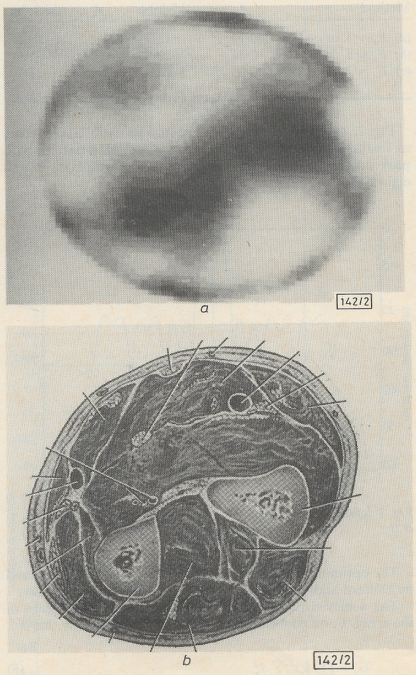
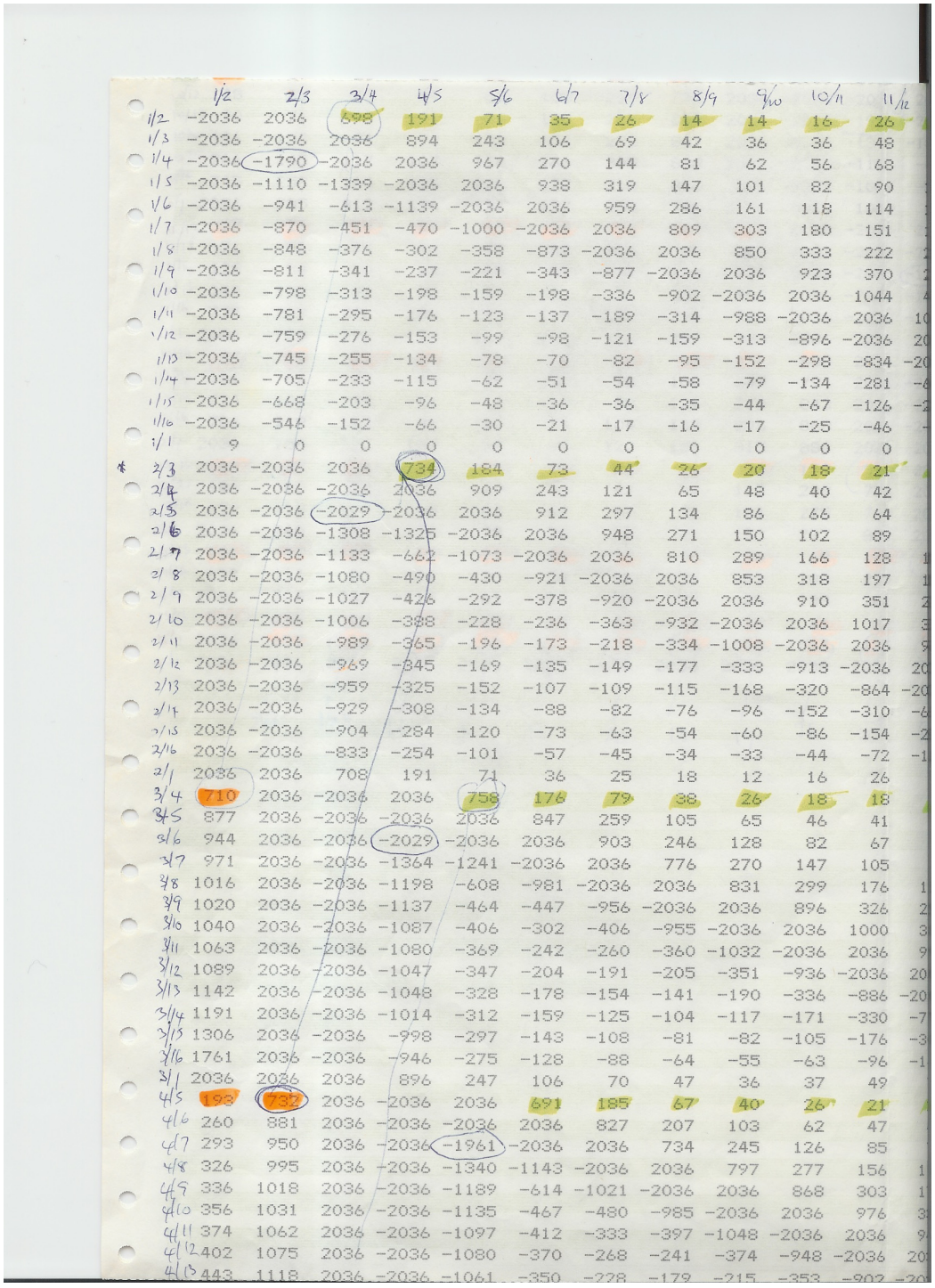


