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Fractal Geometry in Urodynamics of Lower Urinary Tract

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Abstract

The physiological signals are usually extremely complicated and difficult to analyze. Recently, investigators have tried the fractal dimension that can characterize roughness and self-similarity of them. It turns out that it is also suitable for obtaining the modalities of lower urinary tract during normal micturition. In this investigation, the external urethral sphincter electromyogram (EUS EMG) and the cystometrogram (CMG) of the Wistar rats under both room temperature and cold water stimulation of the bladder are studied. The modified relative differential box-counting (RDBC) method is used to calculate the fractal dimensions of EMG and CMG time series. According to the experimental results, the modalities of micturition for the Wistar rats can be characterized as normal if both the fractal dimensions of EMG and CMG are of low values during voiding. Furthermore, the technique is validated in identifying the dyssynergia of the bladder and EUS under cold water stimulation.

Key Words: cystometrogram, external urethral sphincter electromyogram, fractional dimension, relative differential box-counting, urodynamics

Introduction

Most of the urologists think that during urine storage, the bladder is quiescent and the external urethral sphincter (EUS) is active, whereas during voiding in many species (e.g., humans and cats), the bladder is active and the EUS is inhibited (6, 9, 13, 15). Some researchers emphasize that EUS has reduced activity but not quiescent. M. N. Kruse et al. (8) used the Wistar rats to obtain quite different results. The EMG of EUS during voiding was not quiescent and there was no reduced activity. Bursting EUS activity was observed. Hence, they suggested that the normal bursting EUS activity facilitates bladder emptying. Many researchers continue to discuss the relationship of bladder and EUS of various cases, including the rats after decerebration, of spinal cord injury (SCI), under cold-temperature stimulation, and administered medicine during voiding (1-5). However, most of the researches have not characterized the unique properties during the three phases of micturition (i. e., the filling phase, voiding phase and relaxing phase). In this paper, the signals of EUS EMG and CMG are used to obtain such modalities of normal Wistar rats with room-temperature stimulation.

Notice that the conventional signal processing techniques, such as Fourier transform, or autocorrelation analysis, do not work well. In order to obtain useful results, fractal modeling is invoked. This technique does not assume that the objects or signals possess any continuity or smooth properties intrinsically except that they are self-similar (11). Therefore, the dimension of fractal geometry can be

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used as an index to compare the different phases of the EMG and CMG signals. In this paper, the relative differential box-counting (RDBC) method (7) is modified and adopted to estimate the fractal dimension (10, 12).

Materials and Methods

Animals

The experiments were performed on female Wistar rats anesthetized with urethane. The trachea was cannulated to facilitate respiration, and arterial blood pressure was monitored via a pressure transducer connected to a cannula in the common carotid artery. The bladder was exposed via a middle abdominal incision. The rostral half of pubic symphysis was removed to expose the middle urethra and EUS. A neuromuscular blocking agent was used to block EUS activity to show that the EUS EMG was attributed to striated muscle because the activity was eliminated after neuromuscular blockade. Two insulated silver wire electrodes with exposed tips were inserted into lateral sides of midurethra, where muscle fibers of the EUS were identified. The CMG with an infusion rate of 0.123 ml/min using saline solutions at two different temperatures: room temperature and cold temperature (6-8°C) were obtained. The CMG and EUS EMG activities were displayed on a storage oscilloscope and recorded on a videocassette tape recorder and a paper recorder along with the blood pressure.

Fractal Dimension Estimation with the Relative Differential Box-Counting Method

The relative differential box-counting (RDBC) method proposed in (7) was originally formulated to estimate the fractal dimension of two-dimension surfaces. The following modification is required in order to satisfy our cases (10, 12).

The RDBC method is derived from the metric property equation suggested by Pentland (14):

$$P=N(e)e^{D}. \quad [1]$$

In fact, the RDBC method is quite similar to the DBC method except the range of box size as estimating the fractal dimension. In the DBC method, the box size s is satisfied by the condition, $2 \le s \le M/2$ with time series signal of size M, whereas in the RDBC method is $s_{\min} \le s \le s_{\max}$. Both of the lower and upper limits are dependent on M.

$$s_{\min}=\frac{M}{N(e_{mn})^{1/D}}=\frac{M}{M^{2/3}}=M^{1/3}, \quad [2]$$

$$\text{ceil}[M/s_{\max}]+1 \le \text{ceil}[M/(S_{\max}-1)]. \quad [3]$$

But in our cases, if we want to use the lower limit, [2] has to be modified as

$$s_{\min}=\frac{M}{M^{1/2}}=M^{1/2}. \quad [4]$$

Next, the modified RDBC algorithm is summarized step by step as follows:

Step 1

Compute the upper scale limit $s_{\max}$ by [3], and set $s_{\min}=10$. We don't use $s_{\min}$ since the range will be too small if $s_{\min}=M^{1/2}$.

