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Women's Health and Complexity Science

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ABSTRACT

Conceptual frameworks in science have shifted from reductionism and its focus on ever-smaller parts to complexity, an outgrowth of chaos theory that views those parts in relation to one another, to the larger entity they form and to the environment in which that entity exists. Examples of this conceptual shift are occurring in many areas of science, but nowhere is it more germane than in the medical sciences that serve women. After a historical focus on reproduction and the development of obstetrics–gynecology, medicine has now gained a broader view of the woman using sex- and gender-based science, and a new field called "women's health" is evolving. Complexity science does not invalidate or eliminate the need for reductionist science, it simply makes a wider array of phenomena understandable. Its method allows going beyond the metaphor of the body as a machine and challenges the user to re-examine how health and illness are understood. This article explores how these changes in science must inform the development of an academic discipline in women's health. The conceptual framework of complexity science also advances the discussions about women's health from reproduction to a totally new and exciting exploration of the interactions between reproduction and all other organ functioning that occurs in women in the contexts of their lives.

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> . . . creating a new theory is not like destroying an old barn and erecting a skyscraper in its place. It is rather like climbing a mountain, gaining new and wider views, discovering unexpected connections between our starting point and its rich environment. But the point from which we started out still exists and can be seen, although it appears smaller and forms a tiny part of our broad view gained by the mastery of the obstacles on our adventurous way up.
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> —ALBERT EINSTEIN, *The Evolution of Physics*, 1938

Newtonian science dominated scientific thinking for more than 300 years, not only in physics but also in the biological and social sciences. Its dominant metaphor was that of a machine. Any entity could be understood by reducing it to smaller and smaller parts (reductionism). The whole was the sum of its parts and external, "objective," and "universal" rules governed behavior. If the rules were known, the separate parts understood, and the present state characterized, the machine's future behavior could be predicted with linear cause and effect. The machine model provided the underpinnings for the Industrial Age, its capacity for mass production and dependence upon predictable environments. It was also the metaphor that guided professional medicine's coalescence around organ-based disciplines and physiological processes. However, this conceptual framework is no longer sufficient —for business or medicine—to support the Information Age and the unpredictable futures evoked by the Internet's compression of time and space. Most important, living systems cannot be fully understood using the machine metaphor. The body is not a clockwork mechanism, the nucleus is not the master gear, and the individual is more than the sum of organ systems. Living organisms have parts capable of mutual interactions that not only sustain them but also allow them to learn, adapt, and innovate. Through the interactions of the parts, outcomes emerge that are characteristic not of each part, but of the whole. These outcomes cannot be predicted despite accurate knowledge of each and all parts.[1]

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Complexity science uses the metaphor of a living system rather than that of a machine.[2] The unit of study is no longer the smallest part but rather what is called the "complex adaptive system" (CAS)—be it a cell, a neural network, an ant colony, or a market economy.[3] A CAS is a diverse grouping of connected yet independent agents; each agent acts on its local knowledge or conditions and all agents together interact and adapt as a whole system to the larger environment. Each CAS may be nested within a larger CAS and components may interact at all levels of scale. The coherence of the system's behavior is dependent on the interrelationships between the agents, which are neither random nor programmed externally like a machine. These interrelationships are specified by a few simple rules intrinsic to each system that can change as the system gains experience. The complexity is in the organization—all the myriad ways that components of a system can interact as it "strikes an internal compromise between malleability and stability."[4]

Complexity science does not invalidate reductionist science. Reductionism was, and still is, extraordinarily useful for describing many aspects of the physical world. However, it was, and is, inadequate for explaining phenomena at certain levels of scale, particularly the subatomic and cosmic. While reductionism in medicine guided the path from humors to molecular genetics, it has been unable to explain conditions such as diabetes or cancer. The new science of complexity and its quantitative methods to describe dynamic variables links the micro view back to the macro view, making it possible to understand phenomena of the whole as well as of the parts.[5]

Complex systems do have single components, and reductionist approaches are useful to investigate them. However, *the actual functioning of these components taken together* is inadequately described by linear dynamics where small initial differences produce proportionately small differences in outcome. Systems characterized by nonlinear dynamics have components that interact strongly with each other, and small local perturbations can, unpredictably, result in major transformations of the entire system.[6]

The science, technology, and pedagogy of obstetric–gynecology have remained predominantly reductionist despite current efforts to broaden the practice. Major achievements in fertility, pregnancy, safe delivery, and improved fetal outcome were made using this approach. However, issues that appear unrelated to reproduction, such as atherosclerosis in premenopausal diabetic women, or that require attention to the larger contexts in which women live, such as interpersonal violence, have not been well understood. A complexity approach to the science, technology, and pedagogy of women's health may make it possible to advance our understanding of these types of issues.

