Toward Patient-Centered, Personalized and Personal Decision Support and Knowledge Management: A Survey

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Summary

Objective: This paper summarizes the recent trends and highlights the challenges and opportunities in decision support and knowledge management for patient-centered, personalized, and personal health care.

Methods: The discussions are based on a broad survey of related references, focusing on the most recent publications. Major advances are examined in the areas of i) shared decision making paradigms, ii) continuity of care infrastructures and architectures, iii) human factors and system design approaches, iv) knowledge management innovations, and v) practical deployment and change considerations.

Results: Many important initiatives, projects, and plans with promising results have been identified. The common themes focus on supporting the individual patients who are playing an increasing central role in their own care decision processes. New collaborative decision making paradigms and information infrastructures are required to ensure effective continuity of care. Human factors and usability are crucial for the successful development and deployment of the relevant systems, tools, and aids. Advances in personalized medicine can be achieved through integrating genomic, phenotypic and other biological, individual, and population level information, and gaining useful insights from building and analyzing biological and other models at multiple levels of abstraction. Therefore, new Information and Communication Technologies and evaluation approaches are needed to effectively manage the scale and complexity of biomedical and health information, and adapt to the changing nature of clinical decision support.

Conclusion: Recent research in decision support and knowledge management combines heterogeneous information and personal data to provide cost-effective, calibrated, personalized support in shared decision making at the point of care. Current and emerging efforts concentrate on developing or extending conventional paradigms, techniques, systems, and architectures for the new predictive, preemptive, and participatory health care model for patient-centered, personalized medicine. There is also an increasing emphasis on managing complexity with changing care models, processes, and settings.

Keywords

Patient-centered, personalized, personal health systems, decision support, knowledge representation, knowledge management

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1 Introduction

Decision support and knowledge management in health care involve techniques, systems, and tools that would help clinicians and patients make informed decisions in disease prevention, diagnosis, treatment, and prognosis. Despite more than 50 years of progress, many challenges remain in the characterization, differentiation, and control or management of biomedical knowledge and health care processes for improving health outcomes and lowering costs. Recent advancements in distributed and mobile sensors, monitoring devices, electronic repositories, knowledge portals, and network sources have led to new dimensions of information explosion that complicate patient-centered, personalized decision making. The increasing popularity of personal health records and untethered care portfolios have also necessitated a paradigm shift in analyzing, developing, and evaluating care processes and decision aids from the individual patient's perspective.

Patient-centered care, as coined by the Picker Institute in 1988, emphasizes respecting the patient's values, preferences, and needs in integrated and coordinated care. Participation from family and friends, education and communication to support informed and shared decision making are essential in the process, which also focuses on physical comfort, emotional support, continuity of care, and access to care [1, 2]. The Institute of Medicine, in its landmark report "Crossing the Quality Chasm", identified patient-centered care as a key approach to improve the quality of health care in the US [3].

The U.S. National Institute of Health envisioned the future health model as "the 4-P's of Medicine": medicine that will be Personalized, Predictive, Preemptive, and Participatory[1]. The main idea is to use all the information relevant to the individual – including genomic make-up, personal and family history, images and laboratory test data, symptoms and signs, values and preferences – together with personalized biological and physiological models to predict the possible courses of disease progression and to select the best care options for the patient. In the personalized approach, preemptive measures could be taken as early prediction is possible; the decision making process is necessarily participatory due to the pervasive availability of relevant information in different care settings, including that patient's home [4].

Personal health systems (PHS), on the other hand, are a new genre of health information technologies (HIT) that supports patient-centered and personalized care. PHS complement existing institutional-based HIT with patient-initiated and patient-managed information collection, access and communication controls. The European Commission Framework Program 7

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1 "A New Strategic Vision for Medicine", excerpted from the NIH website: http://www.nih.gov/strategicvision.htm (accessed 31 March 2012).

project on Personal Health Systems (the PHS 2020 project)[2] defined PHS as systems and tools that provide continuous, quality controlled, and personalized health services to the individuals. PHS consist of body and environmental devices for individual and contextual information collection and communication, information storage and analytic capabilities, and feedback mechanisms that help in lifestyle management, and preventive, diagnosis, and treatment processes of patient care.

This paper first examine the grand challenges for clinical decision support and biomedical knowledge management, highlighting the main solutions and innovations required to support cost-effective patient-centered, personalized, and personal health care. This is followed by a summary of the major research trends in the past two years.

2 The Grand Challenges

The main challenges and opportunities for the next generation clinical decision support systems are examined in a number of recent review and position articles. Coeira et al [5], for example, discussed the recent development of evaluation methods, consumer informatics, public health informatics, translational bioinformatics, and patient safety. The consumers or patients are increasingly taking charge of their own health and making important health-related decisions. There has also been marked progress in integrating genomic and phenotypic information to develop personalized medicine and to enhance patient-centered care. Hence, a new set of design principles and evaluation metrics is needed to empower personal choices, facilitate predictions, enhance usability, and ensure safety in future clinical decision support systems.

A commemorative volume celebrating the 50th year publication anniversary of *Methods of Information in Medicine* [6] sketched the vision for health and biomedical decision support research in the next fifty years. Decision support is characterized as an evolving science, where new techniques, methodologies, and paradigms need to be developed with the changing needs, processes, and settings. A major focus is on managing complexities at the domain, system, and usage levels in the decision support process. Continuing efforts are needed to integrating genomic, phenotypic, and other system related information to support personalized decision making. Improved care can be facilitated by identifying enablers and barriers to the practical application of decision support technologies in the care settings, including access to information, access to care, and education.