Step 2

Find the amplitude range G of x according to $G=\max(x)-\min(x)$.

Step 3

Compute the number of partitions $N_{pt}(s)$ with variations of s by

$$N_{pt}(s)=\text{ceil}[M/s]. \quad [5]$$

Step 4

Find $d_s(i)$, which is the difference between the maximum and minimum amplitudes in ith interval for $i=1, \ldots, N_{pt}(s)$ and $h(s)$ by $h(s)=G/N_{pt}(s)$.

Step 5

Find the number of elemental units of size $s \times h(s)$ needed to cover the interval by

$$n_s(i)=\text{ceil}[d_s(i)/h(s)]. \quad [6]$$

Step 6

Compute the total number of elemental units needed to cover x at scale s, $N(s)$ by

$$N(s)=\sum_i n_s(i). \quad [7]$$

Step 7

Check the upper limit. If $s \le s_{\max}$, then repeat *step 3* to *step 6*. Else, stop the loop.

Step 8

Fit log$s$ and $-\log [N(s)]$ for $s=10, \ldots, s_{mx}$ with a straight line $y=mx+c$. The estimated fractal dimension we want is equal to m.

Procedure

To establish the statistical fractal dimension of EUS EMG and CMG, we take 44 periods of time series from 8 Wistar rats for room-temperature stimulation cases, and 23 among 5 Wistar rats for cold-temperature stimulation. Each period contains a complete bladder contraction. For processing in computer, the signals were sampled from the videocassette of EUS EMG and CMG via the MP100WSW system. The sampling rate was 500 points/sec. The length of the series with room-temperature stimulation was 30 seconds, i.e. 15000 points, and the length of the series with cold-temperature stimulation was 48 seconds, i.e. 24000 points. The width of the window we used was 800 points for room-temperature stimulation and 1200 points for cold-temperature stimulation. The chosen width has been compared in detail to make sure that it can catch the features of different parts.

Initially, when we estimated the fractal dimension of voiding signals with room-temperature stimulation, the window was placed in the first 800 points of the time series. We estimated the fractal dimension of the subseries covered by the window via RDBC methods. The window was then shifted 40 points to the right and the corresponding value of fractal dimension was estimated. We repeated the above steps until the window was placed in the last 800 points of the time series. For those voiding signals with cold-temperature stimulation, the steps were similar except the window width was 1200 and the shifted points were 60.

In addition to the fractal dimension, we need to retrieve the location of the time series corresponding to the fractal dimension. Hence, we can study each phase and its corresponding properties in the time domain. Even though one value of fractal dimension was calculated from 800 points of the time series, sufficient accuracy in the time domain still can be guaranteed.

Results

Room-Temperature Stimulation

In Fig. 1A and Fig. 1B, the EUS EMG and CMG signals are recorded from the Wistar rats with room-temperature saline infusion. Although there are differences between time series, such as the amplitude and frequency of bursting in the EUS EMG (Fig. 1A) or the amplitude and lasting time of bladder contraction

