Communication

Tertiary Education System for Genetic Technologists, Counselors and Specialists

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In the United States, genetic and genomic medicine is operated by physicians who specialize in clinical genetics and its related entities and laboratory directors who specialize in cytogenetics, molecular genetics and biochemical genetics. Allied health professions, including genetic technologists that perform genetic testing in diagnostic laboratories and genetics counselors that interpret genetic testing results to patients, play important and integral roles. To provide an overview on the structure of the medical genetics education system and its contribution to a well-trained workforce for genetic and genomic medicine, this report presents the requirements, curriculum and certifications from two representative programs for Bachelor's and Master's level genetic technologists and Master's level counselors and outlines training resources for M.D. and Ph.D, genetics specialists. This tertiary education system has built up a professionally trained workforce of approximately 1,500 clinical geneticists, an equal amount of laboratory genetic specialists, as well as over 3,000 genetic counselors, 3,700 cytogenetic technologists and 2,500 molecular genetic technologists in the United States. This system is effective for undergraduate, graduate and medical students seeking a career in medical genetics and genomics. It also serves as a good model for genetic educators working on developing and improving medical genetics education in other countries.
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INTRODUCTION

The current medical practice in the United States is orchestrated by physicians from 24 primary specialties recognized by the American Board of Medical Specialties (ABMS, 1933, www.abms.org) and many allied health professions. All clinical specialties are built on a body of knowledge for the diagnosis and treatment of specific types of diseases and operated under a series of standards and guidelines developed by the professional organizations. Medical genetics was officially recognized by ABMS in 1991. It is the newest specialty and possibly the last of the primary clinical specialties of medicine because its targeted 'organ' chromosome is deeply located within the nuclei of human cells.[1,2] Specialists in medical genetics include M.D. clinical geneticists and M.D. or Ph.D. clinical cytogeneticists, clinical biochemical geneticists and molecular geneticists. To ensure only qualified professionals enter the clinical genetic practice and laboratory diagnosis, the American Board of Medical Genetics and Genomics (ABMGG, 1980, http://www.abmgg.org/) and American College of Medical Genetics and Genomics (ACMG, 1991, https://www.acmg.net) have devoted continuous efforts to organize training programs, define core competencies, offer board examination, and provide continuing medical education.[2~5] This new medical specialty has led to two emerging allied health professions, Master's level genetic counselor certified by the American Board of Genetic Counseling (ABGC, 1993, www.abgc.net) and Bachelor's /Master's level genetic technologists represented by the Association of Genetic Technologists (AGT, 1975, http://www.agt-info.org). To provide a systematic view on the structure of medical genetics education and its contribution to a well-trained workforce for genetic and genomic medicine, this report presents the training requirements and course curriculum from two representative programs for genetic technologists and counselors. Continuous effort to promote medical genetics training in the era of genomic medicine is outlined. This information is useful for not only undergraduate, graduate and medical students seeking a career in medical genetics and genomics but also educators working on developing and improving medical genetics education.

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A PROCESS MODEL FOR PROFESSIONS IN GENETIC AND GENOMIC MEDICINE

The development of a medical specialty or an allied health profession follows a top-down process model with five stages. The first stage occurs when the accumulation of knowledge and the development of technology lead to the recognition of a full-time specialty or profession. In the second stage, a professional organization is established to define the competence and qualification by certifications and licenses. In the third stage, training and educational programs for specialized knowledge and skills are established. In the fourth stage, the standards, guidelines, policies and code of ethics are developed by the professional organization. The final stage involves formal recognition from health and legal administrative. Professionalization of medical genetic technologists, counselors and specialists follows this process model as shown in **Table 1**. As of July 2014, there are 46 clinical genetics programs listed by the Accreditation Council for Graduate Medical Education (ACGME, https://www.acgme.org) as well as 44 clinical cytogenetics programs, 28 clinical biochemical genetics programs and 41 clinical molecular genetics programs listed in the ABMGG. There are 31 United States Master's level and three Canadian Master's level programs for genetics counseling that are accredited by the Accreditation Council of Genetic Counseling (ACGC, http://www.gceducation.org). There are five clinical cytogenetics programs (four Bachelor's/one Master's level) and nine diagnostic molecular genetics programs (six Bachelor's/three Master's level) that are accredited by the National Accrediting Agency for Clinical Laboratory Sciences (NAACLS, 1973, http://www.naacls.org/) for genetics technologists. Genetic technologists are certified by the American Society for Clinical Pathology (ASCP, 1922, http://www.ascp.org/). Core competencies for medical genetics specialists, counselors and technologists have been developed by the corresponding professional organizations.[5-8] As a result, medical genetics now has in place not only a quadripartite structure of a conventional medical specialty: a research society, a college, a certifying board, and a residency review committee as described by Epstein,[3] but also two supportive allied health professions. This tertiary education system has contributed a well-trained workforce for genetics and genomic medicine in the United States.

