# Recent Advances in Medical Informatics

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telemedicine, protocol based decision support, terminological systems, coding and classification

A survey for the general medical public of recent advances in three areas of medical informatics - telemedicine, protocol based decision support systems, and clinical coding and classification.

## Introduction

Medical informatics is as much about computers as cardiology is about stethoscopes. For those who have studied the application of information technologies in medicine, the last decade has delivered one unassailable lesson. Any attempt to use information technology will fail dramatically when the motivation is the application of technology for its own sake rather than the solution of clinical problems (Coiera:1994; Wyatt:1994; van der Lei; 1994).

The role of the information sciences in medicine continues to grow, and the last few years have seen informatics begin to move into the mainstream of clinical practice. The scope of this field is however enormous - informatics finds application in the design of decision support systems for practitioners (e.g. Miller, 1994), in the development of computer tools for research (e.g. Hunter, 1993), and in the study of the very essence of medicine - its corpus of knowledge (e.g. Keravnou, 1992). It is likely that the study of informatics in the next century will become as fundamental to the practice of medicine as the study of anatomy has been to the present.

It is with two seemingly contradictory themes in mind - apparently unbridled technological promise against less than satisfying practical achievement - that recent advances will be examined. Work will be assessed against three criteria - its *possibility*, its *practicability*, and its *desirability*. Possibility reflects the science of information - what in theory can be achieved? Practicability addresses the potential for successfully engineering a system - what can actually be built given the constraints of the real world? Desirability looks at the fundamental motivation for using a given technology.

These criteria are suggested because we need to evolve a framework to judge the claims made for these new technologies, and those who seek to profit from them. Just as there is a long-standing symbiosis between the pharmaceutical industry and medicine, there is a newer and consequently less examined relationship between medicine and the computing and telecommunication industries. Clinicians should try to judge the claims of these newcomers in the same cautious way that they would examine claims about a new drug (Wyatt, 1987). Perhaps more so, given that clinicians are far more knowledgeable about pharmacology than they are about informatics and telecommunications.

The first part of the article reviews a variety of activities that collect under the telemedicine banner. Since this is a new area, major research themes are only appearing now. Next, protocol based decision support systems are discussed. These may be the first substantive clinical information systems to appear in routine clinical practice. Finally, the current state of clinical coding is examined. The terminology and coding enterprise represents the first major attempt to uniformly describe the structure, content and nature of medical knowledge.

## Telemedicine

Definitions of telemedicine abound. The essence of telemedicine is the exchange of information at a distance, whether that information is voice, an image, elements of a medical record, or commands to a surgical robot. It seems reasonable to think of telemedicine as the *communication of information to facilitate clinical care*. And it is not a new enterprise - Einthoven experimented with telephone transmissions using his new invention, the electrocardiograph at the beginning of the century (Nymo, 1994).

At its inception, telemedicine was essentially about providing communication links between medical experts and remote locations. It is now clear that the healthcare system suffers enormous inefficiencies because of its poor communication infrastructure and telemedicine is seen as a critical way of reducing that cost. One estimate suggests that the US health system could save $30 billion per annum with improved telecommunications (Little, 1992). Consequently, telemedicine has now become a significant area for research and development.

As one might expect, the renewed interest in telemedicine also has much to do with the excitement of new technologies. At present the press is flooded with articles about the information superhighway, the Internet, and the rapid growth of mobile telephony. Telemedicine is often presented in the guise of sophisticated new communications technology for specialist activities like teleradiology and telepathology. These are championed by telecommunication companies because they have the potential to become highly profitable businesses for them (Bowles, 1994). Perhaps influenced by these forces, much of the research in telemedicine is driven by the possibilities of technology rather than the needs of clinicians and patients.

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Yet the communications infrastructure used by healthcare will not need to be special. The telecommunications market is competitive and the evolving options are numerous. Healthcare providers will be able to utilise the services of cable television, mobile cellular carriers, and telecommunication companies. Further, communications technology does not need to be sophisticated to deliver benefit. Appropriate use of today's telephone can make significant improvements to the delivery of care. For example, patient follow up can often be done on the telephone (Rao, 1994). Rapid communication of hospital discharge information using existing electronic data transfer mechanisms is beneficial for general practitioners (Branger, 1992). The combination of mobile telephony and paging systems can reduce the 5-10 minutes out of every hour many clinicians spend answer pagers (Fitzpatrick, 1993).

Perhaps more interestingly, inexpensive voice messaging systems can deliver simple but powerful services over existing telephone networks. Voicemail for example, has significant potential for improving the process of care (Constable, 1994). Leirer et. al. (1991) used a voicemail system to automatically phone medication reminders to elderly people at home, and showed that it reduced both tardiness and complete forgetting. As more patients get access to electronic mail, this will offer further avenues for innovative health services. Already in some populations, access to electronic mail is high. Fridsma et. al. (1994) in California found that 46% of their patients at clinic already used email, 89% of which was through their place of work.