Fig. 2

a Resistance image of a normal human forearm. Increasing blackness denotes increasing resistivity

b Diagrammatic cross-section of the human forearm at the level imaged in Fig. 2*a*

Part of the raw data pint out on the line printer



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1/3	-2036	-2036	2036	894	243	106	69	42	36	36	48
1/4	-2036	-1790	-2036	2036	967	270	144	81	62	56	68
1/5	-2036	-1110	-1339	-2036	2036	938	319	147	101	82	90
1/6	-2036	-941	-613	-1139	-2036	2036	959	286	161	118	114
1/7	-2036	-870	-451	-470	-1000	-2036	2036	809	303	180	151
1/8	-2036	-848	-376	-302	-358	-873	-2036	2036	850	333	222
1/9	-2036	-811	-341	-237	-221	-343	-877	-2036	2036	923	370
1/10	-2036	-798	-313	-198	-159	-198	-336	-902	-2036	2036	1044
1/11	-2036	-781	-295	-176	-123	-137	-189	-314	-988	-2036	2036
1/12	-2036	-759	-276	-153	-99	-98	-121	-159	-313	-896	-2036
1/13	-2036	-745	-255	-134	-78	-70	-82	-95	-152	-298	-834
1/14	-2036	-705	-233	-115	-62	-51	-54	-58	-79	-134	-281
1/15	-2036	-668	-203	-96	-48	-36	-36	-35	-44	-67	-126
1/16	-2036	-546	-152	-66	-30	-21	-17	-16	-17	-25	-46
1/1	9	0	0	0	0	0	0	0	0	0	0
2/3	2036	-2036	2036	734	184	73	44	26	20	18	21
2/4	2036	-2036	-2036	2036	909	243	121	65	48	40	42
2/5	2036	-2036	-2029	-2036	2036	912	297	134	86	66	64
2/6	2036	-2036	-1308	-1325	-2036	2036	948	271	150	102	89
2/7	2036	-2036	-1133	-662	-1073	-2036	2036	810	289	166	128
2/8	2036	-2036	-1080	-490	-430	-921	-2036	2036	853	318	197
2/9	2036	-2036	-1027	-426	-292	-378	-920	-2036	2036	910	351
