Cybernetics in Medicine**

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Information science is a new discipline, with a history of no more than 30 years at most, but it is already exerting a great influence on more traditional sciences such as biology, the cultural sciences, the social sciences, and, of course, medicine.

If information science had not been introduced to medicine and biology, the recent advances of clinical medicine could hardly have been achieved. The first encounter between medicine and information science could be considered to date from the advocacy of "cybernetics" in the latter half of the 1940's. It is well known that N. Wiener first introduced the concept of cybernetics as "Control and Communication in the Animal and the Machine"¹⁾; and since then medicine and biology have comprized one of the greatest spheres of interest for cybernetics. At that time, however, it still was lacking in concrete methodology, and as a discipline had not gone beyond the bounds of an idea.

Subsequently, however, the rapid progress made in communication technology, computer technology and measurement technology, as well as development of such theoretical aspects as information theory, control theory and systems theory, have made possible the realization of the concept of cybernetics in a variety of fields, including medicine, and have given birth to a steady stream of outstanding achievements. It would be reasonable to construe information science as that which has systematized these technologies and theories.

The contribution made by information science to medicine can be viewed from two aspects. The first is the theoretical impact of information science on medicine. Since the advent of cybernetics, such concepts essential to medicine as "life", "illness", "diagnosis", and "treatment" have come to be viewed in the fresh perspective afforded by the viewpoint of information science.

The second is the remarkable contribution made to the progress of medical research, or to the improvement of the precision and efficiency of diagnosis and treatment, by the individual introduction of the techniques and theories of information science to medicine.

The foregoing facts are widely known by now, but, in this review, I would like to summarize the impact of information science on internal medicine, and at the same time, to report on the results of the research in this direction that we have carried out in our department over the past 15 years²⁾³⁾.

1. Influence of Information Science on Ideas in Medicine

The idea which, arising from cybernetics, has extended to information science, is in a word a concept of "control". That is, the backgrounding of information science is the development of theory and technology not merely to identify or understand that which is the investigated object, but to control the object in the direction which is determined to be of optimum benefit. This is in contrast to physics and chemistry, which work from begining to end on objective recogni-

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tion as much as possible, in that the reason for information science is that it should be a theory for practical science.

Although medicine itself is primarily a practical science with healing illness as its explicit purpose, such fundamental medical sciences as anatomy and physiology, with the objective understanding of the human body as their purpose, were developed before clinical medicine could achieve its own, individual method as a science. Accordingly, information science exerted a particular influence on clinical medicine, but it also showed a new approach to the fundamental life phenomenon—that is, from the standpoint of information and control.

I will summarize the effect that information science has had on the medical view of the concepts of life, illness, diagnosis, and treatment.

LIFE

From the time of C. Bernard the existence of a dynamic regulation system for living organisms was recognized, but the clarification of this mechanism as being based on a simple but important principle called a “feedback system” dates from cybernetics. And from this principle came the elucidation of a design for the regulation of endocrine secretion, body fluids, circulation, respiration, and the nervous and other systems. Furthermore, even for the complex regulation mechanism of enzyme levels, working hypotheses were established from the feedback control viewpoint, accelerating research in this field.

With the capability to use concepts of control in this way to understand the life phenomenon, and with the discovery of DNA, on the other hand, clarifying the physical bases for life information generation, there came about a recognition of the importance of “information”, added to the concepts of “matter” and “energy” which had formerly reigned supreme in the biological sciences, to the extent that it could be said, “Without information, there can be no life.”

After this came the beginning of the discourse on organism system as to the study of biological information: on the one hand, research at the molecular level for information on heredity, immunity, etc., and concurrently, on the other hand, attempts to grasp the phenomenon of life from the aspect of information distribution and transformation with regard to such functions as control, communication, and assessment.

ILLNESS

There is also a new perspective on illness, based on the information science view of life. Analysis of the etiology and interpretation of the phenomena of endocrine, metabolic, circulatory, and nervous diseases, among others, are now carried out from the standpoint of a malfunction or failure of feedback control mechanisms.

Statistics and probability theory have been adopted in the understanding of illness. With the analysis in multidimensional space of the primary factors and aspects of chronic diseases with complex causes and variegated symptoms, and the weighing of the individual factors and symptoms, the boundary between health and illness is being grasped, not in the black-and-white manner of conventional infectious diseases, but in terms of probability.

DIAGNOSIS

It was pointed out from the advent of cybernetics that the process of diagnosis and treatment, as mutual exchange of information between doctor and patient, is a type of feedback system. Diagnosis has been recognized as a purposeful decision process to determine the optimum medical treatment for the patient. For this reason, diagnosis is not merely a matter of assigning a name to the illness. The view has been advanced that diagnosis includes measuring the state of the illness, estimating the effectiveness of the treatment methods, and making a prognosis.