Graham et al. [7] examined the major information and communication technologies (ICT) challenges from discovery to delivery in personalized health care. These challenges include: i) enabling evidence-based health care by gaining insights from data to knowledge to action; ii) improving healthcare quality by empowering people, including providers and consumers; iii) enhancing human capabilities by computer-based augmentation of human learning, reasoning, decision making, and physical motion; iv) managing health care processes as a complex, large-scale, adaptive distributed evolving system; and v) identifying major research enablers and inhibitors.

Ohno-Machado [8], on the other hand, summarized the critical technical, methodological, systemic, and infrastructure issues in combining public resources to build accurate predictive models and decision support tools. Such resources include online genomic, proteomic data repositories and biomedical literature collections, and personal information across different biological levels – cells, tissues, individuals, and populations.

At a more general scale, the National Academies' Report on "Computational Technology for Effective Health Care: Immediate Steps and Strategic Directions" [9] described the opportunities for improving healthcare processes and enhancing health in general through leveraging the growing avalanche of data relevant to healthcare, and the pervasive availability of these data to the providers, payers, and patients. Recent research in data analysis, machine learning and data mining aims to address these issues [10]; active investigations are on-going for direct solutions in the patient-centered, personalized, and personal care settings.

Reflecting the multidisciplinary nature of the issues, at least 4 out of 14 "Grand Challenges for Engineering in the 21st century" identified by the U.S. National Academy of Engineering [11] are related to health and biomedical informatics: Advance health informatics; Engineer better medicines; Reverse-engineer the brain; and Engineer the tools for scientific discovery. Hence, future health informatics systems "must be engineered for seamless sharing of data", including biological data, and these must be "trusted systems that offer relevant decision support to clinicians and patients ... (by allowing access to) information to treat specific patients and decision support systems to offer 'just in time, just for me' advice at the point of care."

The common themes identified, therefore, focus on supporting the individual patients who are playing an increasing central role in their own care decision processes. New collaborative decision making paradigms and information infrastructures are required to ensure effective continuity of care. Human factors and usability are crucial for the successful development and deployment of the relevant systems, tools, and aids. Advances in personalized medicine can be achieved through integrating genomic and phenotypic information – often from multiple sources and in heterogeneous modalities

[2] Personal Health Systems. http://ec.europa.eu/information_society/activities/health/research/fp7phs/index_en.htm (Accessed 31 March 2012)

– and gaining useful insights from building and analyzing biological and other models at multiple levels of abstraction. Therefore, new ICT and evaluation approaches are needed to effectively manage the scale and complexity of biomedical and health information, and adapt to the changing nature of clinical decision support.

In accordance with these challenges, current research efforts concentrate on developing or extending conventional paradigms, techniques, systems, and architectures for the predictive, preemptive, and participatory health care model for patient-centered, personalized medicine. Major advances are found in the areas of i) shared decision making paradigms, ii) continuity of care infrastructures and architectures, iii) human factors and system design approaches, iv) knowledge management innovations, and v) practical deployment and change considerations.

3 Shared Decision Making

Shared decision making, also called "informed decision making" or "evidence informed patient choice", is considered the corner stone of patient-centered care. Information about the alternatives and risks is shared between the clinicians and patients, who then jointly decide on the optimal course of actions or interventions [12]. While the concept is deemed important, actual adoption and implementation of shared decision making in clinical practice is limited. Most recent efforts focus on understanding the challenges and issues in the model, and finding solutions to overcome the barriers for adoption.

The US Preventive Services Task Force (USPSTF) [13] defined shared decision making as comprising 5 stages where an individual i) understands the nature of the disease or condition, ii) evaluates the services, alternatives, risks, benefits, and uncertainties involved, iii) considers his preferences, iv) participates in the decision making process at a personally desirable level, and v) makes a decision consistent with his or her preference and values.

Power et al [14] argued that based on psychological and behavioral evidences, the mood and emotion of the patients should also be considered in share decision making. They implemented the idea in a cognitive-emotional decision making (CEDM) framework of patient medical decision making.Zikmund-Fisher et al and others [15] reported on the National Survey of Medical Decisions (the DECISIONS study), which was a survey of 3010 adults over the age of 40 years in the US that used a consistent measurement approach and a nationally representative sample to gather data on how patients actually make decisions. The DECISIONS study highlighted the decision patterns, as well as background assumptions, patient-provider communications, and potential pitfalls in the process.

In a related effort, Pauker [16] summarized 5 models of decision making – classical, passive informed consent, active informed consent, shared decision making, and normative shared decision making. The DECISIONS study and the classification of decision making have illuminated important challenges and opportunities in introducing decision aids, in the form of infrastructures, systems, and tools, to facilitate each model in the decision making spectrum in general, and each stage of the shared decision making process in particular.

Barry et al [1] advocated for the common adoption of shared decision making in the health care settings. The effective use of decision aids, in the form of software tools and models, would help the decision makers access the relevant information and insights, and visualize the options available in the shared decision making process. A Cochrane review of 86 trials published through 2009 showed that the use of patient decision aids helped to increase knowledge and improve accuracy of risk perceptions, and led to more decisions consistent with the patient's values and preferences. These in turn reduced internal decisional conflict for the patient, and as a result fewer patients remained passive or undecided. Share decision making could thus help address the problems of overdiagnosis and overtreatment [17]. Moreover, timely information access and proper decision support could help clinicians identify patients who are facing difficult decisions and efficiently elicit their preferences [1].

Similarly, Coylewrite et al [18] identified the goals of shared decision making and highlighted how decision aids could help contextualize the background conditions and facilitate in the communication process. They also described the potential barriers, such as time pressure and negative reward incentives, to adopting the shared decision making model from the providers', payers', and patients' perspectives.