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2/11	2036	-2036	-989	-365	-196	-173	-218	-334	-1008	-2036	2036
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2/14	2036	-2036	-929	-308	-134	-88	-82	-76	-96	-152	-310
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2/16	2036	-2036	-833	-254	-101	-57	-45	-34	-33	-44	-72
2/1	2036	2036	708	191	71	36	25	18	12	16	26
3/4	710	2036	-2036	2036	758	176	79	38	26	18	18
3/5	877	2036	-2036	-2036	2036	847	259	105	65	46	41
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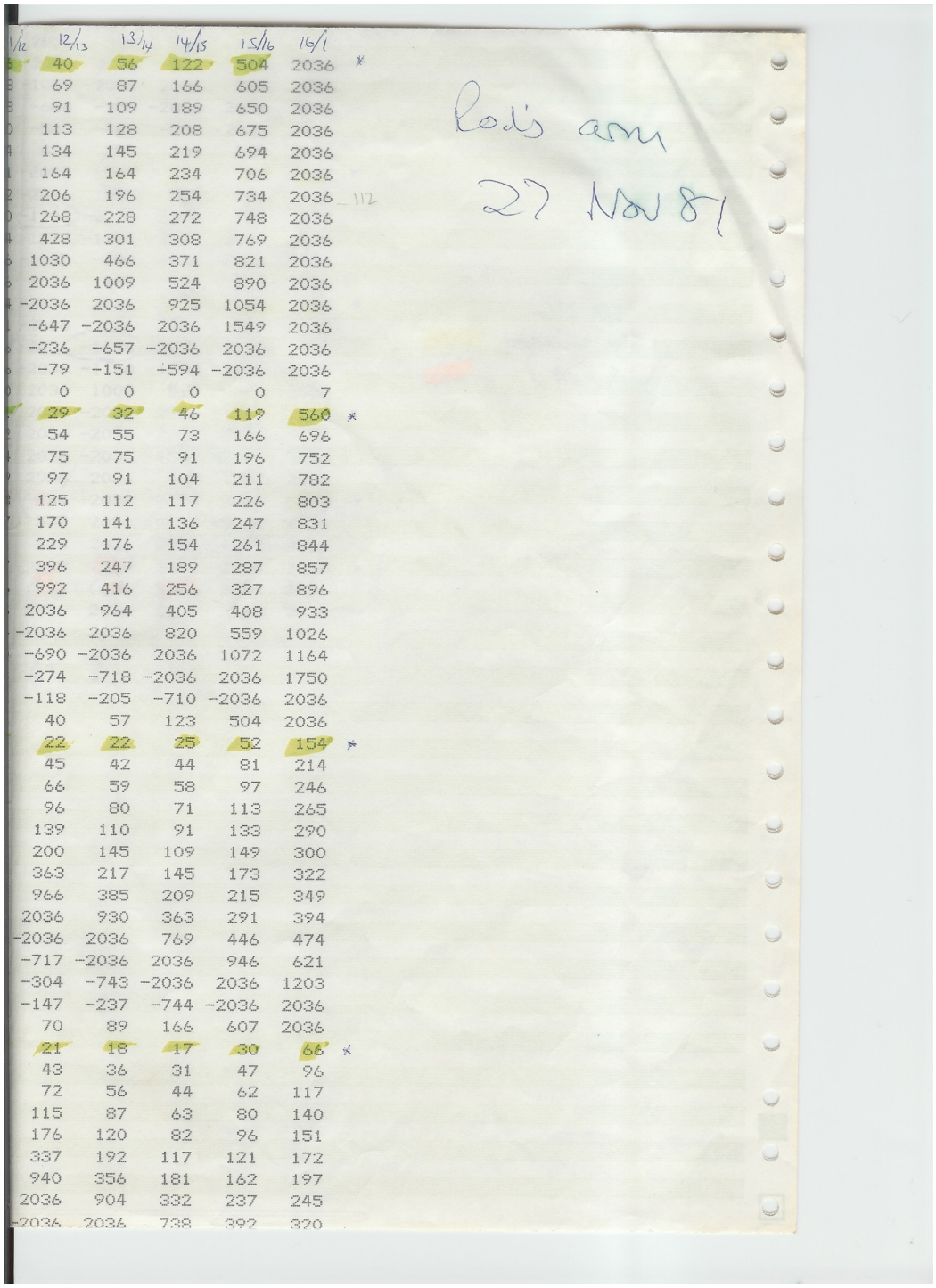
3/10	1040	2036	-2036	-1087	-406	-302	-406	-955	-2036	2036	1000
3/11	1063	2036	-2036	-1080	-369	-242	-260	-360	-1032	-2036	2036
3/12	1089	2036	-2036	-1047	-347	-204	-191	-205	-351	-936	-2036
3/13	1142	2036	-2036	-1048	-328	-178	-154	-141	-190	-336	-886
3/14	1191	2036	-2036	-1014	-312	-159	-125	-104	-117	-171	-330
3/15	1306	2036	-2036	-998	-297	-143	-108	-81	-82	-105	-176
3/16	1761	2036	-2036	-946	-275	-128	-88	-64	-55	-63	-96
3/1	2036	2036	2036	896	247	106	70	47	36	37	49
4/5	193	732	2036	-2036	2036	691	185	67	40	26	21
4/6	260	881	2036	-2036	-2036	2036	827	207	103	62	47
4/7	293	950	2036	-2036	-1961	-2036	2036	734	245	126	85
4/8	326	995	2036	-2036	-1340	-1143	-2036	2036	797	277	156
4/9	336	1018	2036	-2036	-1189	-614	-1021	-2036	2036	868	303
4/10	356	1031	2036	-2036	-1135	-467	-480	-985	-2036	2036	976
4/11	374	1062	2036	-2036	-1097	-412	-333	-397	-1048	-2036	2036
4/12	402	1075	2036	-2036	-1080	-370	-268	-241	-374	-948	-2036
4/13	443	1118	2036	-2036	-1061	-350	-228	-179	-215	-353	-902

