Models for Leprosy. An Appraisal of Graphic Representations of the "Spectrum" Concept as Models and a Suggestion for a Catastrophe Theory Model for Leprosy

Diseases are often thought of as progressing in a linear manner, a more advanced or serious stage being merely an exaggerated version of an earlier less advanced stage. However, many conditions including leprosy do not follow a linear logic. This makes it difficult to formulate a general theory of their behavior; correspondingly, our understanding of those diseases and their dynamics remains unsatisfactory. Nevertheless, we still have some working hypotheses (conceptual models) to help us understand, to some extent at least, the particular disease phenomenon. In the case of leprosy, the concept of Ridley and Jopling—of a "spectrum" of degree of cell-mediated immunity against *Mycobacterium leprae* and its identity with the "spectrum" of clinical manifestations of this disease—serves as the basic hypothesis and conceptual model[1-8]. This concept has proved so useful that today one hardly thinks outside its framework. This is surprising because critical examination will show that the spectrum, a typically linear idea, is an inadequate and probably an inapt metaphor for describing the non-linear behavior of leprosy. This can be demonstrated by representing the concept graphically and using that as a model. In this paper a few such representations are examined with some logical rigor in order to bring out the underlying assumptions and their consequences. In view of the deficiencies discovered, I have also ventured to suggest an alternative metaphor, a different conceptual model, which seems as good as or even better than the spectrum in describing the behavior of leprosy in an individual.

Graphic representations of spectrum concept as models for leprosy. The spectrum concept may be summarized as follows: a) clinical manifestations of established leprosy form a spectrum, ranging from the highly focal tuberculoid leprosy to the globally diffuse lepromatous leprosy; b) the type of leprosy depends on and is a faithful reflection of the degree of specific cell-mediated immunity (CMI) the patient has against *M. leprae,* tuberculoid and lepromatous types being states of high and absent specific CMI, respectively; c) these two types form two poles of the spectrum of degree of immunity against *M. leprae* and in between the poles is a continuum of intermediate states of "borderline" leprosies in which the CMI may be at a relatively high (BT or borderline tuberculoid), low (BL or borderline lepromatous), or intermediate (BB or true borderline) level; and d) polar leprosies are stable (i.e., do not change in type), whereas the nonpolar borderline types are unstable forms[9-14].

[1] Arnold, H. L. and Fasal, P. *Leprosy Diagnosis and Management.* 2nd ed. Springfield: C. C Thomas, 1973, p. 69.

[2] Bryceson, A. and Pfaltzgraff, R. E. *Leprosy.* 2nd ed. Edinburgh: Churchill Livingstone, 1979.

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[5] Gass, H. and Arnold, H. L. Leprosy. In: *Clinical Dermatology.* Denis, D. J., Dobson, R. L. and McGuire, J., eds. Philadelphia: Harper & Row, 1982, vol. 3, units 16–29.

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[8] Jopling, W. H. and Harman, R. R. M. Leprosy. In: *Textbook of Dermatology.* 2nd ed. Rook, A., Wilkinson, D. S. and Edling, F. J. G., eds. Oxford: Blackwell, 1972, vol. 1, pp. 680–693.

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[10] Jopling, W. H. Clinical classification of leprosy. In: *Proc. of the European Leprosy Symposium, 1981.* Quaderni di Cooperazione Sanitaria, 1982, pp. 51–57.

[11] Ridley, D. S. Histological classification and the immunological spectrum of leprosy. Bull. WHO **51** (1974) 451–465.

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[13] Ridley, D. S. and Jopling, W. H. Classification of leprosy according to immunity. A five-group system. Int. J. Lepr. **34** (1966) 255–273.

[14] Ridley, D. S. and Waters, M. F. R. Significance of

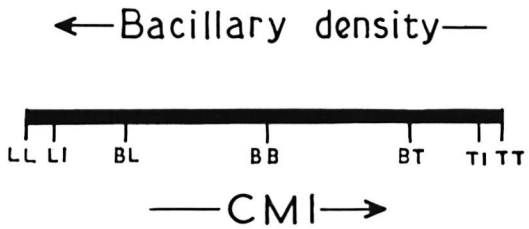

FIG. 1. One-dimensional line model of the spectrum scale–"polar types" concepts. The two ends are the two stable "poles," and the intermediate types are located as points in the line. It is customary to locate the points equidistantly, except for the subpolar types LI and TI which are located nearer their polar neighbors. LL = polar lepromatous; TT = polar tuberculoid; LI and TI = subpolar lepromatous and tuberculoid, respectively; BL = borderline lepromatous; BB = true borderline; and BT = borderline tuberculoid. Cell-mediated immunity (CMI) increases from left to right. Bacillary density (BI) increases from right to left.

Figure 1 shows a horizontal line used for depicting the spectrum concept. The two ends represent the two polar types and points are arbitrarily marked off at different, usually equidistant, sites to locate the different intermediate nonpolar types[2, 9, 15, 16]. Specific CMI is thought of as increasing from "nil" at the lepromatous pole to "high" at the tuberculoid pole, and bacillary density [bacterial index (BI)] as increasing from "nil" at the tuberculoid pole to "high" at the lepromatous pole. This line model is not satisfactory for many reasons. For example, equidistant location of types would indicate that the parameters concerned (e.g., CMI and BI) change at a uniform rate from one type to its neighbor. Uniform increase/decrease of CMI is also explicitly shown in illustrations[7, 10]. However, various observations show that at least some parameters (e.g., number of lymphocytes in the granuloma) do not change gradually[9].

