Research Article

Fractal Characteristics of Porosity of Electrospun Nanofiber Membranes

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In this paper, the method of measuring the porosity of electrostatic nanofiber membrane by VC++ and Matlab is introduced. It is found that the ratio of the calculated porosity to the porosity measured by the mercury intrusion method accords with the famous Feigenbaum constant ($\alpha \approx 2.5029078750957 \ldots$). The porosity distribution of nanofiber membranes was studied by VC++ and Matlab based on the image obtained by using a scanning electron microscope. The porosity distribution calculated by using a computer is magnified by $e^\alpha$ times which was named as relative porosity distribution. According to the relative porosity distribution, we use the algorithm proposed by Grassberger and Procaccia (briefly referred to as the G-P algorithm) to calculate the correlation fractal dimension. The correlation fractal dimension calculated from the relative porosity distribution series was between 1 and 2, consistent with geometric characteristics of coincidence samples. The fractal meaning of the Feigenbaum constant was verified again. In the end, we obtained the relationship between the associated fractal dimension and the filtration resistance by fitting in accordance with the secondary function relationship and reached the maximum correlation fractal dimension when the filtration resistance was 15–20 pa.

1. Introduction

Electrospinning is a technology of drawing polymer solution with high viscosity into fibers by electrostatic force. It can produce nanofibers with high porosity, high surface area, fine and uniform fiber, and other characteristics. Electrospinning has the following advantages: continuous fibers can be prepared directly from polymers and composites; it can be applied to a wide range of polymers; the thickness of membrane can be controlled by adjusting the collection time during the electrospun nanofiber; the dimensions and filtration feature of the electrospun nanofiber can be changed by altering the solution properties and process parameters (see [1]).

Most of the pores exist between the interior of the electrospun nanofiber membrane and the fibers. These pores will directly affect the properties of the electrospun nanofiber membrane. At present, the methods of measuring the porosity of the electrospun nanofiber membrane include density method, image method, and mercury intrusion method (see [2–4]). However, these methods are time-consuming and costly. In recent years, more and more attention has been paid to the calculation of the porosity of electrospun nanofiber membrane by using computers (see [5, 6]). The powerful image processing ability and matrix computing ability of computers make the calculation of the porosity of electrospun nanofiber membrane simple, easy, and of low cost.

Fractal theory is a nonlinear mathematical theory derived in the middle of 1970s. The definition of fractal given by the founder Mandelbrot is that fractal is a form in which parts are in some way similar to the whole. Based on the
complexity of fiber structure in electrospinning nanofiber film, fractal can be used as an ideal mathematical research tool.

As early as the 80s of the last century, it was found by Krohn and Thompson that pores have fractal characteristic, and fractal dimension is the best description of fractal feature as the quantitative characterization and basic parameter of fractal (see [7–9]). They all look at the fractal characteristics of the pores of rocks and soils. At the beginning of the 20th century, this theory was applied to the study of electrospun nanofiber membrane. The fractal dimensions used were generally box dimensions, as given by Ai et al. (see [10, 11]). However, although the box counting method is simple and effective, it is very difficult to study the pore characteristics of electrospun nanofibers because of their obvious distribution. According to the characteristics of electrospun nanofibers, we choose the correlation fractal dimension method to study. We use the algorithm proposed by Grassberger and Procaccia to calculate its correlation fractal dimension (see [12]).

In this paper, we first give a kind of method of calculating the porosity of electrospinning nanofiber membrane by using computers. Then, according to the calculated porosity distribution sequence, using the G-P algorithm, the correlation fractal dimension of the sample is calculated and the mathematical relationship between the fractal dimension and the filtration resistance is finally discussed.

2. Preliminaries

The correlation fractal dimension calculated by the G-P algorithm is as follows:

Let us consider the system as follows:

\[ \{ x_k; k = 1, 2, \ldots, N \}, \]

which is converted into a \( M \) dimensional Euclidean space, as follows:

\[ X_{(M,r)} = \{ x_{n1}, x_{n2}, \ldots, x_{n(M-1)r}, n = 1, 2, \ldots, N \}. \]

First, the correlation function \( C(r) \) is defined as

\[ C_M(r) = \frac{1}{N(N-1)} \sum_{i \neq j} \theta \left( r - \left| X_i - X_j \right| \right), \]

where \( \theta(x) \) is the Heaviside step function defined as

\[ \theta(x) = \begin{cases} 1, & x > 0; \\ 0, & x \leq 0. \end{cases} \]

where \( \left| \cdot \right| \) represents the distance between state vectors \( X_i \) and \( X_j \) in Euclidean space.