All these data points suggest that the potential for the clinical application of communication technologies is indeed great, but equally that there is much still to learn. In particular, the relationship between telemedicine and informatics needs to be explored in greater detail. Informatics focuses on the use of information and telemedicine on its communication. Although seemingly disparate endeavours they are intimately linked, since the goals of communicating information and deciding on its content cannot be separated (McCarthy and Monk, 1994). Further, there is little clinical value in information systems built simply to gather data for administrators, forgetting that the essence of delivering health care is the communication of information *between* members of the clinical team. Coupled together, the technologies of information and communication can enhance access to information, whether it is stored electronically or is in the possession of a colleague.

Several key research questions are apparent. Firstly, clinical practice already revolves around communication, often by telephone, and important information exchanged in this way is often lost because it is not documented (Stoupa, 1990). Capturing the informal information currently lost in healthcare's communication channels may soon become an important issue for those developing the formal electronic patient record. How one decides what information is important and how that information is made available are non-trivial questions involving issues of confidentiality, security, as well as the technology of storage and retrieval of voice recordings.

Secondly, our understanding of the effects of technology on communication is still in its infancy. Researchers in the field of human-computer interaction feel that before these technologies can be successfully introduced, the way in which individuals communicate needs to be understood(McCarthy, 1994). In one recent study, the presence of a computer during doctor-patient consultations had detectable negative effects on the way doctors communicated (Greatbatch, 1993). While they were at the computer, doctors confined themselves to short responses to patient questions, delayed responding, glanced at the screen in preference to the patient, or structured the interview around the computer rather than the patient. On the positive side, recent experiences in Norway have identified benefits to remote telemedical consultation. Services that provided isolated general practitioners with access to specialist expertise had an unexpected side-effect. The skill level of practitioners was raised through repeated interactions with specialists and the management of cases that were previously referred (Akelsen & Lillehaug, 1993). This may arise through the dynamics of the relationship between remote practitioner and specialist. Unlike most educational settings, both are motivated to form a coach and apprentice relationship for the immediate management of a patient.

Probably the most important issue for research will be to understand the effect of introducing technologies that allow *asynchronous* communication. At present, devices like telephones and pagers interrupt individuals when communication is desired - these are known as *synchronous* methods. The messages sent across asynchronous systems like electronic mail and voicemail do not need to be answered immediately and so have the potential to significantly reduce the number of interruptions experienced by clinicians. Such messages may nevertheless carry important information. It will be critical to understand how such systems can be designed to ensure that healthcare workers do not miss critical information, and equally are not inundated with a flood of irrelevant messages.

Finally, along with new communication possibilities, there come new medico-legal implications. In the United States the courts have decided that radiologists are negligent if they fail to personally inform clinicians of a diagnosis. "Communication of an unusual finding in an X-ray, so that it may be beneficially utilised, is as important as the finding itself". Further, leaving a message with an intermediary is not enough - "certain medical emergencies may require the most direct and immediate response involving personal consultation and exchange" (Kline, 1992). The fact that such communication requirements are beginning to be mandated reflects the community's changing perceptions of best medical practice.

The rapid arrival of telemedicine suggests that the healthcare community is beginning to identify the benefits of good clinical communications practice, and realising the costs of poor communication. The next few years should see the research in telemedicine mature. The main focus will become the application of communication technologies rather than their development. This represents the same shift in focus that was required of medical informatics, which initially spent much effort in developing technologies specifically for medicine.

## Protocol-based Decision Support

Many see the development of protocol-based medicine as the essential cultural change in clinical practice that will permit the design of useful clinical information systems (Durinck et al., 1994). It was rightly seen as inappropriate when early computer system designers sought to regularise clinical practice to suit the nature of their systems. The move to evidence based medicine now begins to make it acceptable for clinicians to follow standard assessment and treatment protocols (Mulrow, 1994). In this case it is quite appropriate for clinicians to use information systems to assist them.

The ultimate goal of a protocol-based decision support system is to provide a set of tools that allow a clinician to access up to date guidelines, and then apply these in the management of their patients. It seems likely that simple protocol systems will appear in clinical practice by the end of the decade (Renaud-Salis, 1994). In some sense, first generation systems have already appeared, since one can now begin to access treatment guidelines and clinical trial data on the Internet (Goodlee, 1994) (see text box).

However, evidence suggests that even when guidelines are available, clinicians forget to follow them or deviate from them without clear cause (Renaud-Salis, 1994). Forgetting pre-planned management tasks seems to be especially likely in high stress clinical decision making situations (Coiera et al., 1994). However, it probably will be unacceptable to uniformly enforce adherence to guidelines, given the complexity of individual patient cases. It should be possible however, to make it as easy as possible for clinicians to access them during routine care, making it less likely that steps will be inadvertently forgotten or altered.

This will require the design of more sophisticated systems that will be integrated into the electronic patient record. These will not only be repositories for protocols, but will allow them to be manipulated by clinicians. For example, best practice recommendations may need to be customised for local conditions or for individual patients. Further, guidelines may be incorporated directly into patient records. As elements of the guideline are completed, they could be automatically noted. The records of care generated in this manner might ultimately be used for population-based outcomes analysis.