The same concept is shown with improved accuracy in a two-dimensional line model in Figure 2. This is a graph in which the spectral line forms the horizontal axis, and the vertical axis indicates increasing BI from below upwards. The curve is evidently obtained by plotting the average BI found in each type of leprosy. The graph is a steeply sloping line which levels off at the two ends. This figure, also often used in teaching leprosy[2], implies that while CMI changes uniformly (as indicated by the equidistant location of adjacent types) corresponding changes in BI follow a different pattern. The other implications of this model are: a) CMI is the independent variable (cause) and BI is the dependent variable (effect), i.e., CMI determines BI; b) the value of CMI determines the type of leprosy, i.e., leprosy manifests as one particular type for a particular value of CMI; c) there is a fixed relation between CMI and BI, i.e., when we know the value of one we know the value of the other; d) a change in CMI is associated with a specific kind of change in BI; e) changes in CMI (and so the type of leprosy) follow a fixed sequence (from TI to BT to BB to BL to LI, or the reverse), and so discontinuous changes or "skip sequences" from one type to another not immediately adjacent type cannot occur; and f) patients located close together in the curve (i.e., having very similar disease) will follow the same course when similar changes in CMI occur.

The above consequences are implicit in the model but the behavior of leprosy in real life does not bear them out. As mentioned earlier, we do not know that CMI changes uniformly from one type to the one next to it in the spectrum scale, or that the CMI determines the BI. It is equally possible that the bacillary load determines the immune response[17, 18]. But we do know that the relation between CMI and BI is not fixed and the value of one cannot be predicted from the other. Even within one type (indicating one particular level of CMI) different patients can have different BIs[19]. This shows that the relation between the two parameters is not fixed, and that within certain limits we cannot predict the value of one from the other. We do not know that our

variation within the lepromatous group. Lepr. Rev. **40** (1969) 143–152.

[15] Jopling, W. H. *Handbook of Leprosy*. 2nd ed. London: William Heinemann, 1978, p. 19.

[16] Jopling, W. H. *Handbook of Leprosy*. 2nd ed. London: William Heinemann, 1978, p. 39.

[17] Bryceson, A. Immunology. In: *Proc. of European Leprosy Symposium, 1981*. Quaderni di Cooperazione Sanitaria, 1982, p. 36.

[18] Jopling, W. H. *Handbook of Leprosy*. 2nd ed. London: William Heinemann, 1978, p. 66.

[19] Ridley, D. S. Classification. In: *A Window on Leprosy*. Chatterjee, B. R., ed. Wardha: Gandhi Memorial Leprosy Foundation, 1978, p. 113.

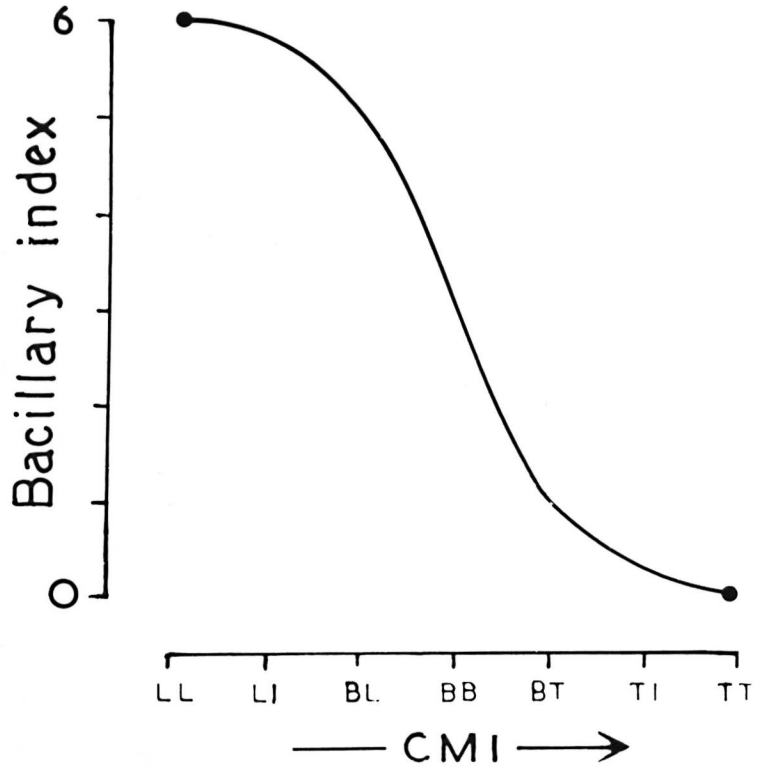

FIG. 2. Two-dimensional line model of the spectrum concept. The spectral line forms the horizontal coordinate and the bacillary density (BI) forms the vertical coordinate. (Bryceson and Pfaltzgraff use this type of figure frequently for explaining a variety of characteristics of leprosy[2].)

assumption of unimodal manifestation of leprosy (identity of one type of leprosy with one level of CMI) is correct, but we know that the lepromin reaction (an indicator of CMI) is negative in BB, BL, LI and LL types of leprosy[18, 20, 21]. There is evidence that other indicators of CMI like lymphocyte transformation or the amount of antibody against *M. leprae* antigen show variations within each type almost as great as between types[9, 22, 23]. Patients may change in the type of their disease according to the sequence indicated by the model, but we know of many instances in which skip sequences have occurred. In fact this appears to be so common that some authorities would delete BB from the spectrum, providing a direct transition from BT to BL, or group BB with BL[10, 24–26]. Lastly, while similar patients may progress similarly, we also know of many instances in which, under apparently similar conditions, two patients, similar to begin with, may reach widely different end states.

This model exhibits other deficiencies too. For example, we cannot locate the normal (nonleprous) state or early leprosy (indeterminate type in which classification, i.e., CMI, is not determined) in this line. As Rid-

[20] Bryceson, A. and Pfaltzgraff, R. E. *Leprosy.* 2nd ed. Edinburgh: Churchill Livingstone, 1979, p. 9.

[21] Godal, T. Immunological aspects of leprosy—present status. Prog. Allergy **25** (1978) 211–242.

[22] Bjune, G. Variation of *in vitro* lymphocyte responses to *M. leprae* antigen in borderline tuberculoid leprosy patients. Int. J. Lepr. **48** (1980) 30–40.