When \( r \) is small enough, define a constant \( D(M,r) \) relative to \( M \) and \( r \) (see [10]):

\[ D(M,r) = \frac{\partial \ln C_M(r)}{\partial \ln r}. \]

With the proper selection of \( M \), we can find the correlation fractal dimension: Select the appropriate value of \( M \); when the double log curve \( \ln C_M(r) - \ln r \) has a linear interval long enough, the sample is considered to have a fractal structure. At this point, the linear slope corresponding to the linear interval is \( D \), that is, the correlation fractal dimension of the sample.

The introduction of fractal theory and fractal methodology is of great significance in scientific methodology. Fractals are often defined as a rough or fragmented geometry that can be divided into several parts, and each part is (at least approximately) the reduced shape of the whole, i.e., having self-similar properties. Fractal and chaos are closely related; most of them are the self-organizing system, but their meanings are different. Feigenbaum, a physicist in the United States, studied the universal behavior of complex systems in detail and put forward the standard law and universality of chaotic theory (see [13]). The discovery of Feigenbaum constant \( (\delta = 4.669201609103\cdots, a = 1/\delta = 2.5029078750957\cdots) \) reflects the order of chaotic evolution and opens the research on the universality of chaos (see [13]).

In this paper, the porosity of the electrospun nanofiber membrane calculated by Matlab software is compared with that of the electrospun nanofiber membrane obtained by the mercury intrusion method. It is found that the ratio of porosity between the two is close to the Feigenbaum constant \( (a = 2.5029078750957) \). This feature, in a sense, reflects the fractal characteristics of the porosity distribution of the electrospun nanofiber membrane. When calculating the porosity of the electrospun nanofiber membrane, the porosity distribution is expanded to \( e^{\alpha} \) multiple at first, and then, the correlation fractal dimension of the porosity distribution is calculated by using the G-P algorithm. It is found that the dimension is between 1 and 2, which is more in line with the geometric characteristics.

3. Experimental

3.1. Experimental Materials and Apparatus

3.1.1. Experimental Materials. Polyvinyl alcohol (PVA) with a relative molecule weight (Mn) of 84000 ~ 89000, alcoholysis degree of 86 ~ 89 mol%, and the average degree of polymerization 1700 ~ 1800 was purchased from Changchun Petrochemical Co., Ltd., Taiwan.

3.1.2. Experimental Apparatus. The experimental apparatus used were as follows: DXES-01 automatic electrospinning machine, produced by Shanghai Dongxiang Nano Technology Co., Ltd.; TSIB130 Automatic Filtration Tester, from Tsai Sai Central Instrument Trade Co., Ltd. (Beijing); TM3030 Desktop Scanning Electron Microscopy, from Japan Hitachi Agency, Hitachi High-Technologies Nagano Office; and AutoPore IV 9510 high-performance automatic mercury presser, from Micromeritics Instrument Co., Ltd. (Shanghai).

3.2. Spinning Solution Preparation. Polyvinyl alcohol was dissolved in distilled water and formulated into a polyvinyl alcohol solution with a concentration of 12% (to avoid
excessive parameters, we fixed the concentration). The resulting mixed solution was stirred in a water bath at 80°C for 1 h until a homogeneous solution was formed, and then, it was statically defoamed.

3.3. Sample Preparation. At room temperature, the prepared spinning solution was poured into four 5-mL syringes with a needle diameter of 1.2 mm. From previous studies, there are five process parameters for the manufacture of electrospun nanofiber membrane as follows: 90 minutes for the spinning time; 12% for the solution concentration; the needle-to-collector distance (cm) taken as 11, 13, 15, 17, and 19; applied voltage (kV) taken as 15, 18, 20, 23, and 26; flow rate (mL/h) taken as 0.5, 0.7, 1, 1.2, and 1.5. To ensure the generality of the experiment and to avoid too many experiments, we adopted an orthogonal experiment idea and added five more experiments based on orthogonal experiments, as shown in Table 1.

The filtration resistance of each sample is tested by the TSI8310 automatic filter tester (see Table 1).