Some researchers advocate the use of computerised protocols in even more sophisticated settings. One group use a set of ventilation protocols to adjust tidal volume and ventilator rate settings for patients with Adult Respiratory Distress Syndrome (ARDS) (Thomsen, 1993). They report using the system for over 50,000 hours on 150 ARDS patients (Morris et al., 1994a). In one trial with 12 patients, 94% of 4,531 protocol-generated recommendations were followed by staff. The survival rate of ARDS patients supported with computerised protocols was four times the expected rate from historical controls (Morris et al, 1994b).

Two key problems will be faced as such systems become more commonplace. The first is the arduous but essential collation of best-practice guidelines which needs to be carried out by bodies like the Cochrane Collaboration (Goodlee, 1994). In the absence of such collections, the value of protocol systems will be minimal. The second will be an issue which is at the heart of informatics - the problem of defining, managing and updating medical terminology.

## Terminological Systems

Medical coding systems like ICD-9-CM, ICD-10, SNOMED and Read are becoming increasingly familiar to clinicians. Their rationale is as follows. Once captured electronically clinical data should be available for subsequent aggregation and analysis. However, the words used to describe conditions vary so much that simple analysis is often not possible. Further, the meanings attached to terms may vary. If there was an agreed set of terms to describe the process of care then data analysis would be simplified (Ackerman et al., 1994). The goal of research into medical terminologies is to arrive at a consensus on the most appropriate set of terms and the way they should be structured.

The fundamental advance in terminological research over the last year or so is the realisation that the goal of constructing a complete and universal thesaurus of medical terms is ill-posed. Terminology evolves in a context of use, and attempting to define context independent terminologies is ultimately implausible. Coupled with this view comes the pragmatic understanding that a more robust scientific approach needs to be brought to the enterprise of terminology construction. Each of these issues deserves to be examined in some detail.

### Universal Terminological systems

The ideal terminological system would be a complete, formal and universal language that allowed all medical concepts to be described and reasoned about. Some researchers have explicitly asserted that building such a singular and "correct" medical language is their goal (Cimino, 1994; Evans et al., 1994). This task emphasises two clear requirements: the ability for the terminological language to cover all the concepts that need to be reasoned about, and the independence of the terminology from any particular reasoning task. A further goal occasionally articulated is that where there are alternative terminologies, they must be logically related such that one can be translated into the other.

Despite the enormous health care investment currently devoted to achieving these goals, current evidence indicates that they are not possible. There is no pure set of codes or terms that can be universally applied in medicine. There are two fundamental and related obstacles to devising a universal terminological system. The first is the *model construction* problem - terminologies are simply a way of modelling the world, and the world is always richer and more complex than any model humans can devise. The second is the *symbol grounding* problem - the words we use to label objects do not necessarily reflect the way we think about the objects, nor do they necessarily reflect defined objects in the real world (Norman, 1993). The cumulative evidence from recent thinking in cognitive science, computer science and artificial intelligence provides a formidable set of supporting arguments.

Cognitive studies of the way people form categories have shifted from the view that categories exist objectively, to the notion that concepts are relative and structured around probabilistic prototypes (Rosch, 1988). The qualities of prototypical categories are only generally true of the examples they classify. For example, most people would happily say that flight was a property of birds, and cope with the fact that some birds are flightless. The category 'bird' has no pure definition. The way in which people use family resemblances to create such categories from examples remains an area of research (e.g. Ahn and Medin, 1992). Many artificial intelligence (AI) researchers also contend that there is no objective model of medical knowledge. Much of this is based on their experiences in constructing and maintaining knowledge-based systems (Clancy, 1993).

Further, people choose categories at a level of description that is appropriate for thinking about an object in most situations (Rosch, 1988). Categories are formed entirely based upon their utility. Medicine's terminologies have evolved over many years and are also subject to the same process of cognitive evolution. Consequently disease entities exist for as long as they are useful mental constructs, and are replaced as better concepts emerge - there is no static body of medical knowledge. Not only are new concepts added, often the very structure of medical knowledge changes as concepts are internally re-organised (Clancy, 1993b) (Laporte, 1995). ICD-9 and 10 are substantially different systems, partly because of the changes in medicine over the 15 year period in which ICD-10 was built (IMG, 1995).

Any attempt at modelling medical knowledge by the imposition of a structure on its terms will thus decay in accuracy over time (Hogarth, 1986; Tuttle and Nelson 1994). Consequently it does not make sense to think of terminological systems developing independently of a context of use. Even those who seek to build a canonical medical terminology are forced to select a clinical application to set a context before they can meaningfully proceed (Friedman et. al, 1995).

Equally, there is no reason to expect that there is any uniform mapping between terminological systems developed in different contexts of use (Glowinski, 1994) (Tuttle, 1994). Even when the systems are of similar construction, problems are encountered when one tries to translate knowledge expressed in one form into another. The authors of one study concluded that the sharing knowledge between terminological systems "does not seem to be easily achievable" (Heinsohn, 1994).