Part of raw data. This is the full data set i.e. all drives and receives



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1	164	164	234	706	2036	
2	206	196	254	734	2036	112
0	268	228	272	748	2036	
4	428	301	308	769	2036	
6	1030	466	371	821	2036	
6	2036	1009	524	890	2036	
4	-2036	2036	925	1054	2036	
	-647	-2036	2036	1549	2036	
6	-236	-657	-2036	2036	2036	
6	-79	-151	-594	-2036	2036	
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	29	32	46	119	560	*
2	54	55	73	166	696	
4	75	75	91	196	752	
7	97	91	104	211	782	
8	125	112	117	226	803	
7	170	141	136	247	831	
	229	176	154	261	844	
	396	247	189	287	857	
	992	416	256	327	896	
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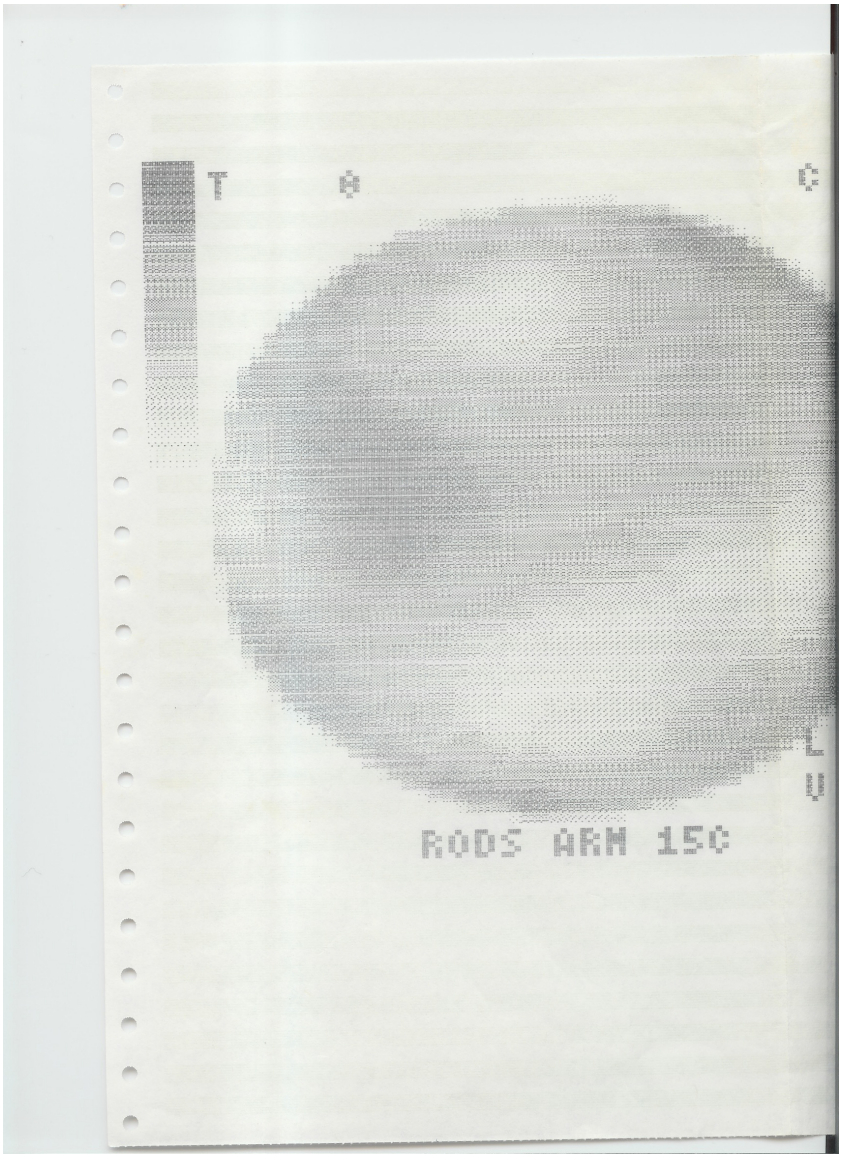