4 Continuity of Care Infrastructures and Architectures

Development of the information infrastructures and architectures for continuity of care center around the concept of "patient-centered medical home" (PCMH). Finkelstein et al [19] defined PCMH as a framework that supports a "well-organized, proactive clinical team" working with "well-informed" patients to address "preventive and disease management in guideline-concordant manner." This approach is a fundamental shift from the episodic, hospital-based health care model to provide seamless support for continuous, collaborative care for the patients. Various roadmaps and approaches to implementing the concept in practice have been proposed. These are based on the current and future landscape for combining multiple information sources to support decision making at the point of care, through different care sites, including the patients' home [20-23]. The model is shown to be promising; on-going efforts are investigating different ways to enhance the possibility of acceptance by clinicians in different specialties and subspecialties [24, 25].

In a more general setting, current information storage and communication models in eHealth and telemedicine are evaluated for their effectiveness in supporting patient-centered, personalized, and personal care [26, 27]. Blobel [26] proposed that personalized health is necessarily a multidisciplinary approach that calls for developing or adapting a unifying framework for communication, modeling, and implementation. Pinciroli et al [27], on the other hand, predicted that the modern consumer and personalized technologies such as iPad and avatars will make big impact in biomedical and health informatics. These personalized devices would complement the advancements in PHR to drive the next generation institutional and personal health information infrastructures.

Personal Health Information Systems

The American Medical Informatics Association (AMIA) College of Medical Informatics Symposium defined personal health records (PHR) as electronic applications through which individuals can access, manage, and share their health information in a safe and secure environment [28]. PHR are usually part of PHS, but can be implemented as components of an institutional based electronic health record system.

Three main areas of PHS research are reported in the literature: instrumentation and sensors for cost-effective monitoring, information processing and classification techniques via embedded intelligence, and platforms for integrating information, data, and knowledge to support clinical care plans and ensuring patient safety [29].

A number of recent efforts have summarized the current implementations and remaining challenges [30, 31], and documented new techniques and approaches to improve PHR [32, 33] and PHS [29]. Brennan et al [31], for example, reported on the Project HealthDesign approach to developing personal health records as a platform for action in support of personal health. A uniform data collection, integration, and analytic infrastructure is shown to facilitate user-centered design and development of decision aids that utilize the recorded personal health data, includig patient-generated "observations of daily living."

There are many technical issues in modelling, designing, and implementing family-based health record for personalized decision support [34, 35]. The main difficulties stem from the "open nature" of the records, the heterogeneous encoding formats and communication protocols used for different platforms, and the lack of an authoritative co-ordinator to help streamline accessibility to the personal information. Hence, new standard formats are developed for information encoding in PHR [36]. New policies are put in place for controlling patient access to clinical data via PHR [37, 38].

Similarly, new networking and communication protocols and techniques are defined to meet the communication, integration, and security challenges in the distributed, mobile, and heterogeneous PHS. Such innovations include body and environmental sensors, online information and knowledge portals and repositories, and simple decision aids and analytical tools. Massey et al [39], for example, leveraged social system networks, which are mobile networks that can extract patterns in interdependent social relations to improve system design, in ubiquitous high-data-rate health systems. They proposed techniques and models to deal with the limited storage resources and connection bandwidth in applying such networks in mobile PHS. Martinez-Espronceda et al [40], on the other hand, implemented and evaluated interoperable personal health devices with low-voltage low-power constraints.

Many PHR and PHS are being developed, applied, and evaluated in specific disease domains to support monitoring, assessment, or self-management functions. These mobile or web-based systems include portable pain, treatment and activity diaries [41], management tools for assessing and preventing comprehensive risks for critical conditions such as cardiovascular diseases [42] and diabetes [43], personal health companions to enhance self-care management of chronic health conditions [44], or medication management for multi-morbidity [45]. There are also patient portals for triaging patients at risk of common conditions such as influenza [46], and community forums such as PatientsLikeMe for sharing health data for better outcomes [47].

5 Human Factors and System Design Approaches

Human factors and usability are critical for the success of PHS and PHR in practical deployment. Different consumers' attitude toward PHRs [48] and the factors affecting acceptance of web-based self-referral systems [49] have been carefully analyzed. Other efforts focus on developing methods for discounting or grading user-centered e-health designs [50], for studying complacency and bias in human use of automation [51], and for improving consumer health IT application development in general [52]. Research evidence in e-health and implications for future policy [53], as well as qualitative studies of patient factors in the implementation of decision aids in general practice [54] have also been reported.

Design and Effectiveness of Decision Aids

Recent studies have shown that decision aids, when designed properly, could improve the effectiveness [17] and hence the adoption [55] of the shared decision making model for patient care. To improve usability, there is a recent debate on how decision aids should be characterized and classified [56, 57]. Stigglebout and Timmermans [57] argued that decision aids should aim at facilitating informed decisions for the patients (and clinicians). Such aids should be defined along the lines of whom and what to support, stage(s) to be addressed, and contextual factors.

Bekker [58] examined the suitability of using gold standards to guide the development of effective decision aids. Such guidelines are based on a conceptual review integrating the science of human decision making and the design criteria for complex, health care interventions. The usage of interactive media, including graphs and game-like settings, have also been explored to communicate with patients about risks and preferences. Such tools would enhance the conceptual clarity of the various information components in the shared decision making stages, thereby facilitating the decision process and standardizing the evaluation approaches [59].