Furthermore, from the standpoint of the apprehension of illness in multidimensional

space as mentioned above, advanced statistical techniques were used, e. g., multivariate analysis methods for differential diagnosis and selection of treatment methods. Moreover, through probability theory the uncertainty of clinical diagnosis was recognized, and prognosis and diagnosis are now conceptualized using stochastic models like the Bayes' theorem and the Markov process. In order to introduce statistical and probability science to diagnosis, the necessity for standardization of clinical data and the construction of large-scale medical record management systems was emphasized.

TREATMENT

Like diagnosis, treatment has also been redefined by control concepts, and there is better understanding of diagnosis and treatment as inseparable, comparable to the system measurement and control of information science. That is, although conventional medicine was mostly straightforward logic in which the selected treatment method followed arbitrarily from naming the malady, which was equated with diagnosis, in the information science approach, treatment is now grasped as a control process which includes feedback, and clinical treatment is understood from the standpoint of the optimization of this "loop". To materialize this type of schema, a necessity to describe a patient's condition in mathematical time and space has emerged along with the need for development of superior means of biological measurement and treatment.

2. Application of Information Science to Internal Medicine

The following is an outline of the forms in which information science is applied to medical science.

The number of scientific journals specializing in the application of information science to medicine or biology at present exceeds 40. If the treatises since 1960 are analyzed, the number of reports rises about 1965, and from 1970 there is a rapid increase. As for the subject range, the most are those related to internal medicine, especially the

cardiovascular system, but there are applications beginning with diagnosis and treatment and extending to such far-flung fields as preventive medicine, epidemiology, education, and hospital administration.

Classified by technique, the greatest number are related to image processing techniques, with such diverse information processing for medical imaging as ECGs, electromyograms, X-rays, RI imaging, and ultrasonic imaging. Next come statistical analysis including multivariate analysis methods, classical control theory including transfer function and frequency analysis, and system and control theory including optimization and state space methods.

(1) Modeling and simulation

With the advent of the computer it became possible to carry out vast quantities of calculations in a short time, and analysis of physiological dynamics using simulation methods was brought about⁽⁴⁾⁽⁵⁾⁽⁶⁾.

Guyton et al drew up enormous models of the body fluid and circulatory systems using nearly 600 factors based on many years of experimental data; beginning with the relationship of blood pressure to body fluids, they analyzed the influence exerted by changes in individual factors on other factors and on the whole body. Using a super-large-sized computer, we reconstructed a QRS-T wave of an electrocardiogram from the action potential of myocardial cells and clarified the relationship of the polarity of the T wave to the action potential⁽⁵⁾, and we also made models of coronary circulation⁽⁶⁾ and cardiac dynamics, and applied the results to evaluation of cardiac functions and assessment of treatment effectiveness.

The advantage of simulation methods is in showing more concretely the results of deductive reasoning from experimental data, in aiding the understanding of complex systems, and in selecting the next experimental proposition. Their clinical usefulness is in the application of mathematical descriptions, verified by simulation, to evaluation of organ function and to treatment control. The insulin secretion model applied in the

artificial endocrine pancreas system is one example of this. That is, the dynamic properties of the insulin secretion from the endocrine pancreas are revealed to be proportional to the blood glucose concentration and its derivative; then, clinical application of the same dynamic properties to an artificial endocrine pancreas system was successful⁷⁾.

(2) Improvements in ability to measure biological systems

There are a great many examples of the contributions made by the application of control and statistical theory to the improvement of measuring ability. The Hodgkin-Huxley voltage clamp, applying feedback control, and measuring electric current in a membrane, is a classic example, and computed tomography is a recent example. Others are RI tomography and ultrasonotomography; the ultrasonic pulsed Doppler flowmetry, which can measure the blood flow velocity at any location inside the cardiac chambers⁸⁾, also belongs in this category.

(3) Information processing

CT and RI tomography are information processing systems directly linked to measuring apparatus, but off-line information processing is also widely used. Especially flourishing areas of research are information processing of ECGs and image processing.

Research into information processing of ECGs began early, and automatic ECG diagnosis⁹⁾¹⁰⁾ and the extended-time ECG recording and reproduction analysis apparatus are successful examples. At present in the U. S. A. 9% (10,000,000 cases per year) of all recorded ECGs are diagnosed automatically, but it is after a lapse of almost 30 years since the commencement of research that automatic diagnosis has finally obtained the confidence of doctors. The extended-time ECGs are recorded on magnetic tape; 10-24 hours of ECGs can be reproduced in a few minutes and rhythm or pattern abnormalities are analyzed, so that today this apparatus is essential to diagnosis of rhythm disorders.