Scholars from many diverse disciplines have been influenced by complexity science.[7] Biologists, for instance, no longer view evolution from the perspective of random mutation but view it as a process of co-evolution within what are called "fitness landscapes."[3] Epidemiologists plan vaccination strategies based on an understanding of the dynamic interactions between infectious agents and the environmental changes that lead to abrupt manifestations of epidemics.[8] Economists are explaining how global factors around the world lead to variability in market economies.[9] Management experts, in response to rapidly changing business environments, have abandoned strategic planning in favor of strategic processes to facilitate corporate innovations.[10] Medical educators, as they struggle quantitatively and qualitatively with a rapidly transforming knowledge base and health care environment, would also benefit from this new approach. Women's health illustrates the tension that exists within the status quo of academic medicine, and alternative states are yet to emerge.

MEDICAL EDUCATION AND COMPLEXITY SCIENCE

At the turn of the 20th century, gross anatomy guided medical inquiry and discipline-bound specialties formed around organ systems. The microscope took the focus down to the cell; advances in imaging and biochemistry have reduced our focus further to the molecule and its biology. Medical education organized its curriculum with discrete basic science courses, and organ-system–based clinical clerkships, residencies, fellowships, and specialties.[11] The explosion of knowledge fueled by faster and faster information technologies has shifted educational goals from knowledge acquisition to critical thinking and information management. In response, the basic sciences have begun to be integrated and new curricular topics, such as medical informatics and evidence-based medicine, have been added. Academic medicine has been slow, however, to create structures for true interdisciplinary learning, teaching, and research where discrete knowledge bases are brought into active connection. Interdisciplinary educational environments can prepare students and trainees not only to process information as it is added or changed but also to create new knowledge and to apply information in complex ways.[12] Medical education in women's health is not just about incorporating new knowledge and improving clinical services, it is about new thinking.[13] That is why faculty interested in growing the field of women's health have articulated the need for *inter*disciplinary approaches in addition to *multi*disciplinary ones, and content adjustments to existing specialties.[14]

Interdisciplinary scholarship in women's health will not eliminate the continuing need for knowledge generated by existing specialties. It will, however, make a broader array of phenomena in women more understandable and lead to better diagnoses and more cost-effective treatments. Contact between and among a multiplicity of existing disciplines as experienced in the mind of the individual learner will lead to entirely new knowledge not currently predictable or expressed by the sum of all disciplinary scholarship. Ultimately, the knowledge that arises from all these venues, both discipline-bound and interdisciplinary, will become the scientific foundation upon which all clinicians will base their clinical decision making.[15]

Complexity science, by nature interdisciplinary, is particularly well suited to women's health scholarship in both content and organization. Organizational theorists have shown that groups that explore possibilities by changing behavior —learning by doing—evolve faster than groups that don't.[7] Nontraditional approaches like those that are emerging in women's health are often the sources of innovation and creativity that lead to major transformations of the entire system. Instead of damping down these "deviations from the norm," as occurs in linear systems, what if medical education took a nonlinear approach and acted as a CAS, attracting any and all disciplines to explore, create, and organize the areas between them? What if the emergent scholarship reflected the expertise and synergy of all participants rather than the predetermined funding streams and entrenched academic hierarchies? What if the only rules governing the behaviors of the autonomous agents in this women's health CAS as they begin to learn together are that: (1) variability is the norm (health); (2) loss of variability indicates disease; (3) sex differences may exist at all levels of scale; (4) adaptations to the pregnant state reflect variability; (5) maladaptations to pregnancy represent a loss of variability; (6) gender differences exist in how men and women experience and respond to their environments; and (7) mind is connected to body through an integrated psychophysiologic state. Below I explore how these rules could guide emerging scholarship in women's health with some help from the field of physics.

LESSONS FROM PHYSICS

Contemporary physics has shown that what you see depends not only on what you look for, but also on how you look for it. Heisenberg's uncertainty principle and Bohr's theory of complementarity demonstrated that an experiment designed to look for the particle nature of an electron obscured its wave characteristics. Indeed, the electron is best described using both of these "partial" perspectives. The more partial perspectives we assemble, the closer we get to the "real" nature of the observed phenomena.

A clinical example of partial perspective is polycystic ovarian syndrome (PCOS). Historically a condition treated by obstetrician–gynecologists because it manifests as menstrual irregularity, PCOS was considered a fertility disorder. From a whole-woman perspective, however, anovulation is seen as merely one of the many effects caused by hyperinsulinism. Other effects are those of non–insulin-dependent diabetes, including hypertension and coronary artery disease. In fact, PCOS in a young woman is predictive of coronary artery disease at a later age, and its diagnosis should lead to preventive interventions as well as treatment to restore fertility, something that may be accomplished with oral hypoglycemics.[16]

Medical knowledge has been limited by its partial perspectives, particularly when one perspective dominates the field. Medical education reform in women's health began as an awareness of how the 70-kg, white, middle-class, North American, heterosexual male perspective dominated normative standards in medicine. Women have been "outliers," deviant from the dominant norm. Even official definitions of women's health describe is as that which is different (implying a male-defined norm).[17] Although developing and adding other perspectives to the dominant one creates a more complete picture, a more fundamental change in thinking is required. That change is to have variability as the norm. By shifting the norm to variability, education and research will automatically accommodate sex, race, age, ethnicity, etc.