6 Knowledge Management Innovations

Current research efforts in personalized medicine focus on new techniques or approaches for modeling and analysis to provide context-sensitive, point-of-care decision support. These techniques usually combine population based data in different modalities, from multiple sources, and integrated with personal profiles, preferences, and values to build personalized predictive and prognostic models [60]. The topics addressed in integrating multiple source of information span a wide range from taking care of inter-individual variability in patient-specific predictions [61], calibrating predictive model estimates to support personalized medicine [62], to constructing patient records from distributed providers [63]. New evaluation approaches are developed to compare personalized treatment effectiveness based on electronic health records [64]. Data privacy and safety are ensured by properly anonymizing longitudinal electronic medical records for generating personalized clinical decision support protocols [65], and for enabling personalized telepathology [66].

Some state of the art machine learning and data mining techniques are motivated by various attempts to learn useful knowledge from biomedical data for personalized decision making. Examples include discovering low-support discriminative, biologically meaningful patterns from dense and high-dimensional data of cancer genes [67], and simulating disease processes or surgical procedures in patient-specific dynamic model computed automatically from 4D images [68].

Similarly, many advances in knowledge extraction, integration and representation are brought about by applying or developing ontological and semantic technologies in personalized medicine. Examples include automated cancer history classification from free-text clinical reports [69], applying semantic technologies on the PHR to match patients for clinical trials for personalized medicine [70], leveraging semantic web technologies on phar-macoeconomics data to facilitate integration of genomic and phenotypic information [71], and deriving disease concepts for family health histories using multi-source sampling [72].

Integration of Genomic and Phenotypic Knowledge in Personalized Medicine

Individual based biological profiles are integrated with population based health data and evidences to derive optimal interventions for targeted disease management and personalized care. The challenges and future trends of personalized medicine and genomics, including the cost-effectiveness assessments and future research priorities, have been carefully examined [73]. Recent research also addresses the technical considerations in inter-operational semantics encoding, and the emerging landscape of integrating genomic and health knowledge into decision models or health information systems such as EHR for personalized medicine [74] and continuity of care [75, 76]. The application domains include pharma-cogenomic decision support [77], functional genomics, and personalized medicine research [78]. The increasing availability of interpretation engines for personal genome is likely to further facilitate such integration [79].

On clinical application, personal information such as biomarkers and PHR is used to match patients for clinical trials to develop more targeted and personalized treatments [80]. The trend continues in shifting from population wide to personalized prognosis for specific diseases with microarrays [81].

On scientific discovery, biological information such as protein interaction networks is used to understand complex diseases [82]. Multimodal approaches are applied in network induction for identifying meaningful biomarker-phenotype complexes spanning multiple levels of granularity [83]. There are also more general investigations on translational bioinformatics and systems biology approaches for personalized medicine [84].

In addition, the feasibility, experiences, and ethical and social implications of personalized decision support are studied in the context of combining genomic, proteomic, and informatics innovations in specific domains such as chronic degenerative diseases [85], diabetes [86] and cancer [87, 88].

7 Practical Deployment and Change Considerations

The heterogeneity, complexity, and constant changes in health and biomedical settings pose major challenges to providing individualized care. Many recent efforts focus on developing innovative solutions for managing complex systems and conditions such as multi-morbidity and evolving disease mechanisms [82, 89], and assessing their effectiveness [90].

An active research topic is on examining human decision making in complex environments to avoid errors. Diagnostic errors are being increasingly recognized as preventable problems that computing technologies can help to reduce cost and improve patient safety [91, 92]. Decisions are made at multiple levels of detail in different contexts, e.g., policy generation, outcome prediction, user interaction, and tactical adaptation, etc. Unexpected occurrences abound, different cognitive biases may arise, and both strategic and real-time reactions and interventions are needed. It is often difficult to generate decision rules or guidelines to steer the doctors away from cognitive biases that would lead to diagnostic errors [93]. Recent efforts in this area include studying the relation between error recovery and cognitive modeling [94], and the unconscious thought effects in the diagnosis stage of clinical decision making [95].

With a recent update to the landmark articles by Eddy on the significance of clinical practice guidelines [96] and the many years of research efforts on computerized guideline models and frameworks, there are now active ongoing efforts to actually put such guidelines into use in personalized decision support [97]. These include work on software environments and frameworks for design and execution of self-adaptive clinical pathways [98] and distributed guidelines [99], and case studies on creating or applying clinical practice guidelines and patient pathways in different domains such as cancer [100] and dementia [101].

8 Discussion

While there is a plethora of research, development, and evaluation activities, the actual effectiveness and impact of the shared decision making model and the related technologies to support personalized medicine are still unclear. The current limitations and future directions can be characterized by potential answers to the main questions below:

1. How to measure cost-effectiveness of the shared decision model and improve its impact on health outcomes?
Suitable evaluation metrics are needed to measure success in the unstructured process in different settings. The participants' under-standings and skills should be improved for effective sharing and collaboration. A rebalancing of "power structure" in the shared decision making process is also needed.

2. How to ensure uniform information access and privacy control in the continuity of care infrastructures and architectures?
Many difficulties persist in distributing institutional and personal control of data encoding and exchange standards, and privacy management in the care continuum. Uniform, scalable and efficient approaches are required to develop tools and applications that can make best use of the personal health data, including patient-generated data that are not normally captured in medical records, to improve health outcomes in heterogeneous environments.

3. How to design and develop decision aids that would facilitate shared decision making in the continuum of care?
Human factors are often subjective and varying. Recent advances in judgmental decision making [102] and health literacy [103] could contribute to reducing biases and improving communications. Behavioral patterns, cognitive abilities, and observations on daily living activities could guide the design of both communication aids and self-management tools.

4. How to integrate, organize, and work with biomedical and health care knowledge at different levels of abstraction, from heterogeneous sources, and in multiple modalities to support personalized decision making?
Continuing development of advanced knowledge acquisition, representation, and reasoning techniques is needed to support a wide range of decisions in increasingly complex biomedical and health care settings. A multidisciplinary approach is crucial for deriving innovative solutions at the technical, social, and policy levels.