3.4. Morphological Characterization. We used the TM-3030 scanning electron microscope (SEM) of the Technology Research Center of Tianjin Polytechnic University to obtain a SEM image of the gold-sprayed sample.

4. Results and Discussion

4.1. Porosity Measurement. Current methods for measuring material porosity include nitrogen adsorption (see [14]), mercury intrusion (see [4]), impregnation (see [15]), and mass density (see [16]). The pore size of materials with pore size less than 50 nm can be measured by this nitrogen adsorption method, but it is only suitable for ultrafine powder materials. The impregnation method is a suitable test porosity method for liquid permeable nonwovens with low surface tension. However, the PVA used experimentally in this paper is a water-soluble material, so the impregnation method is not suitable for electrospinning nanofibers. Both the mercury intrusion porosimetry method and the mass density method are suitable for testing the porosity of electrospun nanofiber membrane. We tested the porosity with the mercury intrusion porosimetry at the Yanhao material laboratory in Beijing, but the test was difficult and costly, with a sample of 550 CNY. As a result, we tested only five samples: 5, 11, 19, 20, and 28. To solve the problems of high cost testing and difficult testing, a new calculation method is proposed. This method makes use of the powerful image processing ability of VC++ software and the matrix computing ability of Matlab software to process the image of electrospun nanofiber membrane. In this way, we calculated the porosity of electrospun nanofibrous membranes by an economical, simple method.

4.1.1. Threshold Segmentation. The threshold command converts gray or color images to high-contrast black and white images by specify a certain color level as the threshold. All pixels brighter than the threshold are converted to white, and all pixels darker than the threshold are converted to black. Scanning electron microscope image of the electrospun nanofiber membrane was read by VC++ software. Firstly, the image was transformed into a gray image, and the threshold value was adjusted according to the average grayscale value of the image to black and white images (binary images). The specific steps are as follows: running the VC++ program, preprocessing the pictures, image gray processing, binary processing, and obtaining binary black and white image, where the black part represents the nonpore part and the white part represents the pore part.

4.1.2. Calculation Using Matlab Software. For the binary black and white image after segmentation, the pixel value of each position is calculated using Matlab software and the table is generated. The porosity is the ratio of the number of white pixels to the total number of pixels, and the porosity can be calculated from the data from the table. If the porosity of the electrospun nanofiber membrane is recorded as \( p \), then

\[
\rho(\%) = \frac{n}{N} \times 100,
\]

where \( n \) is the number of white pixels and \( N \) is the total number of pixels.

4.1.3. Determination of Threshold. The threshold is actually a “critical point,” meaning that greater than this critical point, the threshold, is white, and the one that is less than this critical point, the threshold, is black, so there are only black and white two cases in the image. The selection of threshold is the key to the conversion of grayscale image to binary image. In this paper, we take 85% times of the average gray value of the whole image, rounded, as the image threshold, to the image binarization. The diagram before and after processing is shown in Figure 1.

4.1.4. Porosity Test Results. The measured results of the porosity of electrospun nanofiber membranes calculated by the mercury intrusion method and image processing are shown in Table 2. Table 2 shows that the ratio of porosity calculated by the mercury intrusion method and image processing method is very close to the Feigenbaum constant \( \alpha = 2.5029078750957 \ldots \).

Of course, to further determine this conclusion, we also selected some samples 1, 6, 7, 21, and 2, with large differences in mean gray values for empirical evidence. When the image threshold is selected, about 85% of the average gray value of the entire image is still selected. The experimental and calculated results are shown in Table 3. The set \( a_1 \) represents the porosity of the electrospun nanofibrous membrane obtained by mercury invasion, and the set \( a_2 \) represents the porosity of the electrospun nanofibrous membrane calculated by image processing. Then, the ratio of \( a_1 \) to \( a_2 \) remains essentially consistent with the Feigenbaum constant.
We believe that the measurement of porosity by the mercury intrusion method and the calculation of porosity by the image processing method should satisfy a certain relationship. The experimental results confirm that the ratio of the two is a Feigenbaum constant, which should be derived from the intrinsic structure of the electrospinning nanofibers with fractal properties, thus making their ratio more directly related to the chaotic constants. It also makes it more convenient for us to calculate the porosity of electrospun nanofibers with computer image technology and Matlab.