[23] Myrvang, G., Godal, T., Ridley, D. S., Froland, S. S. and Song, Y. K. Immune responsiveness to *Mycobacterium leprae* and other mycobacterial antigens throughout the clinical and histopathological spectrum of leprosy. Clin. Exp. Immunol. **14** (1973) 541–553.

[24] Bryceson, A. and Pfaltzgraff, R. E. *Leprosy.* 2nd ed. Edinburgh: Churchill Livingstone, 1979, p. 22.

[25] Job, C. K. and Chacko, C. J. G. A simplified 6 group classification of leprosy. Lepr. India **54** (1982) 26–32.

[26] Job, C. K., Selvapandian, A. J. and Kurian, P. V. *Leprosy Diagnosis and Management.* New Delhi: Indian Leprosy Association, 1975, p. 21.

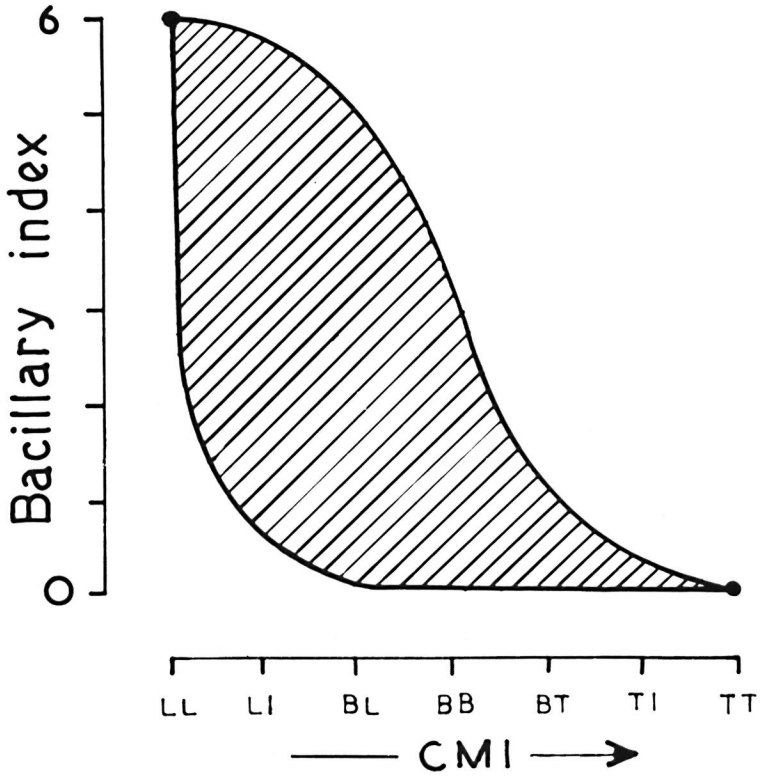

FIG. 3. Two-dimensional figure model of spectrum concept. Coordinates are the same as in Figure 2. Two graphs are drawn to enclose an area representing all possible states of leprosy. The upper (right) and lower (left) graphs represent, respectively, the (hypothetical) maximum and minimum BI found in the different types.

ley himself[27] has put it, "The important point is to realize that the indeterminate group (or better, non-group) is not part of the spectrum" and so evolution of leprosy from the normal state cannot be shown in this model.

Since line models are so grossly inaccurate, we could try some figure models of the spectrum concept. Figure 3 is obtained by drawing two graphs instead of one, using the same coordinates as in Figure 2, encompassing all possible states of leprosy. The upper curve represents the highest and the lower curve represents the lowest values of BI (both hypothetical) that may occur in each type of leprosy. This model allows for a variable BI for a given value of CMI and vice versa, but it hardly tells us anything more. Skip sequences are still not possible. CMI still changes uniformly. We still cannot locate early (indeterminate) leprosy or depict evolution of leprosy from the normal state.

An improvement is shown in Figure 4 in which the horizontal axis has been extended to the right to include indeterminate leprosy, the incubation stage and the normal (nonleprous) state. Harboe uses a somewhat similar line to explain the evolution of leprosy[9, 28]. The vertical axis denotes bacillary population instead of bacillary density, which is too inaccurate a parameter. Nevertheless, even this figure is unsatisfactory as a model. It has limited and erroneous information, and is also poor in predictive potential. According to this model, the level of CMI is higher in indeterminate (early) leprosy than in the tuberculoid (TT) type and is highest in the normal state. While the

[27] Ridley, D. S. Classification. In: *A Window on Leprosy*. Chatterjee, B. R., ed. Wardha: Gandhi Memorial Leprosy Foundation, 1978, p. 111.

[28] Harboe, M. Genetic aspects of leprosy. In: *Modern Genetic Concepts and Techniques in the Study of Parasites*. (TDR Series 4). Michal, F., ed. Basle: Schwabe, 1981, p. 389.

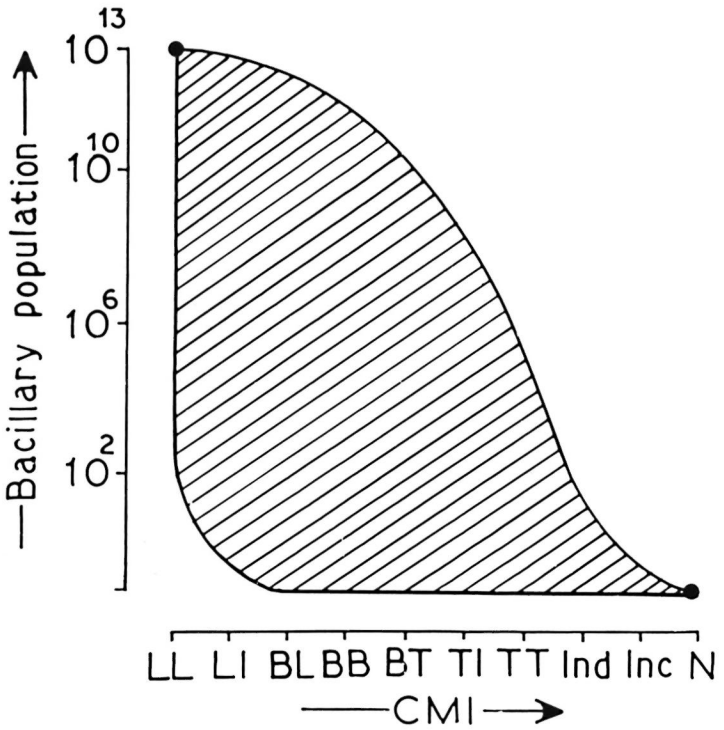

FIG. 4. An improved two-dimensional figure model. The vertical axis represents bacterial population and not density. The horizontal axis has been extended to the right to include early (indeterminate) leprosy (Ind), incubation (Inc) state, and normal (nonleprous) state (N).