5. How to implement patient-centered, personalized, and personal decision support in complex, changing real-life environments?
A new generation of "sustainable" technologies that can adapt to changes are needed. New design paradigms and operating assumptions should be incorporated as mobile devices and personalized tools continue to evolve and integrate with legacy infrastructures to deliver health care decision support.

9 Conclusion

While far from being complete and exhaustive, this survey highlights the main research and development activities in decision support and knowledge management in the past two years. Many recent efforts focus on identifying the requirements, developing the infrastructures, and evaluating the usability of the relevant techniques, tools and systems for supporting shared decision making in patient-centered care. There is also increasing emphasis on the technical solutions and methodological issues in combining heterogeneous information and personal data to provide cost-effective, calibrated, personalized support at the point of care. Advanced decision support, knowledge representation, and machine learning techniques are being invented, adapted, or applied in biomedical informatics in general, and in personalized medicine in particular. There is also an emerging trend on managing complexity with changing care models, processes, and settings.

Many challenges still remain. From the research activities and results shown in the area, however, strong and steady progress is being made toward improving outcomes and lowering costs through better patient-centered, personalized, and personal decision support and knowledge management.

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References

1. Barry MJ, Edgman-Levitan S. Shared decision making—pinnacle of patient-centered care. N Engl J Med 2012 Mar 1;366(9):780-1.
2. Gerteis M, Edgman-Levitan S, Daley J, L. DT, editors. Through the patient's eyes: Understanding and promoting patient-centered care: Jossey-Bass; 1993.
3. Institute of Medicine (U.S.). Committee on Quality of Health Care in America. Crossing the quality chasm : A new health system for the 21st century. Washington, D. C.: National Academy Press; 2001.
4. Zhang YT, Poon CCY. Editorial note on bio, medical, and health informatics. Information Technology in Biomedicine, IEEE Trans Inf Technol Biomed 2010;14(3):543-45.
5. Coiera E, Lau AY, Tsafnat G, Sintchenko V, Magrabi F. The changing nature of clinical decision support systems: A focus on consumers, genomics, public health and decision safety. Yearb Med Inform 2009:84-95.
6. Mitchell JA, Gerdin U, Lindberg DA, Lovis C, Martin-Sanchez FJ, Miller RA, Shortliffe EH, Leong TY. 50 years of informatics research on decision support: What's next. Methods Inf Med 2011;50(6):525-35.
7. Graham S, Estrin D, Horvitz E, Kohane I, Mynatt E, Sim I. Information technology research challenges for healthcare: From discovery to delivery. SIGHIT Rec 2011;1(1):4-9.
8. Ohno-Machado L. Informatics research to enable clinically relevant, personalized genomic medicine. J Am Med Inform Assoc 2012 Mar-Apr;19(2):149-50.
9. National Research Council (US) Committee on Engaging the Computer Science Research Community in Health Care Informatics, Stead WW, Lin HS, editors. Computational technology for effective health care: Immediate steps and strategic directions. Washington DC: National Academy of Sciences; 2009.
10. Bellazzi R, Diomidous M, Sarkar IN, Takabayashi K, Ziegler A, McCray AT. Data analysis and data mining: Current issues in biomedical informatics. Methods Inf Med 2011;50(6):536-44.
11. U.S. National Academy of Engineering. Grand challenges for engineering in the 21st century. 2008 [cited 2012 31 March]; Available from: http://www.engineeringchallenges.org/.
12. McCaffery KJ, Smith SK, Wolf M. The challenge of shared decision making among patients with lower literacy: A framework for research and development. Med Decis Making 2010 Jan-Feb;30(1):35-44.
13. Sheridan SL, Harris RP, Woolf SH, Shared Decision-Making Workgroup of the U.S. Preventive Services Task Force. Shared decision making about screening and chemoprevention. A suggested approach from the u.S. Preventive services task force. Am J Prev Med 2004 Jan;26(1):56-66.
14. Power TE, Swartzman LC, Robinson JW. Cognitive-emotional decision making (CEDM): A framework of patient medical decision making. Patient Educ Couns 2011 May;83(2):163-9.
15. Zikmund-Fisher BJ, Couper MP, Singer E, Levin CA, Fowler FJ, Jr., Ziniel S, Ubel PA, Fagerlin A. The decisions study: A nationwide survey of united states adults regarding 9 common medical decisions. Med Decis Making 2010 Sep-Oct;30(5 Suppl):20S-34S.
16. Pauker SG. Medical decision making: How patients choose. Med Decis Making 2010 Sep-Oct;30(5 Suppl):8S-10S.
17. Stacey D, Bennett CL, Barry MJ, Col NF, Eden KB, Holmes-Rovner M, Llewellyn-Thomas H, Lyddiatt A, Legare F, Thomson R. Decision aids for people facing health treatment or screening decisions. Cochrane Database Syst Rev 2011(10):CD001431.
18. Coylewright M, Montori V, Ting HH. Patient-centered shared decision-making: A public imperative. Am J Med 2012;125(6):545-7.
19. Finkelstein J, Barr MS, Kothari PP, Nace DK, Quinn M. Patient-centered medical home cyberinfrastructure current and future landscape. Am J Prev Med 2011 May;40(5):S225-S33.
20. Bates DW, Bitton A. The future of health information technology in the patient-centered medical home. Health Aff (Millwood) 2010 Apr;29(4):614-21.
21. Leventhal T, Taliaferro JP, Wong K, Hughes C, Mun S. The patient-centered medical home and health information technology. Telemed J E Health 2012 Mar;18(2):145-9.
22. Meyers D, Quinn M, Clancy CM. Health information technology: Turning the patient-centered medical home from concept to reality. Am J Med Qual 2011 Mar-Apr;26(2):154-6.
23. Council on Clinical Information Technology, Schneider JH, Marcus E, Del Beccaro MA, Benson KA, D'Alessandro DM, Drummond WH, Handler EG, Kim GR, Leu MG, Lund GC, Zuckerman AE. Health information technology and the medical home. Pediatrics 2011 May;127(5):978-82.
24. Kirschner N, Barr MS. Specialists/subspecialists and the patient-centered medical home. Chest. 2010 Jan;137(1):200-4.
25. Yee HF, Jr. The patient-centered medical home neighbor: A subspecialty physician's view. Ann Intern Med 2011 Jan 4;154(1):63-4.
26. Blobel B. Architectural approach to ehealth for enabling paradigm changes in health. Methods Inf Med 2010;49(2):123-34.
27. Pinciroli F, Corso M, Fuggetta A, Masseroli M, Bonacina S, Marceglia S. Telemedicine and e-health. IEEE Pulse 2011;2(3):62-70.
28. Tang PC, Ash JS, Bates DW, Overhage JM, Sands DZ. Personal health records: Definitions, benefits, and strategies for overcoming barriers to adoption. J Am Med Inform Assoc 2006 Mar-Apr;13(2):121-6.
29. Maglaveras N, Bonato P, Tamura T. Guest editorial special section on personal health systems. IEEE Trans.Inf Technol Biomed 2010;14(2):360-63.
30. Reti SR, Feldman HJ, Ross SE, Safran C. Improving personal health records for patient-centered care. J Am Med Inform Assoc.2010 Mar-Apr;17(2):192-5.
31. Archer N, Fevrier-Thomas U, Lokker C, McKibbon KA, Straus SE. Personal health records: A scoping review. J Am Med Inform Assoc 2011 Jul-Aug;18(4):515-22.
32. Brennan PF, Downs S, Casper G. Project healthdesign: Rethinking the power and potential of personal health records. J Biomed Inform 2010 Oct;43(5 Suppl):S3-5.
33. Ogbuji C, Gomadam K, Petrie C. Web technology and architecture for personal health records. Internet Computing, IEEE 2011;15(4):10-13.
34. Bonacina S, Marceglia S, Bertoldi M, Pinciroli F. Modelling, designing, and implementing a family-based health record prototype. Comput Biol Med 2010;40(6):580-90.
35. Orlando LA, Hauser ER, Christianson C, Powell KP, Buchanan AH, Chesnut B, et al. Protocol for implementation of family health history collection and decision support into primary care using a computerized family health history system. BMC Health Serv Res 2011;11:264.
36. Li YC, Detmer DE, Shabbir SA, Nguyen PA, Jian WS, Mihalas GI, et al. A global travelers' electronic health record template standard for personal health records. J Am Med Inform Assoc 2012 Jan-Feb;19(1):134-6.
37. Collins SA, Vawdrey DK, Kukafka R, Kuperman GJ. Policies for patient access to clinical data via phrs: Current state and recommendations. J Am