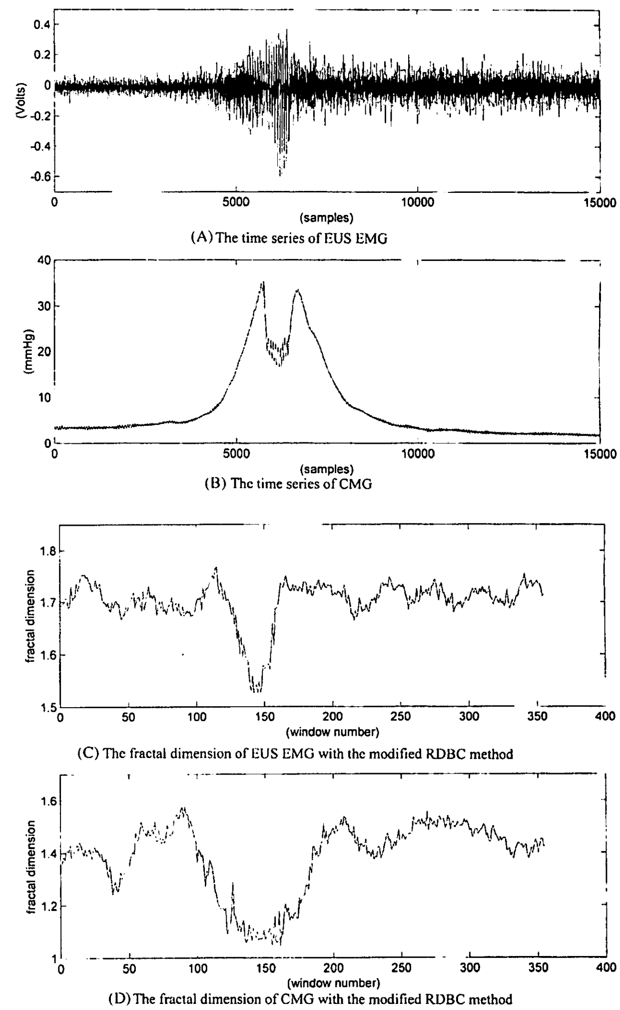

Fig. 1. Signals with room-temperature stimulation.

in the CMG (Fig. 1B), all the diagrams of fractal dimension have the same general patterns (Fig. 1C, Fig. 1D). When the bursting of time series happens, the value of fractal dimension decreases. It lasts at low level until the busting ends. That is, the fractal dimension has minimal value in the voiding phase. In the first phase, i.e. the filling phase, and the third phase, i.e. the relaxed phase, the values of fractal dimension are clearly larger. We can find that the average value of the third phase is a little larger than that of the first phase from Table 1. Although the average values of fractal dimension between different contraction are not the same in Table 1, the patterns of three phases are similar.

On the other hand, the values of fractal dimension of CMG are also obtained. In the time domain, the bladder activity often lasts longer than EUS. In Fig. 1B, the CMG still has active signals when the bursting of EUS EMG ends. We can also find that the fractal dimension of CMG has minimal values when the fractal dimension of EUS EMG

Table 1A. The Average Fractal Dimension Values of EUS EMG of All Normal Rats with Room-Temperature Stimulation (The Modified RDBC Method)

	Mean1	Std1	Mean2	Std2	Mean3	Std3
1	1.5793	0.0290	1.4535	0.0344	1.7097	0.0214
2	1.6277	0.0222	1.4767	0.0494	1.7170	0.0198
3	1.6130	0.0244	1.4654	0.0436	1.7187	0.0187
4	1.6276	0.0253	1.4833	0.0550	1.7092	0.0202
5	1.5549	0.0325	1.4177	0.0327	1.7271	0.0229
6	1.6070	0.0222	1.4553	0.0415	1.7099	0.0244
7	1.7633	0.0113	1.6890	0.0387	1.7451	0.0170
8	1.7530	0.0092	1.6759	0.0407	1.7337	0.0150
9	1.7235	0.0236	1.6375	0.0219	1.7439	0.0164
10	1.7419	0.0173	1.6328	0.0484	1.7360	0.0211
11	1.7362	0.0166	1.6561	0.0318	1.7400	0.0209
12	1.6701	0.0357	1.5705	0.0239	1.7064	0.0265
13	1.6729	0.0331	1.5620	0.0278	1.7223	0.0119
14	1.6668	0.0209	1.5589	0.0393	1.7085	0.0261
15	1.6580	0.0206	1.5633	0.0322	1.7312	0.0208
16	1.7019	0.0211	1.5853	0.0429	1.7150	0.0175
17	1.6761	0.0288	1.5872	0.0139	1.7238	0.0197
18	1.6988	0.0161	1.5850	0.0375	1.7228	0.0199
19	1.7242	0.0206	1.5512	0.0854	1.7138	0.0144
20	1.7049	0.0340	1.5119	0.0673	1.7134	0.0199
21	1.7072	0.0218	1.5348	0.0853	1.7115	0.0230
22	1.7086	0.0204	1.5555	0.0569	1.7025	0.0186
23	1.7204	0.0134	1.5030	0.0974	1.7222	0.0182
24	1.6923	0.0197	1.5462	0.0531	1.6872	0.0772
25	1.7290	0.0142	1.5529	0.0528	1.7523	0.0167
26	1.7295	0.0197	1.5638	0.0504	1.7383	0.0147
27	1.7303	0.0308	1.5510	0.0215	1.7388	0.0216
28	1.7280	0.0133	1.5504	0.0707	1.6794	0.0902
29	1.6402	0.0075	1.6228	0.0076	1.6827	0.0276
30	1.6877	0.0157	1.6225	0.0303	1.6901	0.0366
31	1.6798	0.0235	1.6203	0.0153	1.6827	0.0252
32	1.6545	0.0229	1.6018	0.0451	1.6889	0.0197
33	1.6182	0.0429	1.5334	0.0261	1.6994	0.0285
34	1.6242	0.0241	1.5410	0.0252	1.7084	0.0197
35	1.6137	0.0402	1.5269	0.0269	1.7048	0.0278
36	1.7478	0.0137	1.6514	0.0439	1.7482	0.0181
37	1.7233	0.0334	1.5841	0.0086	1.7521	0.0249
38	1.7533	0.0144	1.6550	0.0500	1.7476	0.0158
39	1.7399	0.0180	1.6104	0.0491	1.7415	0.0215
40	1.7028	0.0241	1.5730	0.0488	1.6987	0.0266
41	1.6690	0.0301	1.5511	0.0336	1.7108	0.0225
42	1.6979	0.0129	1.5888	0.0482	1.6943	0.0192
43	1.6843	0.0326	1.5762	0.0290	1.6982	0.0225
44	1.6962	0.0167	1.5742	0.0500	1.7008	0.0217
Average	1.6769	0.0217	1.5660	0.0517	1.7166	0.0239