## Building Maintainable and Testable Terminologies

While coding systems can never be truly canonical, they still provide a practical basis for managing the language of medicine - as long as it is understood that they define a limited and consensual language that will have to be continually modified. This modification is a predictable consequence of the subjectivity of knowledge. Whenever a knowledge base is applied to a task outside of its intended use, it will require change (Clancy, 1993).

SNOMED, for example was initially developed to classify pathological items. It has now been expanded to produce a general purpose system for all of medicine. However a study of SNOMED's utility in coding nursing reports found it coded only about 69% of terms (Henry et. al., 1994) - with the implication that the missing terms would need to be added. Such additions are required every time a terminology is applied to a new area, making the task of updating problematic (Cimino and Clayton, 1994).

Eventually, as a terminology is continually expanded into new areas, its fundamental organisational structure will be altered to reflect the different structure of these new areas (Clancy, 1993b). The process of terminology growth and alteration introduces huge problems of maintenance, and the very real possibility that the system will start to incorporate errors, duplications and contradictions. If we simply think of terminological thesauri as computer programs then we already know that continued modification is a poor development strategy. Software engineering tells us that the best time to modify a program is early in the development cycle. Introducing changes into a mature system becomes increasingly expensive over time (Littlewood, 1987).

Consequently, we have probably reached the stage where uncontrolled addition of terms to existing thesauri is no longer acceptable. Those who pay for their maintenance will be faced with ever increasing costs. To manage these costs, one would need to measure the performance of a thesaurus on a particular task, and then determine whether proposed additions or alterations will improve that performance, and at what cost.

### Compositional Terminologies

In the longer term, new approaches are needed. Most existing coding systems are *enumerative*, listing out all the possible terms that could be used in advance. A *compositional* approach in which terms are created from a more basic set of components may be more practical to build, maintain and update (Glowinski, 1994). For example, a practitioner may ask, does "severe discomfort in the fifth left metacarpophalangeal joint" in a patient record correspond to "small joint symptoms" in a clinical protocol? An enumerative system would have to have a pre-existing code for the clinical findings, but a compositional system would generate the findings from a set of components (Figure 1). Indeed it should be able to generate many such specific conjunctions, as long as they are medically sensible (Glowinski et al, 1991). Thus rather than developing static terminologies, the combinatorial approach tries to construct dynamic terminology servers to produce answers to a variety of terminological questions (Nowlan et. al., 1994).

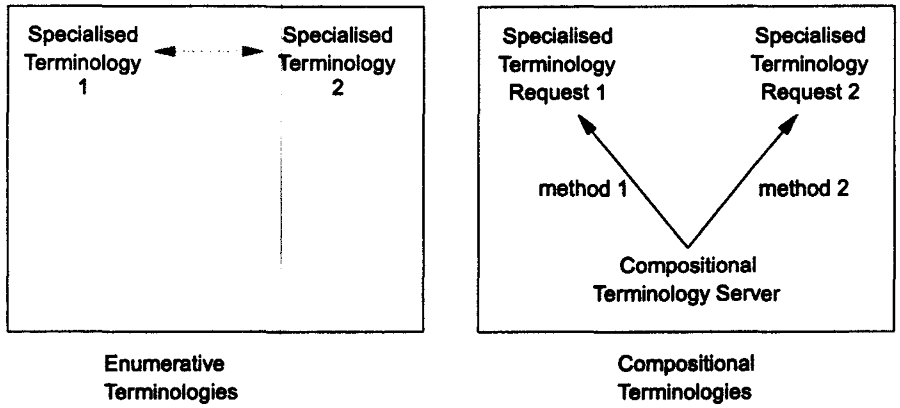



Figure 1: Enumerative terminological systems are developed independently of each other. Compositional systems try to use basic terminology building blocks along with specialised methods to generate terms for specialised needs. Mapping between specialised terms is not uniformly possible with enumerative systems, but inherent in the design of compositional systems.

There are two hypotheses behind the compositional proposal. The first is an engineering hypothesis - that compositional systems are easier and cheaper to maintain and update than enumerative ones. As we have seen, current enumerative systems continually require extensions that will over time introduce inconsistencies to the system. The compositional approach starts from scratch, defining a core of components that constitute a 'deep' model of medical knowledge. The expectation is that terms can be generated from that model. By definition, since they are generated from the same core of knowledge and the method of generation is known, terms can be mapped onto one another logically. Further, as medicine changes these changes can be made to the core and be immediately reflected in any new term generated. Compositional systems should also allow the use of sophisticated internal checks on the correctness of their contents (Gobel, 1994).

Compositional systems should also be more efficient to use. The power of a compositional system is its compactness and maintainability, while the cost of using it is that each answer has to be derived from 'first principles' and this takes computer time. However the more expressive and complete an enumerative system is, the slower it is to use (Heinsohn, 1994). One of the engineering trade-offs to be explored in the future will be to decide whether a compositional system is quicker to interrogate than a larger enumerative one. The evidence from other disciplines is that the compositional approach will eventually be fastest, as enumerative systems grow to be too large. For example in computer engineering, so called reduced instruction set computer chips (RISC) have a small set of basic operations which can be combined to do more complex operations. These chips are much faster than traditional ones that have a large enumeration of operations to cover many eventualities.