Med Inform Assoc 2011 Dec;18 Suppl 1:i2-7.
38. Luna J, Dikaiakos M, Marazakis M, Kyprianou T. Data-centric privacy protocol for intensive care grids., IEEE Trans Inf Technol Biomed 2010;14(6):1327-37.
39. Massey T, Marfia G, Stoelting A, Tomasi R, Spirito MA, Sarrafzadeh M, et al. Leveraging social system networks in ubiquitous high-data-rate health systems. IEEE Trans Inf Technol Biomed 2011;15(3):491-98.
40. Martinez-Espronceda M, Martinez I, Serrano L, Led S, Trigo JD, Marzo A, et al. Implementation methodology for interoperable personal health devices with low-voltage low-power constraints. IEEE Trans Inf Technol Biomed 2011;15(3):398-408.
41. Luckmann R, Vidal A. Design of a handheld electronic pain, treatment and activity diary. J Biomed Inform 2010 Oct;43(5 Suppl):S32-6.
42. Franchi D, Cini D, Iervasi G. A new web-based medical tool for assessment and prevention of comprehensive cardiovascular risk. Ther Clin Risk Manag 2011;7:59-68.
43. Fonda SJ, Kedziora RJ, Vigersky RA, Bursell SE. Combining igoogle and personal health records to create a prototype personal health application for diabetes self-management. Telemed J E Health 2010 May;16(4):480-89.
44. Weinert C, Cudney S, Kinion E. Development of my health companion to enhance self-care management of chronic health conditions in rural dwellers. Public Health Nurs 2010 May-Jun;27(3):263-9.
45. Siek KA, Ross SE, Khan DU, Haverhals LM, Cali SR, Meyers J. Colorado care tablet: The design of an interoperable personal health application to help older adults with multimorbidity manage their medications. J Biomed Inform 2010 Oct;43(5 Suppl):S22-6.
46. Rosenbloom ST, Daniels TL, Talbot TR, McClain T, Hennes R, Stenner S, Muse S, Jirjis J, Purcell Jackson G. Triaging patients at risk of influenza using a patient portal. J Am Med Inform Assoc 2011 Dec 1.
47. Wicks P, Massagli M, Frost J, Brownstein C, Okun S, Vaughan T, Bradley R, Heywood J. Sharing health data for better outcomes on patientslikeme. J Med Internet Res 2010;12(2):e19.
48. Patel VN, Dhopeshwarkar RV, Edwards A, Barron Y, Likourezos A, Burd L, Olshansky D, Kaushal R. Low-income, ethnically diverse consumers' perspective on health information exchange and personal health records. Inform Health Soc Care 2011 Dec;36(4):233-52.
49. Kim E-H, Linker DT, Coumar A, Dean LS, Matsen FA, Kim Y. Factors affecting acceptance of a web-based self-referral system. IEEE Trans Inf Technol Biomed 2011;15(2):344-47.
50. Verhoeven F, Gemert-Pijnen JV. Discount user-centered e-health design: A quick-but-not-dirty method. Proceedings of the 6th international conference on HCI in work and learning, life and leisure: workgroup human-computer interaction and usability engineering; Klagenfurt, Austria. 1947798. Springer-Verlag; 2010. p. 101-23.
51. Parasuraman R, Manzey DH. Complacency and bias in human use of automation: An attentional integration. Hum Factors 2010 Jun;52(3):381-410.
52. Zayas-Cab T, Chaney K. Improving consumer health it application development: Lessons from other industries, a summary. SIGHIT Rec 2011;1(2):4-12.
53. Hordern A, Georgiou A, Whetton S, Prgomet M. Consumer e-health: An overview of research evidence and implications for future policy. HIM J 2011;40(2):6-14.
54. Bhavnani V, Fisher B. Patient factors in the implementation of decision aids in general practice: A qualitative study. Health Expect 2010 Mar;13(1):45-54.
55. Legare F, Turcotte S, Stacey D, Ratte S, Kryworuchko J, Graham ID. Patients' perceptions of sharing in decisions: A systematic review of interventions to enhance shared decision making in routine clinical practice. Patient. 012;5(1):1-19.
56. Elwyn G, Frosch D, Volandes AE, Edwards A, Montori VM. Investing in deliberation: A definition and classification of decision support interventions for people facing difficult health decisions. Med Decis Making 2010 Nov-Dec;30(6):701-11.
57. Stiggelbout AM, Timmermans DR. Revisiting decision aids: About definitions and classifications. Med Decis Making 2010 Nov-Dec;30(6):696-8.
58. Bekker HL. The loss of reason in patient decision aid research: Do checklists damage the quality of informed choice interventions? Patient Educ Couns 2010 Mar;78(3):357-64.
59. Schenker Y, Fernandez A, Sudore R, Schillinger D. Interventions to improve patient comprehension in informed consent for medical and surgical procedures: A systematic review. Med Decis Making 2011 Jan-Feb;31(1):151-73.