Mean1: the mean value of fractal dimension in the first stage.
Mean2: the mean value of fractal dimension in the second stage.
Mean3: the mean value of fractal dimension in the third stage.
std1: the standard deviation of fractal dimension in the first stage.
std2: the standard deviation of fractal dimension in the second stage.
std3: the standard deviation of fractal dimension in the third stage.

Table 1B. The Average Fractal Dimension Values of CMG of All Normal Rats with Room-Temperature Stimulation (the Modified RDBC Method)

	Mean1	Std1	Mean2	Std2	Mean3	Std3
1	1.2441	0.0385	1.1293	0.0211	1.3420	0.0798
2	1.3124	0.0814	1.0864	0.0222	1.4235	0.0341
3	1.4086	0.0437	1.1767	0.0710	1.3559	0.0784
4	1.2420	0.0584	1.1127	0.0342	1.3968	0.1010
5	1.3759	0.0772	1.1242	0.0565	1.2946	0.0644
6	1.4457	0.0395	1.2038	0.0963	1.4002	0.0803
7	1.5513	0.0262	1.2218	0.0906	1.5472	0.0322
8	1.5242	0.0325	1.2330	0.0885	1.5527	0.0229
9	1.5459	0.0301	1.2987	0.1182	1.5561	0.0237
10	1.5530	0.0252	1.3003	0.0808	1.5497	0.0246
11	1.5298	0.0241	1.2592	0.1371	1.5473	0.0217
12	1.3767	0.0599	1.1123	0.0563	1.4215	0.0659
13	1.3725	0.1097	1.1050	0.0262	1.4324	0.0532
14	1.4154	0.0432	1.1195	0.0506	1.4037	0.0685
15	1.4384	0.0473	1.1578	0.0759	1.4716	0.0485
16	1.4093	0.0826	1.0873	0.0313	1.4630	0.0459
17	1.4760	0.0222	1.1253	0.0478	1.4086	0.0525
18	1.4333	0.0547	1.1338	0.0499	1.4263	0.0628
19	1.2099	0.0611	1.0614	0.0102	1.2396	0.0694
20	1.2892	0.0474	1.0878	0.0403	1.2129	0.0934
21	1.2476	0.0589	1.0613	0.0387	1.2546	0.0702
22	1.2434	0.0963	1.0768	0.0297	1.2474	0.0552
23	1.2282	0.0587	1.0083	0.0260	1.2672	0.0394
24	1.3062	0.0687	1.1008	0.0333	1.3327	0.0457
25	1.3405	0.0580	1.1170	0.0346	1.3087	0.0700
26	1.3599	0.0420	1.1185	0.0464	1.3341	0.0620
27	1.3236	0.0341	1.1224	0.0403	1.2605	0.0785
28	1.3454	0.0533	1.1378	0.0626	1.3784	0.0391
29	1.5156	0.0542	1.3646	0.0243	1.5584	0.0678
30	1.4620	0.1050	1.1613	0.0251	1.4976	0.0389
31	1.4887	0.0924	1.1019	0.0061	1.5216	0.0354
32	1.5399	0.0314	1.1668	0.0485	1.4565	0.0383
33	1.3461	0.1696	1.0670	0.0036	1.4992	0.0363
34	1.5178	0.0202	1.3015	0.1691	1.4041	0.1701
35	1.3686	0.1925	1.0590	0.0069	1.5063	0.0249
36	1.2004	0.0368	1.1216	0.0503	1.1953	0.0254
37	1.1866	0.0186	1.1039	0.0328	1.2276	0.1391
38	1.1983	0.0560	1.1289	0.0353	1.2134	0.0291
39	1.2323	0.0402	1.1122	0.0287	1.1800	0.0546
40	1.5995	0.0792	1.2197	0.0634	1.6483	0.0959
41	1.4324	0.1949	1.1044	0.0198	1.6426	0.0282
42	1.4868	0.0373	1.2472	0.1020	1.3835	0.0600
43	1.3532	0.0447	1.1647	0.0349	1.3117	0.0359
44	1.3077	0.0350	1.1651	0.0461	1.3369	0.0280
Average	1.3815	0.0632	1.1470	0.0503	1.3954	0.0566