Table 1. Tertiary Education System for Genetics Technologists, Counslors and Specialists.*

Professions	**Genetic Technologists**	**Genetics Counselors**	**Medical Genetics Specialists**
	Cytogenetics (Cyto)	Genetics Counseling	Clinical Genetics (CG)
	Molecular Biology (MB)		Clinical Cytogenetics (CC)
			Clinical Molecular Genetics (CMG)
			Clinical Biochemical Genetics (CBG)
Education	Bachalor/ Master	Master	MD, DO, PhD
Competency	AGT [7,8]	ABGC [6]	ABMGG, ACMG [5]
Certifications	ASCP	ABGC	ABMGG
Training Programs	4 Cytogenetics	31	46 Clinical Genetics, 44 Cyotgenetics,
	9 Molecular Genetics		28 Biochemical Genetics, 41 Molecular Genetics
Accreditation	NAACLS	ACGC	ABMS, ACGME
Workforce	3,762 Cyto, 2515 MB	3,475 Counselors	1,509 CG, 734 CC, 596 CMG, 315 CBG

*See text for all professional organizations, number within [ ] for listed references.

UNDERGRADUATE PROGRAMS FOR CYTOGENETICS AND MOLECULAR GENETICS TECHNOLOGISTS

Genetics technologists process clinical specimens, perform test procedures, provide analyzed results, and participate in quality assurance and quality control in a genetic diagnostic laboratory. Training for cytogenetics and molecular genetics technologists are organized in the Diagnostic Genetics Science Program in the Department of Allied Health Science at the University of Connecticut and the Cytogenetic Technology, Molecular Genetics Technology, and Diagnostic Genetic Programs in the School of Health Professions at the University of Texas/MD Anderson Cancer Center.[9,10] These programs are designed as two-year training with entry at a junior level for students who fulfilled prerequisite requirements but each also accept one-year training for qualified students. The Master's level program is two years in length with a thesis component. The length of each study plan may differs between programs but the structure is similar which includes a series of didactic theory and student laboratory courses followed by an internship at affiliated accredited clinical laboratories and hospitals. The internship allows students to have hands-on experience with real laboratory operation and make them well-prepared for their career. The core courses for cytogenetics will cover all cytogenetic techniques and theoretical prenatal, postnatal and cancer cytogenetics. The core courses for molecular genetics will cover molecular laboratory techniques and theoretical topics focusing on the four current molecular genetics areas (pre- and postnatal, oncology, infectious disease, and forensics). The core course curriculum from these two programs are summarized in **Supplemental Table 1**** and important textbooks and reference books used in the genetics courses are listed in **Table 2**. Upon completion of the programs, graduates are eligible for taking the certification examination in Cytogenetics (CG) and Molecular Biology (MB) offered by the ASCP. There are approximately 10 to 15 students accepted into the Diagnostic Genetics Science

Program in the University of Connecticut every year. Outcome statistics for 2011-2012 graduates showed 83.5% were employed within 6 months of graduation and 100% pass rate for students who took the ASCP cytogenetics and 75% for molecular biology exams. The program is working on a merge of cytogenetics and molecular genetics training and an integration of genomic and bioinformatics courses so that the graduates can be qualified for certifications in both cytogenetics and molecular biology and prepare themselves for the future genetic diagnosis using high throughput technologies and various bioinformatic tools. There are an average of 85 students accepted each year for the Cytogenetics Technology, Molecular Genetics Technology, and Diagnostic Genetics Programs at the University of Texas/MD Anderson Cancer Center. An outcome survey for graduates from the programs during a six year period (2008-2013) showed the placement rate (either employed or back in school) and the pass rate for ASCP certifications are 82%-100% and 80%-100% for cytogenetics and 93%-100% and 92%-100% for molecular genetics, respectively.

Table 2. Recommended Text and Reference Books from Training Programs.