It is known that with chaos, there are fractals. Only chaos emphasizes dynamic process, while fractal emphasizes geometric structure. In fact, the chaotic attractor is a fractal structure in the phase space, the fractal structure is the product of chaotic dynamics process, and the geometric convergence constant of the attractor is also a fractal.

| Number of samples | Needle-to-collector distance (cm) | Applied voltage (kV) | Volume flow rate (mL/h) | The filtration resistance (pa) | Number of samples | Needle-to-collector distance (cm) | Applied voltage (kV) | Volume flow rate (mL/h) | The filtration resistance (pa) |
|-------------------|----------------------------------|----------------------|-------------------------|--------------------------------|-------------------|----------------------------------|----------------------|-------------------------|--------------------------------|
| 1                 | 11                               | 15                   | 0.5                     | 11.1                           | 16                | 15                               | 20                   | 1.5                     | 43.1                           |
| 2                 | 13                               | 15                   | 0.7                     | 22.1                           | 17                | 17                               | 20                   | 0.5                     | 8.5                            |
| 3                 | 15                               | 15                   | 1                       | 21                             | 18                | 19                               | 20                   | 0.7                     | 4.9                            |
| 4                 | 17                               | 15                   | 1.2                     | 11.1                           | 19                | 11                               | 23                   | 1.2                     | 30.1                           |
| 5                 | 19                               | 15                   | 1                       | 8.9                            | 20                | 13                               | 23                   | 1.5                     | 29                             |
| 6                 | 19                               | 15                   | 1.5                     | 6.1                            | 21                | 15                               | 23                   | 0.5                     | 7                              |
| 7                 | 11                               | 18                   | 0.5                     | 11.5                           | 22                | 17                               | 23                   | 0.7                     | 5.8                            |
| 8                 | 11                               | 18                   | 0.7                     | 19.3                           | 23                | 17                               | 23                   | 1.5                     | 7.3                            |
| 9                 | 13                               | 18                   | 1                       | 15.6                           | 24                | 19                               | 23                   | 1                       | 9                              |
| 10                | 15                               | 18                   | 1.2                     | 19.8                           | 25                | 11                               | 26                   | 1.5                     | 15.7                           |
| 11                | 17                               | 18                   | 1.5                     | 9                              | 26                | 13                               | 26                   | 0.5                     | 9.9                            |
| 12                | 19                               | 18                   | 0.5                     | 8.1                            | 27                | 13                               | 26                   | 1                       | 25.9                           |
| 13                | 11                               | 20                   | 1                       | 31.2                           | 28                | 15                               | 26                   | 0.7                     | 8                              |
| 14                | 13                               | 20                   | 1.2                     | 27.5                           | 29                | 17                               | 26                   | 1                       | 5.7                            |
| 15                | 15                               | 20                   | 0.7                     | 9                              | 30                | 19                               | 26                   | 1.2                     | 4.3                            |

**Table 2: Results of porosity of the electrospun nanofiber membrane.**

| Number of samples | Whole-image average gray value | Image binarization selected threshold | Mercury intrusion method | Image processing | Image selection threshold/whole-image average gray value | Mercury intrusion method/image processing |
|-------------------|--------------------------------|--------------------------------------|--------------------------|------------------|--------------------------------------------------------|------------------------------------------|
| 5                 | 116.357832                     | 98                                   | 83.0                     | 33.9032          | 0.8508                                                 | 2.4461                                   |
| 11                | 119.866425                     | 100                                  | 66.1                     | 28.2820          | 0.8509                                                 | 2.3126                                   |
| 19                | 106.131277                     | 80                                   | 83.5                     | 33.7838          | 0.8480                                                 | 2.4717                                   |
| 20                | 127.836432                     | 115                                  | 85                       | 27.9989          | 0.8527                                                 | 2.8793                                   |
| 28                | 115.542275                     | 98                                   | 78.8                     | 30.1811          | 0.8482                                                 | 2.6109                                   |
| Average           | 116.357832                     | 98                                   | 83.0                     | 33.9032          | 0.8501                                                 | 2.5432                                   |

**Figure 1: Image before and after processing.**
4.2.1. Calculation of Porosity Distribution. First, the image is processed with gray and binary using VC++ software. Second, the black and white images after binary processing are imported into the Matlab software to calculate the correlation fractal dimension of the porosity distribution, the porosity distribution data are enlarged by $e^n$ times (called it the relative porosity distribution) and to study the fractal characteristics of the structure of electrospun nanofiber membrane.