latter may be true, the former is definitely not true. By definition, the CMI status of indeterminate leprosy is not determined one way or the other[10, 27, 29]. Further, even according to this model a horizontal shift, i.e., a change in CMI and therefore a change in type, has to follow a fixed sequence such as from normal to indeterminate to TT to TI and so on (which is not correct), and skip sequences are still not possible.

I have not exhausted all the possible ways of depicting the spectrum concept graphically, and the reader is welcome to try any other kind of representation in which the spectrum will form one coordinate and some feature of leprosy will be represented in the other coordinate. It will be seen that the difficulty of a fixed sequence will always be there whenever we use the spectrum line as a coordinate, i.e., postulate a serial level of CMI and identify each level of CMI with a particular type of the disease. Schematic diagrams of Cochrane[30], Cochrane and Smyly[31], Skinsnes[32, 33], Dharmendra and Ramu[4], and of Godal, *et al.*[34] avoid this difficulty, but they are mere illustrations and are not to be used as models because they are too loosely constructed. Further, they are static in the sense that they do not show how or why changes occur. A scrutiny of the schematic drawing of Skinsnes[32, 33] and Table 1 of Godal[21] will show that within the borderline portion of the leprosy spectrum

[29] New IAL classification of leprosy. Lepr. India **54** (1982) 22–25.

[30] Cochrane, R. G. Classification. In: *Leprosy in Theory and Practice.* Cochrane, R. G., ed. Bristol: John Wright, 1959, p. 156.

[31] Cochrane, R. G. and Smyly, H. J. Classification. In: *Leprosy in Theory and Practice.* 2nd ed. Cochrane, R. G. and Davey, T. F., eds. Bristol: John Wright, 1964, p. 306.

[32] Skinsnes, O. K. Immunology in leprosy. In: *Leprosy in Theory and Practice.* 2nd ed. Cochrane, R. G. and Davey, T. F., eds. Bristol: John Wright, 1964, p. 177.

[33] Skinsnes, O. K. Infectious granulomas; exposit from the leprosy model. Ann. Rev. Med. **33** (1982) 47–69.

[34] Godal, T., Lofgren, M. and Negassi, K. Immune response to *M. leprae* of healthy leprosy contacts. Int. J. Lepr. **40** (1972) 243–250.

(which is practically the whole of the spectrum!) there is so much overlap of characteristics (and different characteristics change at different stages) that the criteria for classification are not at all clearcut. It appears that, under certain conditions, the disease manifests itself as more than one type. Even Ridley, a co-author of the spectrum model, is not quite satisfied with the present situation, as can be seen from his query "does the disease really present two spectra instead of one?"[35]

The above difficulties force us to consider the following possibilities, however implausible they may seem: a) there may not be a fixed sequence of types in the evolution of leprosy; b) it may not always be correct to identify a particular level of CMI with a particular type of the disease; c) within certain limits, BI may not be dependent on CMI; d) the level of CMI may be a dependent variable (effect) and not an independent variable (cause); and e) more than one factor may determine the behavior of the disease.

By now it is clear that a model for leprosy must provide for: a) evolution of indeterminate (early) leprosy, b) changes in type not necessarily following a fixed sequence, c) such changes occurring gradually or suddenly, d) the possibility of the disease manifesting as more than one type under certain conditions, and e) similar patients progressing similarly or differently under similar conditions of change.

It was found that one of the "Catastrophe Theory" models provided for this kind of behavior pattern. This prompted us to apply that model to leprosy. Since some readers may not be familiar with catastrophe theory models, a brief outline based on the description given by Woodstock and Davis[36] is given below.

Catastrophe theory models

Catastrophe theory is a branch of topology in mathematics, topology being the study of geometric properties of surfaces (disregarding magnitudes) as they are bent or deformed. This theory was originated by René Thom in the 1960s to explain how continuous causes could produce sudden, discontinuous consequences (named by him as "catastrophes"), a phenomenon seen widely in nature and society. Catastrophe theory models have found usually apt applications in physical, biological, and social sciences, and the theory itself has been hailed by some as one of the most significant fundamental discoveries. Catastrophe theory presupposes that systems are in dynamic equilibrium, and as controlling conditions change they shift or transit from one state of stability to another, smoothly or suddenly, and that there are not more than four controlling factors. Catastrophe theory models cannot be used if more than four factors control the system.

Catastrophe theory models are graphs having one axis for each control factor and one or two axes for the "behavior" of the system. Within the dimensions defined by the axes, a point represents one particular state of stability of the system. The different points, representing the possible stable states, form a line or a surface. Movement within the line or surface indicates a smooth (continuous) change; a movement that forces the point to leave the line or surface indicates a sudden or discontinuous change ("catastrophe") from one stable state to another.

The simplest catastrophe model is the two-dimensional fold model having two axes, one for the control factor and the other for the behavior of the system. That model, applicable to simple systems controlled by only one factor, is too simple and has very limited applications. The more complicated models are exotically called "swallow tail," "butterfly," "parabolic umbilic," and so on, and have four or more dimensions. The "cusp catastrophe model" is a relatively simple model and has been found to be quite versatile. I propose to apply this model to leprosy.

