

Supplementary Material

Bioactive multiple-bent MWCNTs for sensitive and reliable electrochemical detection of picomolar-level C-reactive proteins

Table S1. EIS data at CRP concentration of 84 pM (MWCNTs/non-CF sample, n = 3).

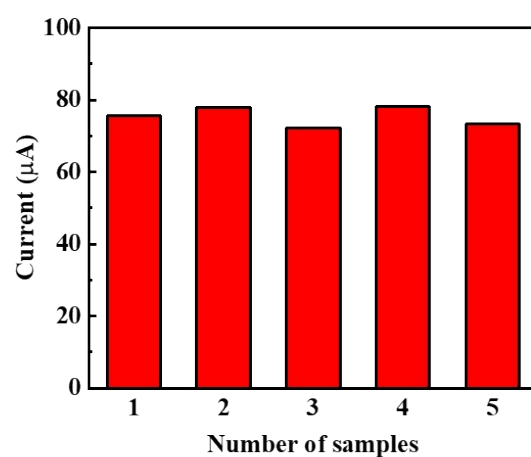
AC frequency (Hz)	Number of the experiment (1) Z' (ohms) -Z'' (ohms)		Number of the experiment (2) Z' (ohms) -Z'' (ohms)		Number of the experiment (3) Z' (ohms) -Z'' (ohms)		Z' Average (ohms)	Z' Standard deviation (S.D)	Z'' Average (ohms)	-Z'' Standard deviation (S.D)
100000.00	27.803	1.875	28.539	2.233	28.562	2.606	28.301	0.3525	2.238	0.2982
79432.82	27.957	2.347	28.146	2.679	28.515	2.748	28.206	0.2316	2.591	0.1750
63095.73	28.190	2.861	28.747	3.049	28.699	3.682	28.545	0.2518	3.198	0.3512
50118.72	28.478	3.487	28.886	3.655	28.967	3.755	28.777	0.2139	3.632	0.1109
39810.72	28.799	4.110	28.947	4.361	29.468	4.930	29.071	0.2872	4.467	0.3428
31622.78	29.164	4.915	29.504	5.334	29.652	5.425	29.440	0.2044	5.225	0.2223
25118.87	29.602	5.827	29.984	6.022	30.208	6.319	29.931	0.2500	6.056	0.2023
19952.62	30.115	6.894	31.074	7.398	30.537	7.239	30.575	0.3926	7.177	0.2104
15848.93	30.698	8.125	31.383	8.223	30.975	8.633	31.019	0.2813	8.327	0.2199
12589.25	31.430	9.512	31.998	10.351	32.338	10.010	31.922	0.3747	9.957	0.3445
10000.00	32.231	11.189	33.024	11.316	32.493	11.493	32.583	0.3297	11.333	0.1249
7943.28	33.313	13.344	33.565	13.595	33.787	13.989	33.555	0.1938	13.642	0.2656
6309.57	34.525	15.639	35.471	15.804	35.370	16.318	35.122	0.4240	15.920	0.2888
5011.87	36.026	18.535	36.603	19.307	36.329	19.240	36.319	0.2356	19.027	0.3492
3981.07	37.824	21.879	38.711	22.503	38.057	22.112	38.197	0.3756	22.165	0.2576
3162.28	39.984	25.612	40.276	26.381	40.871	26.105	40.377	0.3692	26.033	0.3183
2511.89	42.973	30.387	43.630	30.665	43.864	30.477	43.489	0.3773	30.510	0.1156
1995.26	46.241	35.130	47.173	35.593	47.198	35.837	46.871	0.4456	35.520	0.2929
1584.89	50.896	41.175	51.378	41.642	51.138	41.943	51.137	0.1969	41.587	0.3160
1258.93	56.713	47.800	57.220	48.537	57.286	48.170	57.073	0.2557	48.169	0.3009
1000.00	63.451	54.397	63.694	54.881	64.239	55.133	63.795	0.3295	54.804	0.3053
794.33	72.207	61.616	72.537	62.330	72.637	62.411	72.460	0.1840	62.119	0.3572
630.96	83.334	69.000	84.298	69.693	84.270	69.331	83.967	0.4481	69.341	0.2829
501.19	95.331	75.150	95.740	75.591	95.864	75.227	95.645	0.2275	75.323	0.1923
398.11	109.732	80.576	110.425	81.163	110.130	80.631	110.096	0.2842	80.790	0.2644
316.23	125.954	84.254	126.648	84.594	126.478	84.629	126.360	0.2954	84.492	0.1693
251.19	141.141	85.611	141.453	86.436	142.029	86.044	141.541	0.3679	86.030	0.3368
199.53	158.179	85.061	158.890	85.483	158.631	85.241	158.567	0.2939	85.262	0.1725
158.49	174.350	82.125	174.507	82.475	174.871	82.246	174.576	0.2185	82.282	0.1452
125.89	188.133	78.242	188.393	78.658	188.534	78.332	188.353	0.1662	78.411	0.1787
100.00	201.335	72.825	201.778	73.526	201.633	73.423	201.582	0.1847	73.258	0.3088
79.43	212.792	66.504	213.243	67.353	213.543	66.900	213.193	0.3086	66.919	0.3469
63.10	221.909	60.614	222.189	60.914	222.723	60.842	222.273	0.3376	60.790	0.1281
50.12	230.291	54.956	230.585	55.562	230.970	55.718	230.615	0.2783	55.412	0.3288
39.81	237.809	49.345	238.414	50.098	238.386	49.795	238.203	0.2785	49.746	0.3094
31.62	243.807	43.982	244.733	44.019	244.093	44.364	244.211	0.3871	44.122	0.1724
25.12	248.532	39.284	249.073	39.784	249.160	39.350	248.921	0.2777	39.473	0.2219