The second compositional hypothesis is a scientific one and is more controversial - that there is such a thing as a deep or core set of medical knowledge from which terms can be generated (Friedman, 1995). Compositional systems, like their enumerative counterparts are only models of the world. They suffer the same issues of model fidelity and subjectivity. Hence there is no greater 'depth' to the knowledge they encode - it is either just more detailed or more general (Coiera, 1992).

### The way forward

In the short term administration agencies keen to obtain aggregate clinical data are driven to adopt existing systems, even if they are imperfect. This has lead to much debate amongst those supporting particular systems of their merits over competing ones (e.g. Tuttle and Nelson, 1994).

The UK is now being asked to adopt the Version 3 Read codes, both for use in personal clinical systems as well as for audit, research, outcomes and guidelines (Calman, 1994). Such a decision can now be seen to be necessarily interim. What is really needed to help rationale choices in the longer term is impartial empirical research, comparing the cost and efficacy of different systems in support of well defined *tasks and contexts*. For example, in a recent study comparing the utility of different coding schemes in classifying problem lists from medical records, none of the major systems were found to be comprehensive. UMLS and SNOMED were found to be superior to Read and ICD-9-CM (Campbell and Payne, 1994).

In contrast to the UK approach, the Board of Directors of the American Medical Informatics Association have suggested that it is not necessary or desirable to have all codes coming from a single master system. They suggest that one should embrace several existing and tested approaches, despite their imperfections, to progress quickly. A first phase system could be created by borrowing from the different existing code systems, each created for and therefore better suited to, different subject domains (Ackerman et al., 1994).

The longer term need will be to introduce more maintainable and extensible systems, as the cost of supporting existing systems becomes insupportable. A solution based in part on multiple compositional systems would seem to be the most desirable one. Since any general medical terminology will only cover a small part of the specific vocabulary of any medical speciality, separate systems may need to developed for use *between* specialities and *within* specialities - "vocabularies need to be constructed in a manner that preserves the context of each discipline and ensures translation between disciplines (Brennan, 1994)". Indeed over a century ago when Farr constructed the classification system ultimately resulting in ICD, he noted that "several classifications may, therefore, be used with advantage; and the physician, the pathologist, or the jurist, each from his own point of view, may legitimately classify the diseases and the causes of death in the way that he thinks best adapted to facilitate his enquiries" (ICD-9, 1975).

Compositional systems will thus need to be constructed that agree on a restricted subset of terms necessary for the passage of information between specialities - an Esperanto as it were, between different cultures. Work on such communication standards is at present still in it's infancy (e.g. Ma, 1995) and more substantive work should be expected in the future. Presently terms are created without explicit tasks in mind, in the hope that all unseen eventualities will be served. Inter-speciality systems would probably need to be tightly task based to ensure maximum utility.

It is at this point that the importance of protocol-based medicine becomes very clear. Protocols are constructed with an explicit task and context in mind. They are written by a experts within a speciality, who arrive at a consensus on the management of a specific condition. In the process of doing so they have to define their terms. The communication of information to another speciality can also be defined in the same manner - in the context of a patient on a protocol, what information is needed by an allied specialist? While it is clearly the case that good terminologies will be needed to construct computer-based protocol systems (Glowinski, 1994), the discipline of writing protocols will constrain the terminology problem sufficiently such that a well defined and relevant set of terms can be agreed upon.

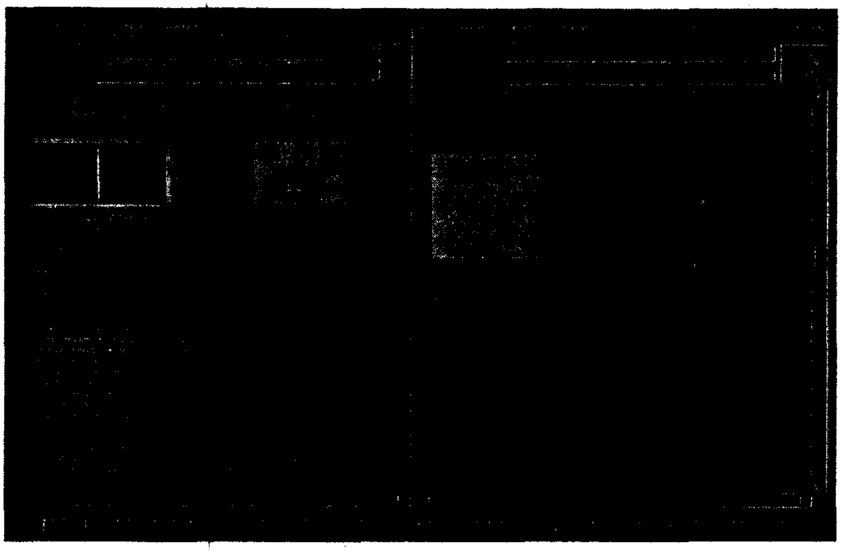
## Conclusion

This paper has reviewed three apparently quite separate areas - telemedicine, protocol based decision support systems, and terminologies. They can now be seen to be inextricably entwined, since the goals of communicating information and deciding on the content of information cannot be separated. Human communication involves information exchange in a context (McCarthy, 1994). What is said depends on the intended message, the method used to convey the message, who is speaking, and who is being spoken to. With the development of protocol based systems and their supporting terminological systems, we have the perfect example of that symbiosis.