60. Hoffman MA, Williams MS. Electronic medical records and personalized medicine. Hum Genet 2011 Jul;130(1):33-9.
61. Wiesner M, Pfeifer D. Adapting recommender systems to the requirements of personal health record systems. Proceedings of the Proceedings of the 1st ACM International Health Informatics Symposium; Arlington, Virginia, USA. 1883053. ACM; 2010. p. 410-14.
62. Jiang X, Osl M, Kim J, Ohno-Machado L. Calibrating predictive model estimates to support personalized medicine. J Am Med Inform Assoc 2012 Mar-Apr;19(2):263-74.
63. Malin B. Secure construction of k-unlinkable patient records from distributed providers. Artif Intell Med 2010 Jan;48(1):29-41.
64. Hoffman S, Podgurski A. Improving health care outcomes through personalized comparisons of treatment effectiveness based on electronic health records. J Law Med Ethics 2011 Fall;39(3):425-36.
65. Tamersoy A, Loukides G, Nergiz M, Saygin Y, Malin B. Anonymization of longitudinal electronic medical records. IEEE Trans Inf Technol Biomed 2012;PP(99):1-1.
66. Blobel B. Intelligent security and privacy solutions for enabling personalized telepathology. Diagn Pathol 2011;6 Suppl 1:S4.
67. Gang F, Pandey G, Wen W, Gupta M, Steinbach M, Kumar V. Mining low-support discriminative patterns from dense and high-dimensional data. IEEE Trans Knowl Data Eng 2012;24(2):279-94.
68. Mansi T, Voigt I, Assoumou Mengue E, Ionasec R, Georgescu B, et al. Towards patient-specific finite-element simulation of mitralclip procedure. Med Image Comput Comput Assist Interv 2011;14(Pt 1):452-9.
69. Wilson RA, Chapman WW, Defries SJ, Becich MJ, Chapman BE. Automated ancillary cancer history classification for mesothelioma patients from free-text clinical reports. J Pathol Inform 2010;1:24.
70. Patel C, Gomadam K, Khan S, Garg V. Trialx: Using semantic technologies to match patients to relevant clinical trials based on their personal health records. Journal of Web Semantics 2010 Nov;8(4):342-47.
71. Samwald M, Coulet A, Huerga I, Powers RL, Luciano JS, Freimuth RR, et al. Semantically enabling pharmacogenomic data for the realization of personalized medicine. Pharmacogenomics 2012 Jan;13(2):201-12.
72. Hulse NC, Wood GM, Haug PJ, Williams MS. Deriving consumer-facing disease concepts for family health histories using multi-source sampling. J Biomed Inform. 2010 Oct;43(5):716-24.
73. Conti R, Veenstra DL, Armstrong K, Lesko LJ, Grosse SD. Personalized medicine and genomics: Challenges and opportunities in assessing effectiveness, cost-effectiveness, and future research priorities. Med Decis Making 2010 May-Jun;30(3):328-40.
74. Ullman-Cullere MH, Mathew JP. Emerging landscape of genomics in the electronic health record for personalized medicine. Human Mutation 2011 May;32(5):512-16.
75. Masys DR, Jarvik GP, Abernethy NF, Anderson NR, Papanicolaou GJ, Paltoo DN, et al. Technical desiderata for the integration of genomic data into electronic health records. J Biomed Inform 2011 Dec 27.
76. Jing X, Kay S, Marley T, Hardiker NR, Cimino JJ. Incorporating personalized gene sequence variants, molecular genetics knowledge, and health knowledge into an ehr prototype based on the continuity of care record standard. J Biomed Inform 2012 Feb;45(1):82-92.
77. Overby CL, Tarczy-Hornoch P, Hoath JI, Kalet IJ, Veenstra DL. Feasibility of incorporating genomic knowledge into electronic medical records for pharmacogenomic clinical decision support. BMC Bioinformatics 2010;11 Suppl 9:S10.
78. Yang JY, Niemierko A, Bajcsy R, Xu D, Athey BD, Zhang A, et al. 2k09 and thereafter : The coming era of integrative bioinformatics, systems biology and intelligent computing for functional genomics and personalized medicine research. BMC Genomics 2010;11 Suppl 3:I1.
79. Karczewski KJ, Tirrell RP, Cordero P, Tatonetti NP, Dudley JT, Salari K, et al. Interpretome: A freely available, modular, and secure personal genome interpretation engine. Pac Symp Biocomput 2012:339-50.
80. Mandrekar SJ, Sargent DJ. Design of clinical trials for biomarker research in oncology. Clin Investig (Lond) 2011 Dec;1(12):1629-36.
81. Shao L, Fan X, Cheng N, Wu L, Xiong H, Fang H, et al. Shifting from population-wide to personalized cancer prognosis with microarrays. PLoS One 2012;7(1):e29534.
82. Koyuturk M. Using protein interaction networks to understand complex diseases. Computer 2012;45(3):31-38.
83. Payne PR, Huang K, Keen-Circle K, Kundu A, Zhang J, Borlawsky TB. Multi-dimensional