Nonlinear quantitative analysis of living systems is, in fact, showing that variability is normal and regularity (fixed response) indicates disease. Health and vitality are expressions of the system's plasticity in response to unpredictable environments.[18,19] In clinical medicine, a healthy heart is one that has a high degree of variability between successive beats. The diseased heart has a regular beat-to-beat pattern, as seen in congestive heart failure and preceding sudden death.[20] This seems counterintuitive given our grounding in homeostasis, where physiologic systems act to reduce variability and return perturbations to a "normal" steady state. The loss of variability and the appearance of pathologic periodicity have now been found to occur in several diseases such as epilepsy, Parkinson's disease, and bipolar disorder.[12] Interestingly, women have higher rates of heart-rate variability than do men and maintain it longer as they age.[21] Could a higher degree of complexity in physiologic systems be the reason women exhibit more heartiness at the extremes of life, as neonates and elders?[22] As we move further away from measures that describe only the range, mean, and standard deviation toward nonlinear measures that appreciate the "types" of information present in a data set rather than collapsing them into a mean, our knowledge about variability as the norm in complex systems will dramatically increase.

Perhaps the ultimate example of complexity in biological systems is women's capacity for adaptation to the pregnant state. During pregnancy, every organ system within the woman must shift its interaction with every other organ and the fetoplacental unit to survive and maintain the woman's overall structural integrity. *What is invariant is the pattern of relationships between the elements*. Maladaptations to the pregnant state may represent failures in variability. For example, placental blood vessels in pre-eclamptic women show evidence of atherosis and a failure of remodeling.[23] Educationally linking this vasculopathy to hypertension in general would stimulate learners to think about approaches to hypertension in both women and men that have not been evident as yet. Similarly, viewing a myocyte's failure to adapt to the pregnant state may be a way not only to explain the cardiomyopathy of pregnancy, but also to understand congestive heart failure.[24]

Multiple interactions occur at the boundary of mother and fetus, as each adapts to the other. For example, maternal DNA expression interacts with the sex of the fetus. The female fetus of a mother carrying the gene for neural-tube defects will more often emerge with anencephaly; the male fetus with spina bifida.[25] Low-birth-weight boy babies have, as adults, significantly higher cortisol levels, reflective of an altered hypothalamic–pituitary–adrenal axis and a higher risk of non–insulin-dependent diabetes later in life.[26] Girl babies below the 10th percentile at birth have a 3.6-fold increased risk of manifesting gestational diabetes in their 20s.[27] Pregnancy is also not a discrete and finite event for the mother. It can increase or decrease the mother's risk for subsequent disease (such as breast cancer, diabetes, hypertension), and persistence of fetal cells in the postpartum maternal circulation may lead to autoimmune disease.[28] The uterine context and the dynamic interplay between fetus and mother may influence them both for future health and disease.[29]

Reductionist models have further assumed that systems are closed or insulated from their contexts by impermeable boundaries, making predictions about the future possible. In contrast, complex systems are described as having permeable boundaries, with no way of knowing the future apart from the system's context. An example of the importance of context in complex systems is that of post-traumatic stress disorder (PTSD), which demonstrates the interdependencies between biology, cognition, relational contexts, and the larger environment in which women live.[30,31] Although many individuals are exposed to trauma, only one in four will develop PTSD.[32] Women, who are not at greater risk for exposure to trauma than men, are more likely to develop PTSD when exposed. Life-threatening physical injuries do not reliably predict PTSD or that psychiatric or somatic symptoms will subsequently emerge. Instead, perceived threat, the sexual nature of the trauma, and age under 15 are more predictive. Girls and women suffering from sexual trauma may be more effectively understood and treated with a perspective that links social context with plasticity in the neural network, its neurochemical milieu, cognition, and subsequent behavior. Psychotherapy based on relational theory could create a new relational context for altering connections in the neural network. The goal of such therapy would be the emergence of healthier psychic structures instead of the control of unhealthy behaviors, emotions, or thoughts.[33,34] Imagine the understanding and treatment of other psychophysiological states, be they depression in women or uncontrolled aggression in men, in an academic environment that nudges the complex adaptive system of women's health into a place where it is at its most creative. In the language of complexity science, that place is at "the edge of chaos"—somewhere between order and disorder, a place of maximum possibilities.[35]

CONCLUSION

The scientific community and the medical profession are focusing more attention on the health of women and gender-based science. As these efforts progress, a new clinical science is emerging that reflects women's health in ways that existing disciplines cannot. This new field is rooted in complexity, a scientific approach that is transforming many areas of scholarship within traditional fields as diverse as physics, biology, economics, and management. Medical educators can use women's health as a model for all the medical sciences as it shifts from rote learning of facts to learning how to think and apply information from multiple perspectives. As Einstein inferred, the traditional disciplines are not being replaced. Women's health is simply expanding the view.

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