19.95	253.255	35.233	254.023	35.666	253.835	35.407	253.704	0.3267	35.435	0.1775
15.85	257.520	31.511	258.407	31.756	258.023	32.125	257.983	0.3632	31.798	0.2524
12.59	260.801	28.401	261.526	28.803	261.292	28.748	261.206	0.3021	28.651	0.1779
10.00	263.690	25.351	264.251	26.189	264.319	25.978	264.087	0.2818	25.839	0.3563
7.94	266.478	22.904	267.324	23.634	266.994	23.580	266.932	0.3480	23.373	0.3324
6.31	269.048	20.748	269.653	20.934	270.000	21.231	269.567	0.3932	20.971	0.1993
5.01	271.337	18.805	271.942	19.052	271.531	19.505	271.603	0.2523	19.120	0.2899
3.98	273.496	17.196	273.701	17.626	273.861	17.539	273.686	0.1492	17.454	0.1855
3.16	275.523	15.767	276.387	16.437	275.847	16.172	275.919	0.3564	16.125	0.2754
2.51	277.331	14.451	277.682	14.597	277.708	14.838	277.573	0.1718	14.629	0.1593
2.00	279.007	13.329	279.934	13.749	279.757	13.754	279.566	0.4016	13.610	0.1991
1.58	280.661	12.302	280.825	12.665	281.599	12.519	281.029	0.4092	12.495	0.1495
1.26	282.153	11.368	283.098	12.185	283.063	11.489	282.771	0.4372	11.681	0.3601
1.00	283.498	10.598	283.613	11.296	284.372	10.766	283.828	0.3874	10.887	0.2975
0.79	284.851	9.806	285.682	10.618	285.023	10.357	285.186	0.3580	10.260	0.3384
0.63	286.112	9.106	286.841	9.682	286.371	9.675	286.441	0.3016	9.487	0.2699
0.50	287.249	8.458	287.678	9.026	287.904	8.842	287.610	0.2713	8.775	0.2365
0.40	288.273	7.793	288.849	8.397	288.417	8.520	288.513	0.2449	8.237	0.3176
0.32	289.266	7.215	290.071	7.698	289.550	7.908	289.629	0.3333	7.607	0.2902
0.25	290.217	6.757	290.413	7.389	290.721	7.515	290.450	0.2074	7.220	0.3318
0.20	291.026	6.193	291.415	6.981	291.408	6.462	291.283	0.1818	6.545	0.3270
0.16	291.759	5.765	292.176	6.143	291.943	6.266	291.959	0.1703	6.058	0.2131
0.13	292.438	5.382	292.710	5.791	293.302	5.518	292.817	0.3609	5.564	0.1702
0.10	293.064	4.855	293.398	4.938	293.843	5.688	293.435	0.3189	5.160	0.3746
Average								0.2990	Average	0.2559
S.D.								0.0791	S.D.	0.0747

Table S2. EIS data at CRP concentration of 84 pM (MWCNTs/CF sample, n = 3).