Cusp catastrophe model. This model is used when there are two control factors. It has three axes, two horizontal axes representing the two control factors and a vertical axis representing the "behavior" of the system. The graph is therefore three dimen-

[35] Ridley, D. S. Hypersensitivity and immunity reaction and classification. (Editorial) Lepr. Rev. **47** (1976) 171–174.

[36] Woodcock, A. E. R. and Davis, M. *Catastrophe Theory.* Harmondsworth, England: Penquin Books, Ltd., 1980.

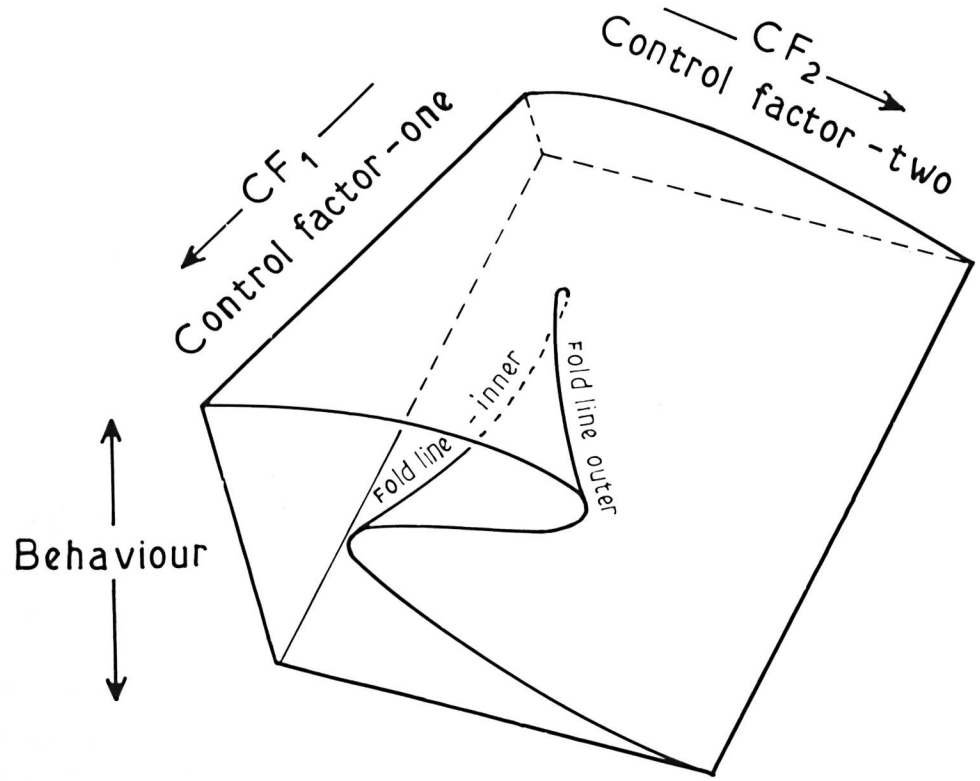

FIG. 5. Cusp catastrophe model. Curved surface slopes down to the right and toward the near right corner. Surface includes a fold or cusp. Vertical displacement represents the behavior of the system. A system will be represented by a point on the surface and any change in the control factors represented in the two horizontal axes will shift the position of the point. Note that such a shift always has a vertical component representing a particular kind of behavior of the system. Every point on the surface represents a particular stable state except the points on the undersurface of the cusp which are impossible or very unstable states. (See text for full explanation.)

sional, a curved surface with a fold or "cusp" as shown in Figure 5. Every point on the surface represents a particular stable state, except the points on the undersurface of the cusp which are impossible or very unstable states. The model displays bimodality, divergence, catastrophe, and hysteresis (explained below).

Biomodality. For a given value of control factors, a system is normally expected to exist in one particular position of stability. According to the cusp model a system can have two positions of stability for certain values of control factors. In the region of the cusp, the system can have one position of stability on the upper surface of the cusp and another position on the surface below the cusp. The system can exist in this manner in one of two modes of stability in this region and this quality is called bimodality. A third state, located on the undersurface of the cusp, is so unstable as to be impossible or, if a system happens to be there, any disturbance will force it to a stable point on the surface above or below.

Divergence. When a system exists in a particular stable state, it is represented by a point, appropriately located on the surface. If the controlling conditions change, the stable position of the system also changes and this is visualized as the point moving on the surface. Let two points A′ and A″ be located side by side near the far side, one a little higher than the other (Fig. 6), indicating two systems having the same value for one control factor (CF_1) but slightly different values for the second control factor (CF_2). Let CF_1 increase. Both points will move forward (toward us) tracing parallel paths. Their behavior will continue to be similar if both