Mean1: the mean value of fractal dimension in the first stage.
Mean2: the mean value of fractal dimension in the second stage.
Mean3: the mean value of fractal dimension in the third stage.
std1: the standard deviation of fractal dimension in the first stage.
std2: the standard deviation of fractal dimension in the second stage.
std3: the standard deviation of fractal dimension in the third stage.

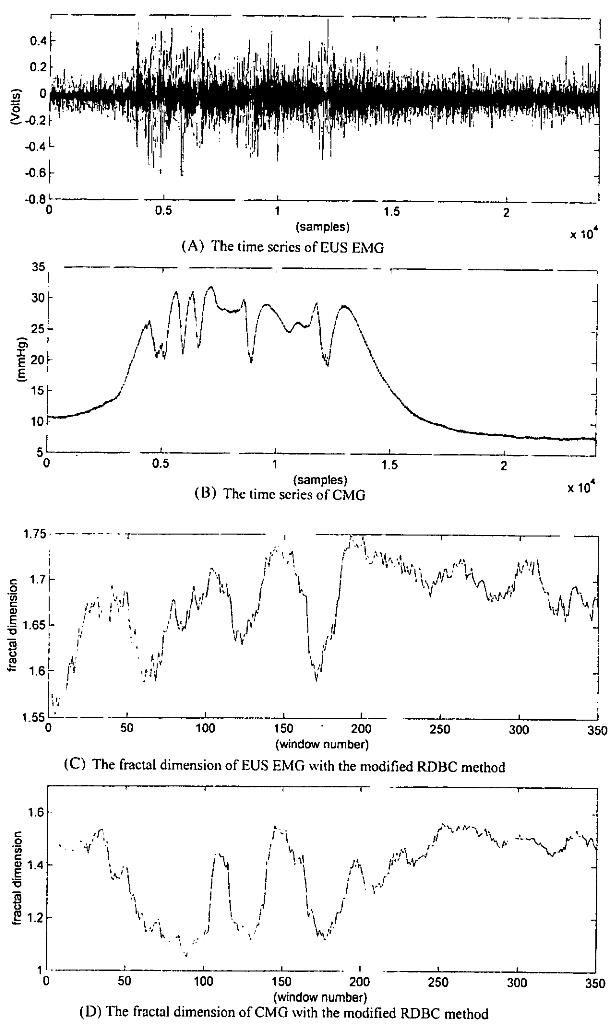

Fig. 2. Signals with cold-temperature stimulation.

decreases. Only when both of the fractal dimensions of EUS EMG and CMG decrease, there is efficient urination.