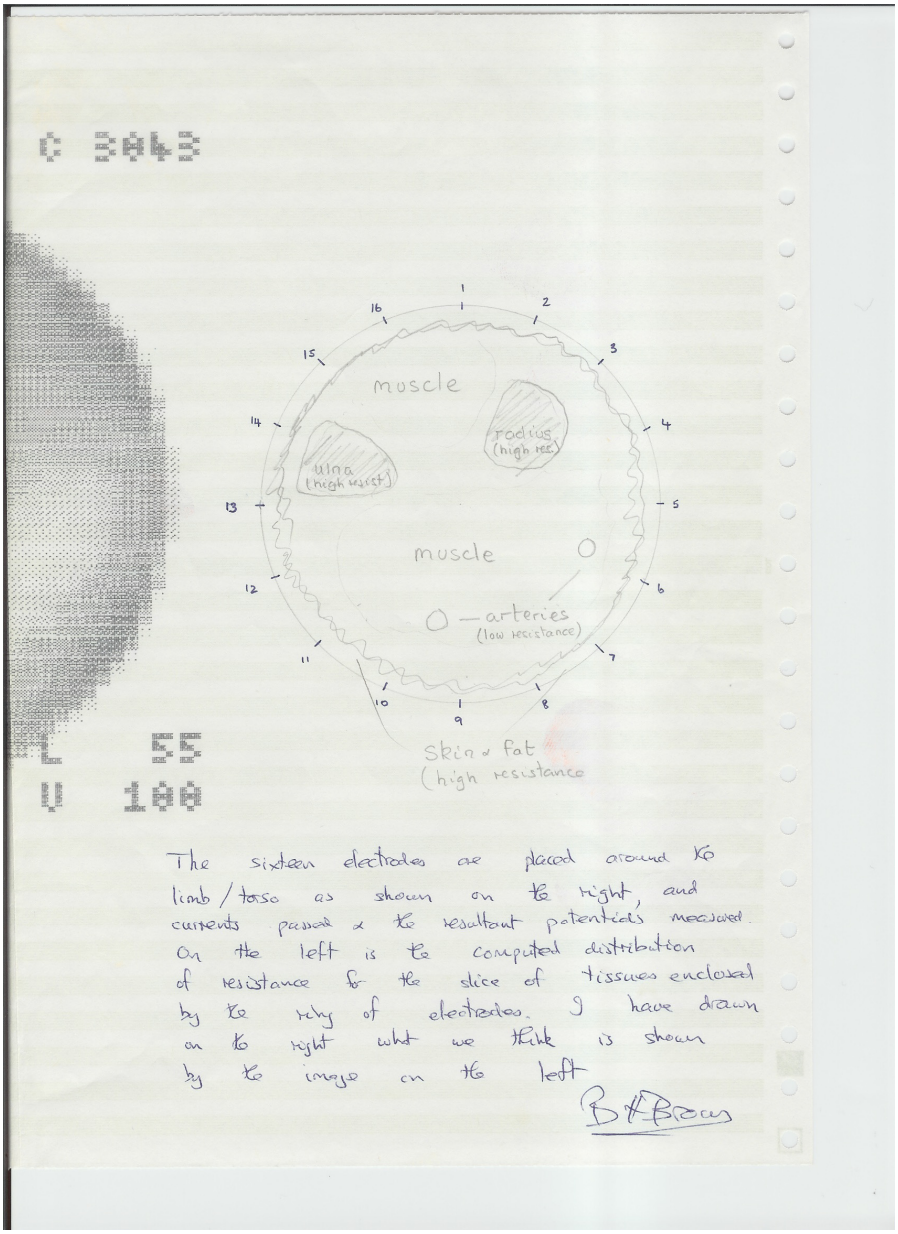
	-2036	2036	820	559	1026	
	-690	-2036	2036	1072	1164	
	-274	-718	-2036	2036	1750	
	-118	-205	-710	-2036	2036	
	40	57	123	504	2036	
	22	22	25	52	154	*
	45	42	44	81	214	
	66	59	58	97	246	
	96	80	71	113	265	
	139	110	91	133	290	
	200	145	109	149	300	
	363	217	145	173	322	
	966	385	209	215	349	
	2036	930	363	291	394	
	-2036	2036	769	446	474	
	-717	-2036	2036	946	621	
	-304	-743	-2036	2036	1203	
	-147	-237	-744	-2036	2036	
	70	89	166	607	2036	
	21	18	17	30	66	*
	43	36	31	47	96	
	72	56	44	62	117	
	115	87	63	80	140	
	176	120	82	96	151	
	337	192	117	121	172	
	940	356	181	162	197	
	2036	904	332	237	245	
	-2036	2036	738	392	320	