As for image processing, improvements

in image quality have been devised by means of such measures as noise elimination, marginal outline extraction, and enhancement of distinctive features. Along with extensive research to aid the physician in diagnosis, recently such advanced technology as three-dimensional image construction and moving image processing have been applied to medical imaging.

As for processing of cardiac images, we developed a system to reconstruct a three-dimensional image of the heart by computer processing from a series of ultrasonic tomograms¹¹⁾, and a system to obtain automatically the dimension of the ventricular cavity and wall thickness during one cardiac cycle, from cine left ventriculograms¹²⁾. These systems were used in the evaluation of regional cardiac function.

(4) Diagnosis quantification

When computers were introduced to the domain of medical science, one of the first themes to be taken up was the use of computers to quantify diagnosis¹³⁾. Boolean algebra, the Bayes' theorem, the discriminant function, and other methods were used as the logic of computer diagnosis for differential diagnosis of each type of disease.

Unfortunately, however, there are few examples which are still of clinical value even today. The reason for this is not that the theory is in error, but that there were problems in the quality and extent of the data used. In fact, for applications in which the projected large amounts of data were gathered, such as assessing the efficacy of drugs and analysis of risk factors, multivariate analysis and multilogistic models are extremely useful.

A little over ten years ago we had the experience of analyzing, using a discriminant function, the adaptation of steroid therapy for nephrotic syndrome; subsequently, followup examinations for prognosis of nephrotic syndrome and chronic nephritis have been carried out nationwide. If quantitative analysis theory can be applied to data in this way, we can look forward to the demonstration of diagnosis models

of clinical value.

(5) Treatment control

Treatment control is made possible by coming to grips with treatment from the standpoint of system control theory. In order to carry out treatment control, both precise modeling and continuous, quantitative measurement of the subject are necessary, as well as a computer with extensive capacity. With these, one can measure and determine the current condition of the patient, make a prognosis, and decide the kind and quantity of treatment to be given. The results of this treatment should be fed back once more into the same process. In this way the final goal of the introduction of information science to medicine and internal medicine can be considered to be treatment control.

Until now reports of clinical examples of treatment control based on system theory have been very few, but we adapted a simulation of a blood-sugar regulation system to treatment control, and we successfully constructed a computer program for adaptive optimization of administration of insulin dosage to patients in diabetic coma¹⁴⁾.

Control of plasma concentration of drugs is also an important step in treatment control; by simulating the dynamics of the drug in the blood with a compartment model, the conditions for reasonable control ability can be clarified from the standpoint of linear system theory¹⁵⁾.

(6) An accumulation and retrieval system for extensive data

One of the outstanding functions of a computer is its memory. If extensive patient medical records are entered into a computer, research into such subjects as the elucidation of etiology, efficacy of a drug and evaluation of its side effects, quantification of diagnosis, and prognosis can be facilitated by statistical analysis¹⁶⁾. Instances of success in ideal medical record management so far are rare, however. The reasons are that medical data are not standardized for every individual, and that the data to be managed are not only numerical but also include the

large volume of qualitative data, graphic data, and descriptive data. Accordingly, until now successful medical databases have been limited to those with specific diseases as their object, or to those in which standardized data can be obtained as from a check-up unit, or to some specific areas of epidemiological research. It is clear, however, that to make better use of information science in the future, the full development of medical databases is an extremely important condition.

3. The Future of an Information Science Approach to Internal Medicine

As previously stated, although it has a history of only 30 years at most, information science has influenced medical science in many respects, both ideologically and technologically. If we think of the extent of the ideological impact of information science on medicine, and especially on clinical medicine, however, the resultant meaningful products and byproducts must still be considered insufficient. There are many reasons for this, but I would like to stress the following two especially.

The first is that information science is still an immature discipline, and is probably still incapable, both theoretically and technologically, of taking such an exceedingly complex system as the human body, especially, for its subject. Henceforth, we should expect information scientists and medical scientists to collaborate to propel research towards an information science that will measure up to the expectations of medicine.

The second is that both doctors and patients do not sufficiently understand information science and its relationship to medicine. In the final analysis the application of information science to medical science is carried out where medicine is practiced; therefore whether information science becomes a more powerful medical tool or not is largely dependent on the awareness of each individual doctor. Without doubt one of the important directions for medicine to follow is that which has been opened up by information science. If progress is made in

this direction by accumulating concrete results, a new internal medicine worthy of being called a modern science can be born.

I am looking forward to giving this internal medicine of the future the name "Systems Internal Medicine".

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