### Table 3: Porosity of electrospun nanofiber membrane in contrast experiment.

| Number of samples | Whole-image average gray value | Image binarization selected threshold | Mercury intrusion method | Image processing | Image selection threshold/whole-image average gray value | Mercury intrusion method/image processing |
|-------------------|-------------------------------|--------------------------------------|--------------------------|-----------------|------------------------------------------------|------------------------------------------|
| 1                 | 121.414597                    | 104                                  | 83.043                   | 34.0404         | 0.8565                                          | 2.4539                                   |
| 6                 | 126.814396                    | 109                                  | 86.123                   | 33.6947         | 0.8595                                          | 2.5560                                   |
| 7                 | 119.745632                    | 102                                  | 85.519                   | 35.4594         | 0.8518                                          | 2.4936                                   |
| 21                | 133.343546                    | 113                                  | 86.606                   | 37.5705         | 0.8549                                          | 2.3584                                   |
| 29                | 131.217394                    | 113                                  | 89.107                   | 33.4530         | 0.8535                                          | 2.6636                                   |
| Average           |                               |                                       |                          |                 | 0.8552                                          | 2.5028                                   |

4.2.2. Calculation of the Correlation Fractal Dimension. After the porosity distribution is calculated, the correlation fractal dimension of porosity distribution is calculated by the G-P algorithm. However, we are not simply using porosity distribution data to calculate correlation fractal dimensions. In the previous section, we introduce a Feigenbaum constant associated with chaos. So, when we calculate the correlation fractal dimension of the porosity distribution, the porosity distribution data are enlarged by $e^n$ times and the correlation fractal dimension obtained in this way accords with its geometric characteristics between 1 and 2 (see Table 4).

4.3. Filtration Resistance Test. The TSI8310 automatic filter tester is used to test the filtration resistance of each sample (see Table 1).

4.4. Relationship between the Correlation Fractal Dimension of Porosity Distribution and the Filtration Resistance of Electrospun Nanofiber Membrane. The porosity of electrospun nanofiber membrane has an extremely important influence on the filtration performance of electrospun nanofiber membrane (see [17]). The porosity distribution data are enlarge by $e^n$ times and the correlation fractal dimension obtained in this way accords with its geometric characteristics between 1 and 2.

The fitting diagram is shown in Figure 3. From Figure 3, we can see that when the filtration resistance is 15–20 pa, the filtration resistance is extremely significant.
Figure 2: (a) Grayscale image. (b) Binary image.

Table 4: Correlation fractal dimension of the porosity distribution.