Rod's arm
27 Nov 87

Part of the line printer image of Rod's arm



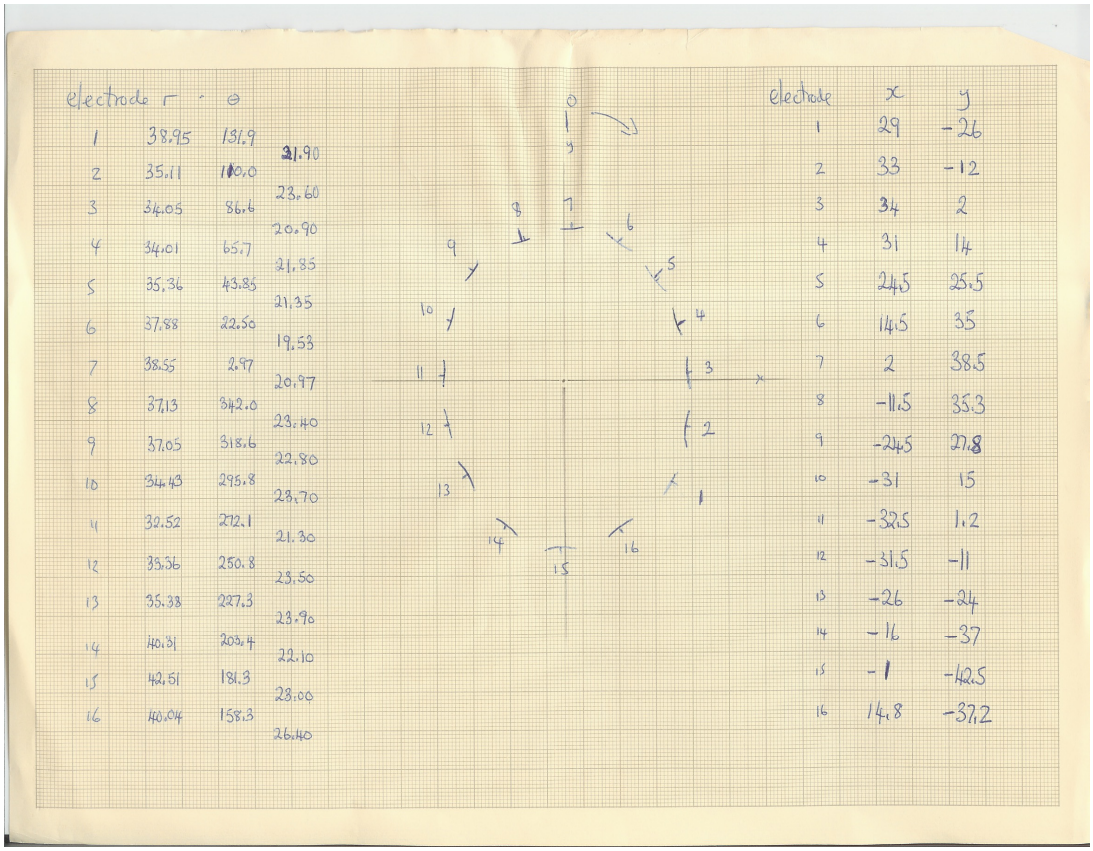
The other half of the dor matrix output



The sixteen electrodes are placed around the limb / torso as shown on the right, and currents passed & the resultant potentials measured. On the left is the computed distribution of resistance for the slice of tissues enclosed by the ring of electrodes. I have drawn on the right what we think is shown by the image on the left

B K Brown

Electrode positions on Rod's arm



Electrode	r	θ	
1	38.95	131.9	21.90
2	35.11	110.0	23.60
3	34.05	86.6	20.90
4	34.01	65.7	21.85
5	35.36	43.85	21.35
6	37.88	22.50	19.53
7	38.55	2.97	20.97
8	37.13	342.0	23.40
9	37.05	318.6	22.80
10	34.43	295.8	23.70
11	32.52	272.1	21.30
12	33.36	250.8	23.50
13	35.33	227.3	23.90
14	40.31	203.4	22.10
15	42.51	181.3	28.00
16	40.04	158.3	26.40

Electrode	x	y
1	29	-26
2	33	-12
3	34	2
4	31	14
5	24.5	25.5
6	14.5	35
7	2	38.5
8	-11.5	35.3
9	-24.5	27.8
10	-31	15
11	-32.5	1.2
12	-31.5	-11
13	-26	-24
14	-16	-37
15	-1	-42.5
16	14.8	-37.2

My notes showing the data from Rod's arm mold filled with saline. I have added the highlight and the red values that were missing. I have used the reciprocal values.