### Textbox - *The Internet*

At present, the Internet is an open and unregulated community of individuals communicating freely across an international electronic computer network. The number of medical sites joining the Internet increases monthly, as does the number of information resources available on it. Indeed, it would require a lengthy article to enumerate what is currently available, and that listing would be out of date well before it appeared in print.

There is now good evidence that such services are valuable and in constant use. The OncoLink information resource for example, provides oncologists with up to date trial and treatment information, as well as acting as an educational resource for cancer patients and their families. OncoLink was reportedly accessed 36,000 times in March 1994 (Buhle, 1994). The figure for January 1995 was 284,412 accesses.



*[Fig 2 - screens from J. Clin. Imaging ]*

The World Wide Web is perhaps the most important innovation on the Internet in the last few years, and is a software layer that provides Internet users with a simple way of accessing information. The Web allows users to create and exchange text, image and video documents. The quality of these documents are now so high that the Web is used by some medical educational institutions. The University of Utah, for example, has an extensive library of anatomical pathology images called WebPath for its students. At the University of Iowa a set of teaching materials is assembled in their Virtual Hospital. The National Library of Medicine's 'Visible Human' project aims to create a complete, anatomically detailed, three-dimensional representations of the male and female human body and to make this available on the Internet. The project is collecting transverse CAT, MRI and cryosection images of male and female cadavers at one millimetre intervals.

Medical research is also taking advantage of the Web as journals begin to appear on the Web in preference to, or in advance of print. For example the *Journal of Medical Imaging* will publish papers on the net. Its field is moving so quickly that printed media are now seen only as the archival form of knowledge. The form best suited to rapid dissemination is electronic, with the additional advantage that one can create papers which contain text, graphics, sound, and moving images. Similarly, the move to evidence based medicine will be able to use the Web for rapid distribution of important clinical management data. The Cochrane Collaboration, which seeks to collect, review and disseminate high quality overviews of the effects of health care, has already set up a publicly accessible resource on the Web. It's intent is to make the updated systematic reviews it collects accessible via the Internet (Goodlee, 1994).

## World Wide Web addresses

**General Medical indexes to Internet resources**

*The World Wide Web Virtual Library: Biosciences - Medicine*
*http://golgi.harvard.edu/biopages/medicine.html*

*The Whole Internet Catalog - Health & Medicine*
*http://nearnet.gnn.com/wic/med.toc.html*

*HealthNet*
*http://hpb1.hwc.ca/healthnet/#medapp*

**Internet Services mentioned in the text**

*HospitalWeb*
*http://dem0nmac.mgh.harvard.edu/hospitalweb.html*

*Interactive Medical Student Lounge*
*http://falcon.cc.ukans.edu:80/~nsween/*

*Journal of Medical Imaging*
*http://jmi.gdb.org/JMI/ejourn.html*

*U.S. National Library of Medicine (NLM)*
*http://www.nlm.nih.gov/*

*OncoLink*
*http://cancer.med.upenn.edu/*

*The Virtual Hospital*
*http://indy.radiology.uiowa.edu/VirtualHospital.html*

*The Visible Human Project*
*http://www.nlm.nih.gov/extramural_research.dir/visible_human.html*

*WebPath: Internet Pathology Laboratory*
*http://www-medlib.med.utah.edu/WebPath/webpath.html*

*Cochrane Collaboration*
*http://hiru.mcmaster.ca/cochrane/cochrane.htm*

## References


[1] E. Coiera, Question the Assumptions, in P. Barahona, J. P Christensen (eds.) *Knowledge and Decisions in Health Telematics*, IOS Press:Amsterdam, 1994:61-66.

[2] J. Wyatt, Promoting use of medical knowledge systems: Lessons from computerised ECG interpreters, in P. Barahona, J. P Christensen (eds.) *Knowledge and Decisions in Health Telematics*, IOS Press:Amsterdam 1994;73-80.

[3] J. van der Lei, Computer-based Decision Support: The unfulfilled promise, in P. Barahona, J. P Christensen (eds.) *Knowledge and Decisions in Health Telematics*, IOS Press:Amsterdam 1994;67-72.

[4] R. A. Miller, Medical Diagnostic Decision Support Systems - Past, Present, and Future: A threaded bibliography and brief commentary, *J Am Med Informatics Assoc* 1994;**1**:8-27.

[5] L. Hunter (ed.), *Artificial Intelligence and Molecular Biology*, AAAI Press/ The MIT Press:Menlo Park, Ca 1993.