Cold-Temperature Stimulation

In Fig. 2A and Fig. 2B, the EUS EMG and CMG signals are recorded from the Wistar rats with cold-temperature saline infusion. In Fig. 2C and Fig. 2D, the following results are observed. They are not similar to those of room-temperature stimulations. During the voiding phase, even though the bursting of time series happens, the values of fractal dimension of both EUS EMG and CMG are not decreasing to low levels at the same time. The phenomenon may well be due to the fact that cold-temperature stimulation have caused abnormal spasms of the muscle. Therefore, the bursting phase is interrupted by several spasms. That means the rat may void twice or more in one bladder contraction. In such case, the diagrams of fractal dimension of EUS EMG and CMG will not have the monotone decreasing to low levels as the normal case. We advocate that only when both values of fractal dimension fall down to lower values, will the rats then void efficiently. It is believed that the muscle acts differently in two different experimental conditions. This explains that our results with cold-temperature stimulation will induce sphincter and detrusor dyssynergia (Table 2).

Discussion

The values of the fractal dimension usually correlate with the degree of the complexity of the analyzed signals. There exist three parts in the curve of the variation of fractal dimension after analyzing the signals of the voiding EUS EMG and CMG of the Wistar rats. The mean values of fractal dimension of the three parts are high, low, and high separately. In addition, when the fractal dimension value of EMG is low, it indicates positive correlation among the muscle cells of EUS. Electophysiologically, this means that most of the EUS muscle cells are depolarized and fired in a synchronized fashion. The situation is similar for the bladder case. It indicates the synergia of detrusor and urethral sphincter. Hence, the process of micturition can go on efficiently.

In the report of Bors and Blinn, they suggested that the instillation of a small volume of cold water into the urinary bladder elicited involuntary detrusor contractions and micturition in the patients with chronic spinal cord lesions rostral to the sacral segments. Hence, this procedure has been used in paraplegic patients as a clinical diagnostic test to demonstrate the integrity of the sacral spinal cord and the emergence of spinal micturition reflex pathways. And the cold-envoked detrusor reflex is not present in neurologically normal patients. That is why our analyzed results of cold-temperature stimulation are not the same as general patterns of room-temperature stimulation. Hence, it can be concluded that only when both fractal dimensions of EUS EMG and CMG decrease, the voiding is efficient.

In the future, the different muscular mechanisms of the Wistar rats with spinal cord injure (SCI) will be investigated. It is imperative to understand the relationship between the signals of EUS EMG or CMG and the injured positions of the animals. Of course, the modified RDBC method may not be enough to analyze all cases. Hence, it can be assorted with other parameters. It is believed that this investigation will be definitely helpful to our understanding of the voiding mechanism during micturition.

Acknowledgments

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Table 2A. The Average Fractal Dimension Values of EUS EMG of All Normal Rats with Cold-Temperature Stimulation (The Modified RDBC Method)

	Mean	Std
1	1.6790	0.0415
2	1.6862	0.0435
3	1.6841	0.0480
4	1.6814	0.0439
5	1.7169	0.0366
6	1.7214	0.0415
7	1.7167	0.0361
8	1.7263	0.0320
9	1.7104	0.0501
10	1.7098	0.0226
11	1.7141	0.0263
12	1.7127	0.0351
13	1.7102	0.0316
14	1.7080	0.0344
15	1.6985	0.0411
16	1.7009	0.0795
17	1.7004	0.0652
18	1.7062	0.0743
19	1.6586	0.0881
20	1.7062	0.0476
21	1.7058	0.0357
22	1.7018	0.0586
23	1.7137	0.0467
Average	1.7030	0.0461

Table 2B. The Average Fractal Dimension Values of CMG of All Normal Rats with Cold-Temperature Stimulation (The Modified RDBC Method)

	Mean	Std
1	1.3771	0.1476
2	1.3992	0.1575
3	1.4090	0.1774
4	1.3921	0.1788
5	1.5015	0.1491
6	1.5150	0.1610
7	1.1394	0.2274
8	1.5117	0.1518
9	1.5444	0.1291
10	1.4323	0.1091
11	1.3989	0.1436
12	1.4320	0.1294
13	1.4218	0.1332
14	1.4248	0.1647
15	1.3814	0.1237
16	1.3141	0.1239
17	1.3119	0.1149
18	1.3596	0.1055
19	1.3324	0.1258
20	1.3466	0.1453
21	1.2753	0.1622
22	1.4068	0.1791
23	1.4356	0.1889
Average	1.3940	0.1491

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