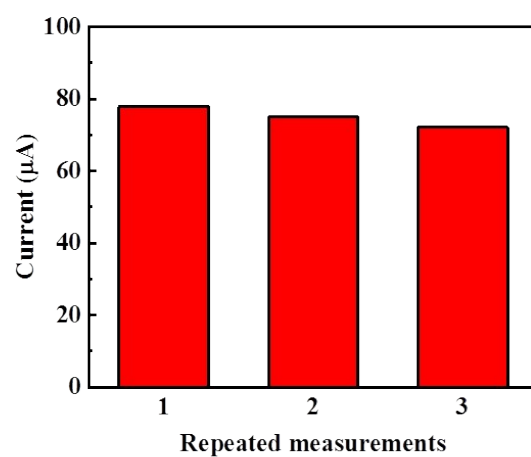
AC frequency (Hz)	Number of the experiment (1) Z' (ohms) -Z'' (ohms)		Number of the experiment (2) Z' (ohms) -Z'' (ohms)		Number of the experiment (3) Z' (ohms) -Z'' (ohms)		Z' Average (ohms)	Z' Standard deviation (S.D)	Z'' Average (ohms)	-Z'' Standard deviation (S.D)
100000.00	27.803	1.875	28.049	2.105	28.120	2.122	27.990	0.1360	2.034	0.1124
79432.82	27.957	2.347	28.241	2.509	28.170	2.492	28.123	0.1205	2.449	0.0727
63095.73	28.190	2.861	28.433	3.191	28.456	3.198	28.360	0.1203	3.083	0.1572
50118.72	28.478	3.487	28.677	3.590	28.704	3.773	28.620	0.1007	3.617	0.1182
39810.72	28.799	4.110	28.920	4.218	29.030	4.273	28.916	0.0945	4.200	0.0674
31622.78	29.164	4.915	29.425	5.133	29.349	5.298	29.313	0.1094	5.115	0.1569
25118.87	29.602	5.827	29.932	6.153	29.871	6.095	29.802	0.1434	6.025	0.1417
19952.62	30.115	6.894	30.449	6.951	30.374	7.042	30.312	0.1431	6.962	0.0609
15848.93	30.698	8.125	30.818	8.259	30.801	8.315	30.773	0.0529	8.233	0.0798
12589.25	31.430	9.512	31.641	9.775	31.745	9.754	31.605	0.1311	9.680	0.1196
10000.00	32.231	11.189	32.545	11.228	32.479	11.363	32.419	0.1351	11.260	0.0745
7943.28	33.313	13.344	33.504	13.680	33.598	13.504	33.472	0.1184	13.509	0.1373
6309.57	34.525	15.639	34.795	15.808	34.711	15.736	34.677	0.1127	15.728	0.0692
5011.87	36.026	18.535	36.326	18.665	36.291	18.870	36.214	0.1340	18.690	0.1380
3981.07	37.824	21.879	38.114	22.183	38.163	22.119	38.034	0.1493	22.061	0.1308
3162.28	39.984	25.612	40.149	25.939	40.237	25.975	40.123	0.1050	25.842	0.1632
2511.89	42.973	30.387	43.125	30.587	43.170	30.535	43.089	0.0844	30.503	0.0844
1995.26	46.241	35.130	46.523	35.453	46.503	35.399	46.422	0.1286	35.328	0.1411
1584.89	50.896	41.175	51.171	41.434	51.051	41.340	51.039	0.1124	41.316	0.1070
1258.93	56.713	47.800	57.100	47.907	57.059	47.862	56.957	0.1733	47.856	0.0441
1000.00	63.451	54.397	63.662	54.426	63.736	54.642	63.616	0.1206	54.488	0.1091
794.33	72.207	61.616	72.525	61.782	72.448	61.873	72.393	0.1356	61.757	0.1064
630.96	83.334	69.000	83.602	69.236	83.508	69.121	83.481	0.1112	69.119	0.0961
501.19	95.331	75.150	95.506	75.297	95.675	75.487	95.504	0.1403	75.311	0.1379
398.11	109.732	80.576	110.039	80.892	109.977	80.858	109.916	0.1328	80.775	0.1414
316.23	125.954	84.254	126.300	84.455	126.241	84.377	126.165	0.1511	84.362	0.0828
251.19	141.141	85.611	141.451	85.946	141.459	85.737	141.351	0.1481	85.765	0.1379
199.53	158.179	85.061	158.322	85.202	158.445	85.126	158.315	0.1087	85.130	0.0575
158.49	174.350	82.125	174.596	82.386	174.673	82.214	174.539	0.1378	82.242	0.1085
125.89	188.133	78.242	188.465	78.330	188.497	78.409	188.365	0.1645	78.327	0.0684
100.00	201.335	72.825	201.685	72.936	201.558	73.057	201.526	0.1448	72.939	0.0945
79.43	212.792	66.504	212.929	66.654	213.096	66.816	212.939	0.1241	66.658	0.1273
63.10	221.909	60.614	222.252	60.936	222.291	60.957	222.151	0.1718	60.836	0.1572
50.12	230.291	54.956	230.468	55.261	230.525	55.065	230.428	0.0999	55.094	0.1263
39.81	237.809	49.345	238.166	49.510	238.193	49.505	238.056	0.1749	49.453	0.0767
31.62	243.807	43.982	244.157	44.226	244.179	44.233	244.047	0.1704	44.147	0.1170
25.12	248.532	39.284	248.775	39.532	248.710	39.575	248.672	0.1029	39.464	0.1281