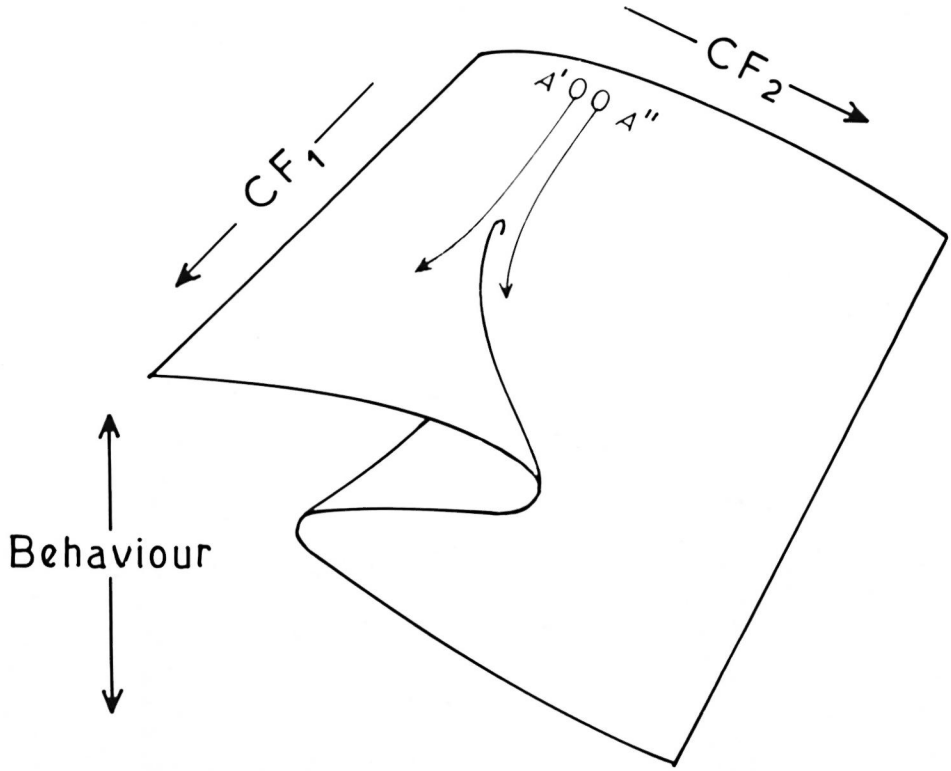

FIG. 6. The phenomenon of divergence. To start with, the two systems are very close together at A′ and A″. If CF_1 increases, both systems will move towards us in a parallel path. Note that under the same condition of change, A′ will reach the upper surface of the cusp but A″ ends up on the surface below the cusp, reaching an entirely different end state.

reach the same side of the fold. But, as shown in Figure 6, it is also possible for one (A′) to reach the upper surface of the cusp, while the other (A″) travels on to the surface below the cusp. Although starting close together, the two systems reach different end states under the same conditions of change. This is termed divergent behavior.

Catastrophe. When a change in controlling conditions forces a point to leave the surface on which it is located, a sudden transition to another surface occurs. It can be seen from Figure 7 that movements from A to B and back, A to C and back, and C to D and back are smooth transitions indicating continuous changes. Let the system be at B and let CF_2 increase. The system will now move to the right until it reaches the outer fold line at E. Any further increase in CF_2 will force it to leave the upper surface of the fold and "drop down" to D, located on the surface below the fold, i.e., transit to D suddenly. Such a sudden, discontinuous transition is termed a "catastrophe."

Another catastrophic transition will occur if CF_2 decreases when the system is at D, on the surface below the cusp. In that case, it will move to the left until it reaches the inner fold line at F and then it has to jump to B, located on the upper surface of the cusp, since it cannot proceed smoothly any further.

Hysteresis. Let the system be at B (Fig. 7) and let CF_2 increase and decrease alternately by an appropriate amount; a cyclical pattern of behavior linking B and D catastrophically (B-E-D, D-F-B) will result. The system will keep jumping back and forth from B to D. Such a cycle is termed "hysteresis" and is found in many dynamic systems[36].

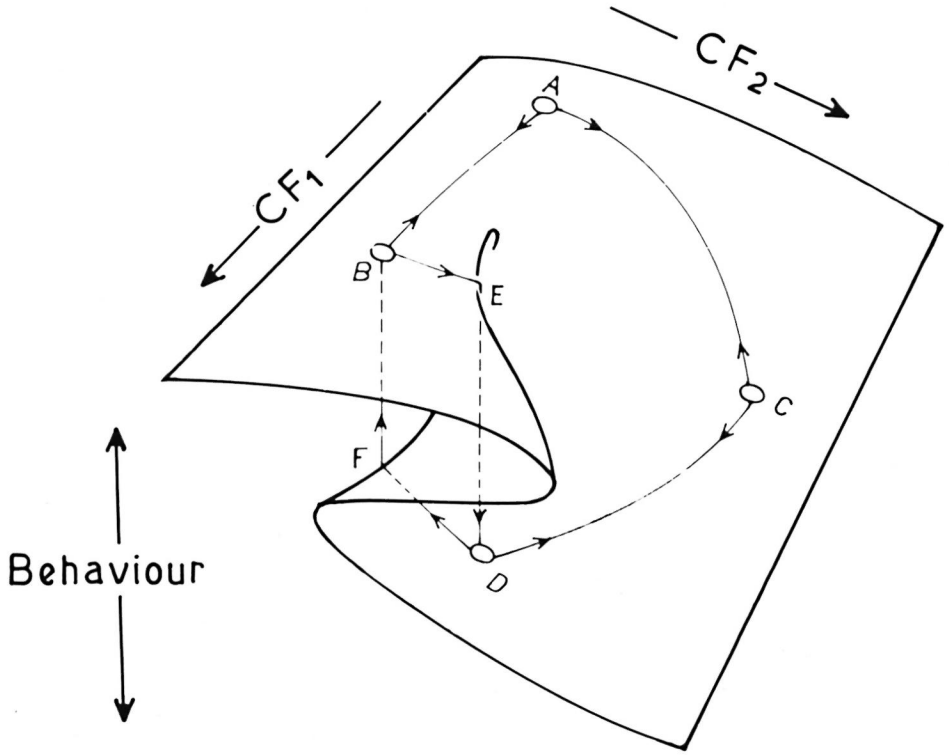

FIG. 7. Smooth and catastrophic transitions and hysteresis cycle. Shifts such as A ⇌ B, A ⇌ C, and C ⇌ D are smooth transitions because the point does not leave the surface during these movements. However, shifts from B to D via E as well as from D to B via F are catastrophic transitions, i.e., sudden and discontinuous changes, because the point has to leave one surface. B–E → D–F → B represents a hysteresis cycle. (See text for full explanation.)

Cusp model of leprosy

The following assumptions have been made in order to apply the cusp model to leprosy: a) "Leprosy" is a state of dynamic equilibrium of the body in the presence of infection with *M. leprae*; b) the type of leprosy at a given time represents a particular stable state; c) one state of stability will change into another (i.e., one type of leprosy will change into another) if the factors controlling the equilibrium change; and d) two different factors control the state of equilibrium. The first three are general statements which need not be contested. The last is an arbitrary assumption that has been made because it is logically impossible to explain complex behavior of a system if controlled by one factor only.