[6] E. Keravnou (ed.), *Deep models for medical knowledge engineering*, Elsevier Science Publishers B.V.:Amsterdam 1992.

[7] J. Wyatt, The evaluation of clinical decision support systems: a discussion of the methodology used in the ACORN project, *Proceedings of AIME 87, Lecture Notes in Medical Informatic* Springer-Verlag:Berlin 1987;**33**:15-24.

[8] B. J. Nymo, Telemedicine, *Telektronikk* 1993;**89**(1):4-11.

[9] A. D. Little, *Telecommunications: Can it help solve America's health care problems?* Arthur D. Little:Cambridge, Ma.1992.

[10] R. A. Bowles, R. Teale, Communications services in support of collaborative health care, *BT Technology Journal* 1994;**12**(3): 29-44.

[11] J. N. Rao, Follow up by telephone, *BMJ* 1994; **309**:1527-1528.

[12] P. J. Branger, J. C van der Wouden, B. R. Schudel, E. Verboog, et. al, Electronic communication between providers of primary and secondary care, *BMJ* 1992;**305**:1068-1070.

[13] K. Fitzpatrick, E. Vineski, The role of cordless phones in improving patient care, *Physician Assistant* 1993; June:87-92.

[14] J. Constable, Active Voice, *BJ Healthcare computing and Information management* 1994;**11**:30-31.

[15] V. O. Leirer, D. G. Morrow, E. D. Tanke, G. M. Pariante, Elders' nonadherence: Its assessment and medication reminding by voice mail, *The Gerontologist* 1991;**31**(4):514-520.

[16] D. B. Fridsma, P. Ford, R. Altman, A survey of patient access to electronic mail: attitudes, barriers and opportunities, *Proceedings of the Symposium on Computer Applications in Medicine*, Journal of the American Medical Informatics Association, Symposium Supplement 1994: 15-19.

[17] J. C. McCarthy, A. F. Monk, Channels, conversation, co-operation and relevance: all you wanted to know about communication but were afraid to ask, *Collaborative Computing* 1994;**1**:35-60.

[18] R. Stoupa, J. Campbell, Documentation of ambulatory care rendered by telephone: Use of a computerized nursing module, *Proceedings of the Symposium on Computer Applications in Medicine*, IEEE Computer Society Press:Los Alamitos, Ca. 1990;890-893.

[19] Greatbatch, P. Luff, C. Heath, P. Campion, Interpersonal communication and human-computer interaction: an examination of the use of computers in medical consultations, *Interacting with Computers* 1993; **5**(2):193-216.

[20] S. Akelsen, S. Lillehaug, Teaching and learning aspects of remote medical consultation, *Telektronikk* 1993;**89**(1):42-47.

[21] E. L. Buhle, J. W. Goldwein, I. Benjamin, OncoLink: A multimedia oncology information resource on the Internet, *Proceedings of the Symposium on Computer Applications in Medicine, Journal of the American Medical Informatics Association* Symposium Supplement 1994:103-107.

[22] T. J. Kline, T. S. Kline, Radiologists, communication and resolution 5: A medicolegal issue, *Radiology* 1992;**184**:131-134.

[23] J. Durinck, E. Coiera, R. Baud et. al, The Role of Knowledge Based Systems in Clinical Practice, in P. Barahona, J. P. Christensen (eds.), *Knowledge and Decisions in Health Telematics - The Next Decade*, IOS Press, Amsterdam 1994:199-203.

[24] C. D. Mulrow, Rationale for systematic reviews *BMJ* 1994;**309**:597-9.

[25] J. L. Renaud-Salis, Distributed Clinical Management-Information Systems: An enabling technology for future health care programmes, in P. Barahona, J. P. Christensen (eds.), *Knowledge and Decisions in Health Telematics - The Next Decade*, IOS Press:Amsterdam, 1994;139-146.

[26] F. Goodlee, The Cochrane Collaboration, *BMJ* 1994;309:969-70.

[27] E. Coiera, V. Tombs, G. Higgins, T. H. Clutton-Brock, Real-time clinical decison making, *HP Laboratories Technical Report* 1994; HPL-94-79.

[28] G. E. Thomsen, D. Pope, T. East, A Morris, A. tupper Kinder, D. Carlsom et al., Clinical Performance of a rule-based decision support system for mechanical ventilation of ARDS patients, *Proceedings of the Symposium on Computer Applications in Medicine*, McGraw Hill: New York 1993; 339-343.

[29] A. Morris, T East, C Wallace, J Orme, T Clemmer, L Weaver et al, Ethical implications of standardization of ICU care with computerized protocols, *Proceedings of the Symposium on Computer Applications in Medicine, Journal of the American Medical Informatics Association* Symposium Supplement 1994:501-505.

[30] A. Morris, C Wallace, R Menlove, T Clemmer,J Orme, L Weaver et al, A randomised clinical trial of pressure-controlled inverse ratio ventilation and extracorporeal CO2 removal from ARDS, *Am J Respir Crit Care Med* 1994:149(2):295-305.