Book Title	GMG	GC	CG	MG	BG
Barch MJ, Knutsen T, Spurbeck JL, eds. ***Cytogenetics Laboratory Manual***. 3rd ed, Lippincott Raven; 1997.			X	X	
Blau N, Duran M, Blaskovics ME, Gibson, KM, Scriver CR, eds. ***Physician's Guide to the Laboratory Diagnosis of Metabolic Disease.*** Springer; 2004.					X
Buckingham L, ed. ***Molecular Diagnostics: Fundamentals, Methods, and Clinical Applications.*** 2nd ed, F.A. Davis; 2011.				X	
Coleman WB, Tsongalis GJ, eds. ***Molecular Diagnostics: For the Clinical Laboratorian***. 2nd ed. Humana Press; 2010.				X	
Firth HV, Hurst JA, Hall JG, eds. ***Oxford Desk Reference Clinical Genetics***. Oxford University Press; 2005.	X	X	X	X	X
Gardner RJM, Sutherland GR, Shaffer LG, ***Chromosome Abnormalities and Genetics Counseling***. Oxford University Press; 2011.		X	X		
Gersen S, Keagle M, eds. ***The Principles of Clinical Cytogenetics***. 3rd ed, Spinger; 2013.		X	X	X	
Hartwell L, Hood L, Goldberg ML, Reynolds AE, Silver LM, eds. ***Genetics: From Genes to Genomes***. 4th ed. McGraw-Hill; 2010.	X		X	X	
Heim S, Mitelman F, eds. ***Cancer Cytogenetics: Chromosomal and Molecular Genetic Abberations of Tumor Cells***. 3rd ed. Wiley-Balckwell; 2009.			X		
Hu P, Hegde M, Lennon PA, eds. ***Modern Clinical Molecular Techniques***. Springer; 2012.					
Jones KL, ed. ***Smith's Recognizable Patterns of Human Malformation***. 6th ed. Elsevier; 2005.	X	X	X	X	
MacFarlane I, Veach PM, LeRoy BS, eds. ***Genetic Counseling Research, A Practical Guide***. Oxford University Press; 2014.		X			
Milunsky A, ed. ***Genetics Disorder and the Fetus: Diagnosis, Prevention and Treatment***. 6th ed. Plenum Press; 2013.	X	X	X	X	X
Nussbaum R, McInnes R, Willard H, Hamosh A, eds. ***Thompson and Thompson Genetics In Medicine.*** 7th ed. Elsevier; 2007.	X	X	X	X	X
Saudubray JM, Van Den Berghe G, Walter JH, eds. ***Inborn Metabolic Diseases: Diagnosis and Treatment***. 5th ed. Springer; 2012.					X
Schrijver I, ed. ***Diagnostic Molecular Pathology in Practice: A Case-Based Approach***. Springer; 2011.				X	
Shaffer LG, McGowan-Jordan J, Schmid M, eds. ***An International System for Human Cytogenetic Nomenclature (2013)***. Karger; 2013.			X		
Strachan T, Reed A. ***Human Molecular Genetics***. 4th ed. Garland Science; 2010.	X	X		X	
Swerdlow SH, Campo E, Harris NL, et al., eds. ***WHO ClassificationL of Tumors of Haematopoietic and Lymphoid Tissues***, 4th ed, WHO Press; 2008.			X	X	
Uhlmann WR, Schuette JL, Yashar BM, eds. ***A Guide to Genetic Counseling***. 2nd ed. Wiley-Blackwell; 2009.		X			
Valle D, Beaudet AL, Vogelstein B, et al., eds. ***The Online Metabolic and Molecular Bases of Inherited Disease.*** McGraw-Hill Medical (www.ommbid.com)	X	X	X	X	X
Veach PM, LeRoy BS, Bartels DM, eds. ***Facilitating the Genetic Counseling Process, A Practice Manuel***. Springer; 2003.		X			
Weil J. ed. ***Psychosocial Genetic Counseling***. Oxford University Press; 2000.		X			
Weiner MP, Gabriel SB, Stephens JC, eds. ***Genetic Variation: A Laboratory Manual***. Cold Spring Harbor Laboraotry Press; 2007.				X	

GMG, general medical genetics, GC, genetic counseling, CG, Cytogenetics, MG, Molecular Genetics, BG, Biochemic Genetics