Determining what the control factors are and what constitutes "behavior of the disease" are matters of importance. After trying out various parameters, it was felt that the "amount of dead bacilli" and the "amount of living bacilli" (or their indicators) could serve as the two control factors, CF_1 and CF_2, respectively. They may not actually be so, but we have used them as control factors for the sake of argument and also because they seemed to fit that role better than other characteristics. It can be objected that they are not independent of each other and so cannot be considered as two different factors. However, it is theoretically possible to reach, in the body, any of the four extreme states—a) no bacilli living or dead, b) all bacilli dead, c) all bacilli living (the dead ones having been eliminated instantaneously), or d) some living and some dead bacilli—indicating that the two characteristics are more or less independent. This is possible because the processes that kill the bacilli and eliminate them are not identical. Therefore, we have selected these two parameters as the two control factors. After

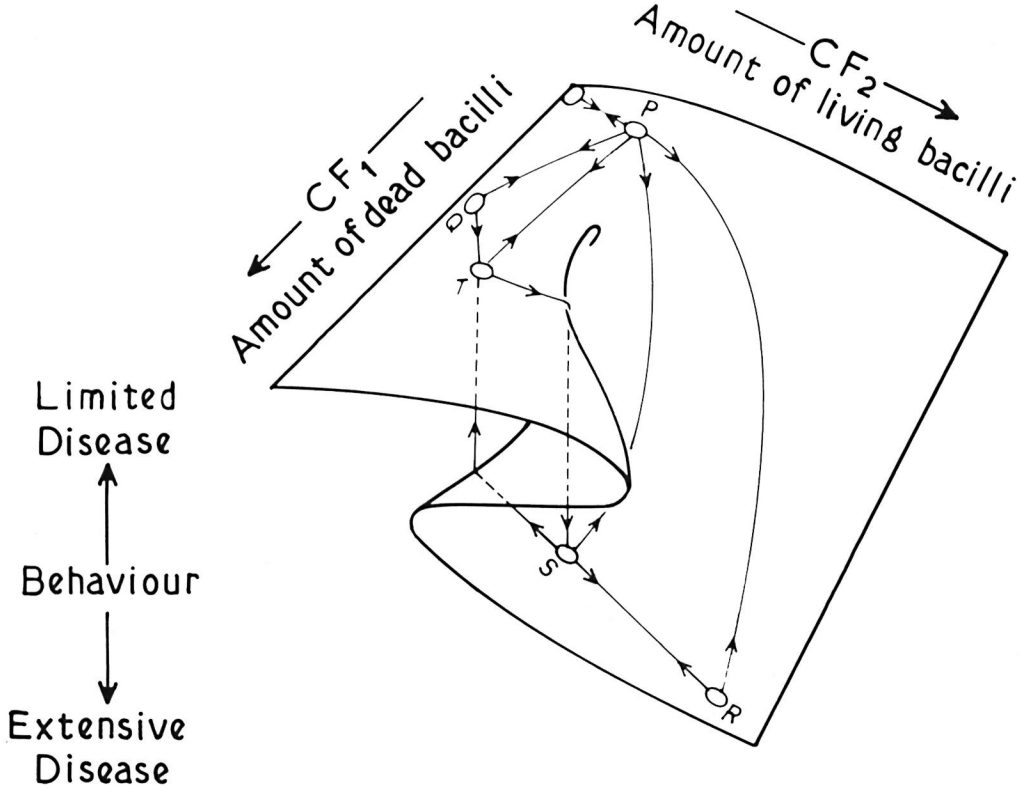

FIG. 8. Cusp model applied to leprosy. Far left corner is the "normal" corner indicating nonleprous state. Upward and downward movements indicate progression to developing limited or extensive disease, respectively. P = early (indeterminate) leprosy; Q = tuberculoid; R = lepromatous; S = BL leprosy; T = BT leprosy. T → S = downgrading reaction. S → T = upgrading reaction. The control factors are hypothetical and arbitrarily selected. The scale for the magnitudes of the control factors is very likely to be a logarithmic one. (See text for full explanation.)

many trials, we found that it would be most convenient to consider "progression towards limited or extensive disease" as the behavior pattern of the disease.

The cusp model applied to leprosy is shown in Figure 8. An increase in CF_1 (amount of dead bacilli) will move the point (representing a particular stable state of the system) toward us and an increase in CF_2 (amount of living bacilli) will move it to the right. The vertical axis represents "behavior" of the disease, and the surface slants downward from left to right toward the near right corner. Upward and downward movements indicate progression to limited and extensive disease, respectively. The far left corner (no living or dead bacilli) represents the normal (nonleprous) state. It will be noticed that if the system moves in the horizontal plane, in any direction, it will also be shifted in the vertical direction as well.

When the body harbors a few (living and dead) bacilli, early (indeterminate) leprosy can develop and that will be indicated by the system shifting from the far left (normal) corner to P; death and clearance of all bacilli will cause the system to return to the normal corner. If, however, CF_1 increases while CF_2 diminishes to close to zero, the system will instead move over to Q, representing tuberculoid leprosy (limited disease with very few bacilli, mostly dead). It may be mentioned that Q can be located anywhere along the left margin and not just at one point as shown in Figure 8, although it is highly unlikely that it is located too far away from the normal (far left) corner. If CF_1 and CF_2 both increase, very much and more or less at the same rate, the system will transit to R located close to the near right corner, indicating development of extensive disease associated with an enormous increase in the

amount of living and dead bacilli, viz., lepromatous leprosy. If, on the other hand, CF_1 increases faster than CF_2, the system will transit from P to S, indicating progression to extensive disease but not with as many living bacilli as in lepromatous leprosy, viz., BL or borderline lepromatous leprosy. Depending on the changes in the control factors (e.g., considerable increase in CF_1 with very little increase in CF_2), the system can also reach T, indicating a limited form of the disease but with some bacillary load, viz., BT or borderline tuberculoid leprosy.