[31] M. Ackerman, M. Ball, P. D. Clayton, M. E. Frisse, R. M Gardner, et al., Standards for medical identifiers, codes and messages needed to create an efficient computer-stored medical record, *J Am Med Informatics Assoc* 1994;**1**:1-7.

[32] J. J. Cimino, Controlled medical vocabulary construction: Methods from the CANON group, *J Am Med Informatics Assoc* 1994;**1**:296-297.

[33] D. Evans, J. J. Cimino, W. R. Hersh, S. M. Huff, D. S. Bell, Toward a medical-concept representational language, *J Am Med Informatics Assoc* 1994;**1**:207-217.

[34] D. A. Norman, Cognition in the Head and in the World: An introduction to the special issue on situated action, *Cognitive Science* 1993;**17**(1):1-6.

[35] E. Rosch, Principles of Categorization, in E. Rosch, B. B. Lloyd (eds.), *Readings in Cognitive Science*, Morgan Kaufmann:Los Altos, CA 1988;312-322.

[36] W. Ahn, D. L. Medin, A two-stage model of category construction, *Cognitive Science* 1992;**16**:81-121.

[37] R. Laporte, Patterns of disease: diabetes mellitus and the rest, *BMJ* 1995;**310**:545-6.

[38] A Guide to the use of tables of equivalence between ICD-9 and ICD-10, NHS Centre for Coding and Classification 1995;Report F6110.

[39] R. M. Hogarth, Generalisation in decision research: The role of formal models, IEEE Trans. Syst. Man. Cybernet 1986; **16**(3):439-449.

[40] S. Tuttle, S. J. Nelson, The role of the UMLS in 'storing' and 'sharing' across systems, *Int J Bio-Med Comp* 1994;**34**:207-237.

[41] C. Friedman, S. M. Huff, W. R. Hersh, E. Pattison-Gordon, J. J. Cimino, The CANON Group's Effort: Working toward a merged model, *J Am Med Informatics Assoc* 1995;**2**:4-18.

[42] M. S. Tuttle, The position of the CANON group: A reality check, *J Am Med Informatics Assoc* 1994;**1**:298-299.

[43] J. Heinsohn, D. Kudenko, B. Nobel, H. Profitlich, An empirical analysis of terminological representation systems, *Artificial Intelligence* 1994;**68**:367-397.

[44] W. J. Clancy, Notes on "Heuristic Classification", *Artificial Intelligence* 1993;**59**:191-196.

[45] A. J. Glowinski, Integrating guidelines and the clinical record: the role of semantically constrained terminologies, in *Health Telematics for clinical guidelines and protocols*, C. Gordon, J. P. Christensen (eds.), IOS Press:Amsterdam 1994.

[46] Henry S, Campbell K, Holzemer W, Representation of nursing terms for the description of patient problems using SNOMED III, *Proceedings of the Symposium on Computer Applications in Medicine*, McGraw Hill: New York 1993; 700-704.

[47] J. J. Cimino, P. D. Clayton, Coping with changing controlled vocabularies, *Proceedings of the Symposium on Computer Applications in Medicine*, *Journal of the American Medical Informatics Association* Symposium Supplement 1994:135-139.

[48] W. J. Clancy, Notes on "Epistemology of a rule-based expert system", *Artificial Intelligence* 1993;**59**:197-204.

[49] B. Littlewood (ed), *Software Reliability - Achievement and Assessment*, Blackwell Scientific Publications 1987; Oxford.

[50] A. J. Glowinski, E. W. Coiera, M. J. O'Neil, the role of domain models in maintaining the consistency of large medical knowledge bases, Proceedings of the Third AIME, *Lecture Notes in Medical Informatics* 1991;**44**:72-81.

[51] W. A. Nowlan, A. L. Rector, T. W. Rush, W. D. Solomon, From Terminology to Terminology Services, *Proceedings of the Symposium on Computer Applications in Medicine*, Journal of the American Medical Informatics Association, Symposium Supplement 1994;150-154.

[52] C A Goble, A J Glowinski, A Nowlan, A Rector, A Descriptive Semantic Formalism for Medicine, *Proc 9th IEEE Intl Conf Data Enginnering*, IEEE Computer Society Press 1993; 624-632.

[53] E. Coiera, Intermediate depth representations, *Artificial Intelligence in Medicine* 1992;**4**:431-445.

[54] K. C. Calman, New National Thesaurus, *CMO's Update* 1994;**4**:1.

[55] J. R. Campbell, T. H. Payne, A comparison of four schemes for codification of problem lists, *Proceedings of the Symposium on Computer Applications in Medicine*, *Journal of the American Medical Informatics Association* Symposium Supplement 1994:201-204.

[56] F. Brennan, On the relevance of discipline in informatics, *J Am Med Informatics Assoc* 1994;**1**: 200-201.

[57] *Manual of the international statistical classification of diseases, injuries and causes of death*, World Health Organisation:Geneva 1977.

[58] Ma, Mapping clause of Arden syntax with the HL7 and ASTM E 1238-88 standard, Int J Bio-Med Comp 1995;**38**:9-21.