| Number of samples | Correlation fractal dimension | Straight line intercept | Correlation coefficient | F test | Collinear interval left-end point | Collinear interval right-end point | M value |
|-------------------|-------------------------------|-------------------------|-------------------------|--------|----------------------------------|------------------------------------|---------|
| 1                 | 1.56139686172                | -9.8763242714585       | 0.97572039             | 10247.6407 | 301                              | 557                               | 10      |
| 2                 | 1.38839671912               | -8.383876963477        | 0.96888635             | 3705.6886 | 264                              | 384                               | 36      |
| 3                 | 1.44812324781               | -8.945075864163        | 0.98810103             | 15777.7817 | 278                              | 469                               | 35      |
| 4                 | 1.4313907248                | -8.3576487968196       | 0.95253119             | 1986.5803  | 261                              | 361                               | 34      |
| 5                 | 1.4846835618                | -9.46271587316         | 0.97047590             | 6837.0920  | 387                              | 596                               | 14      |
| 6                 | 1.50022407525               | -10.49195120001        | 0.95075924             | 1032.8740  | 289                              | 411                               | 17      |
| 7                 | 1.33696289787               | -8.468109385468        | 0.94754834             | 1424.6480  | 339                              | 442                               | 45      |
| 8                 | 1.5660120630                | -9.300910312696        | 0.97796717             | 7687.9222  | 242                              | 416                               | 12      |
| 9                 | 1.62172150467               | -9.797105817880        | 0.94924793             | 2225.7320  | 239                              | 473                               | 16      |
| 10                | 1.69049555394               | -10.43691393399        | 0.96850045             | 7163.9328  | 239                              | 473                               | 16      |
| 11                | 1.39038706342               | -8.193039921638        | 0.92011168             | 1209.3348  | 280                              | 386                               | 26      |
| 12                | 1.43218883519               | -8.83403316209         | 0.97796717             | 7687.9222  | 242                              | 416                               | 12      |
| 13                | 1.3597419018                | -8.229620287107        | 0.92136516             | 2648.0441  | 249                              | 476                               | 20      |
| 14                | 1.61659152319               | -9.39137962001         | 0.90790099             | 995.6459   | 249                              | 351                               | 22      |
| 15                | 1.35311753723               | -8.018632899234        | 0.94924793             | 2225.7320  | 267                              | 387                               | 13      |
| 16                | 1.02169015267               | -6.1646459547954       | 0.94651734             | 1840.5557  | 338                              | 443                               | 40      |
| 17                | 1.50027056401               | -8.877593433643        | 0.92285285             | 992.8661   | 308                              | 392                               | 20      |
| 18                | 1.4409252032                | -9.088740173833        | 0.97236387             | 717.6416   | 330                              | 535                               | 10      |
| 19                | 1.54486251839               | -9.140409326107        | 0.93143693             | 1181.9048  | 302                              | 390                               | 33      |
| 20                | 1.50943943985               | -8.193039921638        | 0.90790099             | 995.6459   | 249                              | 351                               | 22      |
| 21                | 1.35311753723               | -8.018632899234        | 0.94924793             | 2225.7320  | 267                              | 387                               | 13      |
| 22                | 1.32247337693               | -8.0590456568434       | 0.95292453             | 3906.8002  | 269                              | 463                               | 11      |
| 23                | 1.4120104077                | -8.526061055409        | 0.95869219             | 3202.7729  | 208                              | 347                               | 9       |
| 24                | 1.55990236576               | -9.6003829927966       | 0.95863387             | 3267.5838  | 343                              | 485                               | 15      |
| 25                | 1.66255509007               | -10.14252604392        | 0.94636998             | 2099.9066  | 341                              | 461                               | 21      |
| 26                | 1.41933998306               | -9.2910837497103       | 0.97327046             | 6590.3368  | 304                              | 486                               | 12      |
| 27                | 1.55758791438               | -9.4910847598210       | 0.98852764             | 15251.3988 | 239                              | 417                               | 9       |
| 28                | 1.44789169077               | -8.776103051857        | 0.9733818             | 3876.2389  | 253                              | 360                               | 18      |
| 29                | 1.599860069689              | -10.023238276336       | 0.95830634             | 4321.0791  | 356                              | 545                               | 11      |
| 30                | 1.42842868531               | -8.958936349393        | 0.93127739             | 1395.7789  | 453                              | 557                               | 36      |

Table 5: F test table.

| Source of variance | Sum of squares | Degrees of freedom | Square | F     | Conspicuousness |
|--------------------|---------------|--------------------|--------|-------|----------------|
| Regression         | SSR           | 2                  | SSR/2  | 12.4165092 | Extremely significant |
| Residual error     | SSE           | 27                 | SSE/27 | 12.4165092 | Extremely significant |
| Sum                | Lyy           | 29                 |        |        |                |
correlation fractal dimension of porosity distribution is maximum.

5. Conclusion

In this paper, the porosity using the mercury intrusion method and that calculated using the image processing method are compared. It was found that the ratio of porosity between the two was very close to the Feigenbaum constant (α = 2.502907850957 · · ·). Secondly, the correlation fractal dimension of the electrospun nanofibrous membrane treated with the Feigenbaum constant (expansion e times) is between 1 and 2 (more consistent with its geometric characteristics). Finally, through regression analysis, we use Matlab software to prove the relationship between the related fractal dimension and the filtration resistance. The quadratic function relationship between them is very significant. It is known that the correlation fractal dimension is maximum when the filtration resistance is 15–20 pa.

Note. This result is similar to the relationship between fractal dimension and the filtration resistance of the spatial distribution of electrospinning nanofibers membrane in reference [18].

Data Availability

All the data used to support the findings of this study are included within the supplementary information files.

Conflicts of Interest

The authors declare that there are no conflicts of interest.

Authors’ Contributions

Ting Wang and Ying Chen contributed equally to this work.

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Supplementary Materials

Samples 1–5 are the original data selected every 10 times and are also the data group that we actually use to calculate the dimensionality; samples 6–30 are the original full data.

( Supplementary Materials )

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