discovery of biomarker and phenotype complexes. BMC Bioinformatics 2010;11 Suppl 9:S3.
84. Yan Q. Translational bioinformatics and systems biology approaches for personalized medicine. Methods Mol Biol 2010;662:167-78.
85. Licastro F, Caruso C. Predictive diagnostics and personalized medicine for the prevention of chronic degenerative diseases. Immun Ageing 2010;7 Suppl 1:S1.
86. Augstein P, Vogt L, Kohnert KD, Heinke P, Salzsieder E. Translation of personalized decision support into routine diabetes care. J Diabetes Sci Technol 2010 Nov;4(6):1532-9.
87. van Rooij T, Marsh S. Improving oncology outcomes through targeted therapeutics will require electronic delivery systems. Future Oncol2011 May;7(5):649-56.
88. Fenstermacher DA, Wenham RM, Rollison DE, Dalton WS. Implementing personalized medicine in a cancer center. Cancer J 2011 Nov-Dec;17(6):528-36.
89. Pielawa L, Helmer A, Brell M, Hein A. Intelligent environments supporting the care of multi-morbid patients: A concept for patient-centered information management and therapy. Proceedings of the 4th International Symposium on Applied Sciences in Biomedical and Communication Technologies; Barcelona, Spain. 2093713. ACM; 2011. p. 1-5.
90. Fricton J, Rindal DB, Rush W, Flottemesch T, Vazquez G, Thoele MJ, et al. The effect of electronic health records on the use of clinical care guidelines for patients with medically complex conditions. J Am Dent Assoc 2011 Oct;142(10):1133-42.
91. Newman-Toker DE, Pronovost PJ. Diagnostic errors - the new frontier for patient safety. JAMA 2009 March 11;301(10):1060-62.
92. Jalote-Parmar A, Badke-Schaub P, Ali W, Samset E. Cognitive processes as integrative component for developing expert decision-making systems: A workflow centered framework. J Biomed Inform 2010;43(1):60-74.
93. Warner JL, Najarian RM, Tierney LM. Uses and misuses of thresholds in diagnostic decision making. Acad Med 2010 March;85(3):556-63.
94. Franklin A, Liu Y, Li Z, Nguyen V, Johnson TR, Robinson D, et al. Opportunistic decision making and complexity in emergency care. J Biomed Inform 2011;44(3):469-76.
95. de Vries M, Witteman CL, Holland RW, Dijksterhuis A. The unconscious thought effect in clinical decision making: An example in diagnosis. Med Decis Making 2010 Sep-Oct;30(5):578-81.
96. Eddy DM, Adler J, Patterson B, Lucas D, Smith KA, Morris M. Individualized guidelines: The potential for increasing quality and reducing costs. Ann Intern Med 2011 May 3;154(9):627-34.
97. Gooch P, Roudsari A. Computerization of workflows, guidelines, and care pathways: A review of implementation challenges for process-oriented health information systems. J Am Med Inform Assoc 2011 Nov-Dec;18(6):738-48.
98. Alexandrou DA, Skitsas IE, Mentzas GN. A holistic environment for the design and execution of self-adaptive clinical pathways. IEEE Trans Inf Technol Biomed 2011;15(1):108-18.
99. Yaqub E, Barroso A. Distributed guidelines (dig): A software framework for extending automated health decision support to the general population. Perspect Health Inf Manag 2010;7.
100. Abernethy AP, Basch E. Clinical cancer informatics: Creating pathways for personalized medicine and rapid learning cancer care from the guest editors. Cancer J 2011 Jul-Aug;17(4):195-6.
101. Lindgren H. Towards personalized decision support in the dementia domain based on clinical practice guidelines. User Modeling and User-Adapted Interaction 2011 Oct;21(4-5):377-406.
102. Kahneman D. Thinking, fast and slow: Doubleday Canada; 2011.
103. Gigerenzer G, Gray JAM. Better doctors, better patients, better decisions: Envisioning health care 2020. MIT Press; 2011.

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