These shifts are all smooth transitions. However, sudden changes can occur under certain conditions. If CF_2 increases when the system is at T, it will move to the right until it reaches the fold line beyond which it cannot progress smoothly. It has to leave the surface and drop down to S, i.e., change suddenly from BT to BL type leprosy (downgrading). Similarly, if CF_2 decreases when at S, the system will move left until it reaches the inner fold line, then it has to leave this surface and jump up to T on the upper surface of the cusp, i.e., change suddenly from BL to BT type leprosy (upgrading). If CF_2 changes alternately in an appropriate manner, the system can be caught up in a hysteresis cycle and keep jumping back and forth between T and S, i.e., the patient would develop alternating upgrading and downgrading reactions.

If we believe that all infiltrated cutaneous lesions start as macules, we can even designate the far side as the "macular zone" and the near side as the "zone of infiltration." This would provide for the macular varieties of tuberculoid, borderline and lepromatous leprosies.

It is evident that the cusp region is the "borderline zone." For certain values of the control factors, the disease may manifest as one of two different stable states, one on the upper surface of the cusp (BT leprosy) and the other on the surface below the cusp (BL leprosy). The undersurface of the cusp containing impossible or highly unstable states probably represents true borderline (BB) leprosy. The apparent rarity of true borderline or BB[10, 24, 37] seems to corroborate the model. According to this model, borderline leprosies illustrate bimodal behavior of leprosy.

This model, as mentioned previously, also permits divergent behavior. Two patients, or possibly two lesions in one patient, can be at A′ and A″ (see Fig. 6) close to each other, and under similar conditions of change (CF_2 increases) they both will transverse parallel paths toward us. However, one may end up on the upper surface of the cusp (develop into BT leprosy), while the other reaches the surface below the cusp and develops into the BL type of leprosy.

COMMENTS

It is seen from the above that the known behavior of leprosy can be reproduced, with reasonable verisimilitude, in the cusp model. This model gives us a "landscape of leprosy" with some sign posts as it were, enabling us to ask meaningful questions. A number of features suggested or implied by the cusp model—control factors, predicted changes, conditions that favor such changes, as well as those that favor bimodal manifestation, divergent behavior, and a host of others—can be looked for. The cusp model thus seems to provide good scope for deepening our understanding of leprosy.

Puzzling manifestations noticed in some patients are better explained by the cusp model. For example, simultaneous occurrence of qualitatively different lesions in the skin and nerve tissues has been reported of some patients[38]. This is difficult to explain with the spectral model, but according to the cusp model this could be an instance of divergence, two lesions starting more or less similarly but ending quite differently under similar conditions of change.

The cusp model also suggests new therapeutic approaches in the management of leprosy. The therapeutic goal according to this model is to pull the patient back to the normal (far left) corner, avoiding a "cusp situation." If the patient is already in a cusp situation, he will have to be eased out from there and then shifted to the normal corner.

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[37] Job, C. K., Selvapandian, A. J. and Kurian, P. V. *Leprosy Diagnosis and Management.* New Delhi: Indian Leprosy Association, 1975, p. 20.

[38] Srinivasan, H., Rao, K. S. and Iyer, C. G. S. Discrepancy in the histopathological features of leprosy lesions in the skin and peripheral nerve. Lepr. India **54** (1982) 275–282.

For example, in a case of BT leprosy—a cusp situation—the system should be shifted to the left away from the outer fold line by decreasing CF_2 and then moved toward the normal corner by decreasing CF_1. Many such "therapeutic route maps" can be derived from this model.

The cusp model for leprosy thus appears rich in possibilities and it would be worthwhile to develop it further. It is true that it is speculative, qualitative, and may be too simple. It has other deficiencies also, of which the most glaring is the validity of the suggested control factors. The aim of the present exercise, however, is not to claim to have discovered the factors that control the behavior of leprosy, or even to stake a claim for the cusp model. It will have been noticed that the cusp model, although it uses their terminology, does not employ the concepts of spectrum scale or polar types. It is true that these concepts have helped us to understand the pleomorphism of leprosy, but it is difficult to believe that they are the ultimate in the general description of the behavior of this disease. It is likely that more sophisticated concepts will help further progress. The present venture is an attempt at developing an alternative metaphor, and it appears that in the cusp model of the catastrophe theory we may have such an alternative.

SUMMARY

Graphic representations of the spectrum concept of leprosy are examined in some detail as models for this disease. This reveals that this concept is somewhat inadequate and that the spectrum metaphor may itself be inappropriate because, by its very linearity of logic, it may not be able to depict the nonlinear behavior of leprosy properly. The assumptions underlying this concept and their logical consequences, brought out by the graphic representations, include an invariable relation between CMI and BI, identity of one type of leprosy with one specific level of CMI, a fixed sequence of types, and the consequent impossibility of skipping the sequence. However, our experience with leprosy does not bear out these assumptions. Further, development and progress of leprosy from a normal (nonleprous) state cannot be represented in these models. A search for alternative conceptual models therefore appears reasonable and even necessary.

The catastrophe theory (a branch of topology in mathematics) describes a number of models for explaining how continous causes could produce sudden or discontinous changes. Of the various catastrophe theory models available, the relatively simple "cusp" model appears capable of application to leprosy. This model, as applied here, requires two control factors (identifed tentatively as the amount of dead bacilli and the amount of living bacilli or their indicators) and one pattern of behavior, identified as progress towards limited or extensive disease. This model suggests under what conditions leprosy will change from one type to another and whether that will happen gradually or suddenly. It also suggests that for certain values of control factors the disease may manifest in one of two forms of borderline leprosy, and that lesions very similar to start with can progress to quite different states under similar conditions of change. The behavior of leprosy agrees more or less with that suggested by this model. The cusp model thus seems to: a) provide an insight into the behavior of leprosy, enabling us to understand the dynamics of the disease; b) explain some of its intriguing manifestations; c) ask meaningful questions; and d) plan new therapeutic approaches. Although this is a highly speculative and probably too simple a model, this attempt shows that it is possible to view leprosy outside the framework of the concepts of spectrum scale and polar types of leprosy, the conceptual models which dominate all of our current thinking about the disease.

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