19.95	253.255	35.233	253.588	35.427	253.453	35.589	253.432	0.1366	35.416	0.1452
15.85	257.520	31.511	257.751	31.611	257.831	31.682	257.701	0.1320	31.601	0.0702
12.59	260.801	28.401	261.066	28.595	261.052	28.573	260.973	0.1219	28.523	0.0866
10.00	263.690	25.351	263.976	25.489	263.933	25.513	263.866	0.1259	25.451	0.0715
7.94	266.478	22.904	266.678	23.257	266.753	23.102	266.636	0.1158	23.087	0.1445
6.31	269.048	20.748	269.251	20.920	269.271	20.961	269.190	0.1008	20.876	0.0924
5.01	271.337	18.805	271.676	18.941	271.688	19.082	271.567	0.1629	18.942	0.1129
3.98	273.496	17.196	273.632	17.230	273.733	17.240	273.620	0.0972	17.222	0.0186
3.16	275.523	15.767	275.726	15.851	275.710	15.932	275.653	0.0919	15.850	0.0674
2.51	277.331	14.451	277.591	14.780	277.579	14.533	277.500	0.1199	14.588	0.1399
2.00	279.007	13.329	279.339	13.651	279.204	13.518	279.184	0.1363	13.499	0.1321
1.58	280.661	12.302	280.871	12.483	280.918	12.471	280.817	0.1116	12.418	0.0828
1.26	282.153	11.368	282.408	11.439	282.415	11.594	282.326	0.1220	11.467	0.0944
1.00	283.498	10.598	283.699	10.675	283.715	10.661	283.638	0.0987	10.645	0.0333
0.79	284.851	9.806	285.151	10.086	285.176	10.037	285.059	0.1473	9.976	0.1221
0.63	286.112	9.106	286.397	9.214	286.308	9.412	286.273	0.1194	9.244	0.1267
0.50	287.249	8.458	287.456	8.649	287.577	8.680	287.427	0.1351	8.596	0.0981
0.40	288.273	7.793	288.540	7.832	288.566	7.905	288.460	0.1325	7.843	0.0464
0.32	289.266	7.215	289.510	7.315	289.561	7.570	289.446	0.1289	7.367	0.1494
0.25	290.217	6.757	290.585	7.018	290.401	6.893	290.401	0.1505	6.889	0.1069
0.20	291.026	6.193	291.346	6.285	291.261	6.415	291.211	0.1352	6.298	0.0911
0.16	291.759	5.765	292.053	5.941	292.038	5.999	291.950	0.1350	5.902	0.0993
0.13	292.438	5.382	292.779	5.601	292.688	5.592	292.635	0.1442	5.525	0.1012
0.10	293.064	4.855	293.261	5.059	293.248	5.163	293.191	0.0899	5.026	0.1279
Average								0.1268	Average	0.1051
S.D.								0.0235	S.D.	0.0336



1	2	3	4	5	RSD
75.47	77.91	72.25	78.11	73.25	3.15 %

Figure S1. Reproducibility of MWCNTs/CF samples for CRP solution (0.084 nM)



1	2	3	RSD
77.89	75.11	72.15	3.12 %

Figure S2. Repeatability of a MWCNTs/CF sample for CRP solution (0.084 nM)

Table S3. Comparison of the analytical performance between the present and previously-reported works to detect CRPs.

Sensor	Analytical technique	Detection range	LOD	Reproducibility (R.S.D)	Repeatability (R.S.D)	Ref.
MPA/Au substrate	EIS, CV	5 – 220 fg/mL	2.25 fg/mL	3.12%	1.28%	1
ZnO/MPC/IL-CPE	EIS, CV	0.01 – 1000 ng/mL	5.0 pg/mL	5.1%	4.2%	2
Gold nanoparticles/Graphene/Screen-printed carbon electrode	EIS	0.05 – 100 µg/mL	0.015 µg/mL	2.19 to 3.39%	1.54%	3
CNT-TF	EIS	0 – 4000 pg/mL	6 pg/mL	0.85% - 1.44%	-	4
Interdigitated chain-shaped electrode	EIS	10^{-3} – 10^3 ng/mL	100 pg/mL	-	-	5
GWEs/PS/MIPA GWEs/PP/MIPL	EIS, CV	0 – 50 µg/mL for A 1 – 32 ng/mL for L	0.25 µg/mL for A 0.110 ng/mL for L	-	-	6
MWCNTs/CF	EIS, CV	10 – 1000 ng/mL	40 pM	3.15%	3.12%	This work

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