GRADUATE PROGRAMS FOR GENETIC COUNSELORS

According to the National Society of Genetic Counselors (www.nsgc.org), genetic counselors help people understand and adapt to the medical, psychological and familial implications of genetic contributions to disease. The process integrates interpretation of family and medical histories to assess the chance of disease occurrence or recurrence, education about inheritance, testing, management, prevention, resources and research, and counseling to promote informed choices and adaptation to the risk or condition. A Master of Science Program in Genetic Counseling is available within the Graduate School of Biomedical Sciences at the Icahn School of Medicine at Mount Sinai in New York City, New York.[11] The Program accepts eight to twelve students annually. Applicants must hold a Bachelor or graduate degree and have coursework in biology, genetics, biochemistry, psychology, and statistics. Competitive applicants should demonstrate an understanding of the genetic counseling profession and have experience in a

communication or support organization. Experience could include any peer counseling related activities or working with external agencies which provide counseling services. Examples may include suicide hotlines, domestic violence hotlines/shelter, homeless or AIDS shelters or other service foundations or organizations. The core courses include embryology, molecules and cells, general medical genetics, genomics, genetics counseling, epidemiology, ethics and other related topics (**Supplemental Table 2****). Related textbook and reference books are listed in Table 2. Major emphasis for the counseling training is placed on clinical rotations. Students are required to rotate through a variety of clinical settings including reproductive genetics, general pediatric and adult genetics, inborn errors of metabolism, cancer genetics and clinical research. These rotations provide opportunities for extensive supervised experience in history taking, interviewing, psychosocial assessment, and genetic risk assessment. Students also have the opportunity to serve as volunteers for a week at Camp Sunshine, a retreat center for children with life threatening illness and their families, during the summer between first and second year. As a requirement for graduation, candidates for the Master of Science in Genetic Counseling must complete an original institution review board (IRB) approved in-depth study of a selected genetic counseling issue or topic. Students are strongly encouraged to study topics appropriate for national presentation and/or publication.

There is a similar Master's level program for genetic counseling in the Boston University School of Medicine.[12] The first year of study focuses primarily on coursework in general genetics and counseling skills. Clinical, laboratory, research, and advocacy experiences complement the didactic curriculum. The second year of study focuses on clinical experience and research project development. In addition, the coursework covers more advanced topics in medical genetics, professional issues, and genetic counseling sub-specialties (**Supplemental Table 2****). The number of required credits is decreased during the second year, so as to allow students adequate time to complete their research projects, acquire a robust array of fieldwork experiences, and begin interviews for job placement. Graduates from genetic counseling programs accredited by the ACGC are eligible to sit for the ABGC examination to become a certified genetic counselor.

FELLOWSHIP PROGRAMS FOR MEDICAL GENETICS SPECIALISTS

Clinical geneticists require an earned M.D. or D.O. degree, two-year training in a clinical residency, two-year residency training in clinical genetics, and a valid license. They have the competence to provide comprehensive genetic diagnosis, management, therapy, and counseling services. Laboratory genetic specialists require an earned doctoral degree (MD, DO, and PhD), two-year fellowship training in a specialized genetics laboratory, and certifications from ABMGG. Recommended medical genetics textbooks and reference books from different training programs are list in Table 2. A web-based in-service exam for medical genetics residency has been developed and implemented.[13] Certified laboratory specialists can direct a clinical cytogenetic, a molecular genetics or a biochemical genetics laboratory by performing and interpreting genetics testing results relevant to the diagnosis and management of human genetic diseases. The organization of the professional training programs and its impact in providing medical genetics service, developing guideline, standards and policies for genetic and genomic medicine, and promoting genetic education to non-genetics health professions and general public have been described in a report of the Associate of Chinese Geneticists in America.[4]

Despite steady growth in the medical genetics workforce through the two-year training programs and bi-annual board exams, the number of physicians who complete the ABMGG certification has remained flat for recent years due mostly to it being a non-high-paying specialty at this stage and also partly to the lack of visibility. The medical genetics community has discussed ways to increase the 'pipeline' of medical genetic trainees and present competencies for the physician medical geneticist in the 21st century.[14] Enhancing exposure to genetics and genomics through a track curriculum running in parallel to current medical school curriculum has been introduced in Baylor College of Medicine.[15] This track includes didactic sessions, small group discussions, longitudinal clinical experiences, clinical and laboratory rotations, community outreach, and scholarly projects related to genetics. Few PhD students are aware of medical genetics as a career path and most lack an understanding of laboratory operations for genetic diagnosis and the training requirements that lead to eligibility for ABMGG certification in a laboratory specialty. To raise awareness about medical genetics as a career path among Ph.D. graduate students and postdoctoral fellows at Baylor College of Medicine, a medical genetics internship with a weekly rotation through diagnostic genetics laboratories was first introduced and quickly exceeded its capacity. As a result, a course titled "Introduction to Medical Genetics" was developed to replace the internship. Fang and Alford give an outline of this course as follows:

> *The course includes 11 lectures that will define the specialty of medical genetics and its place in the practice of medicine in the United States; outline educational and training requirements for eligibility for certification by the American Board of Medical Genetics in a laboratory specialty; introduce technologies used in medical genetics laboratories; explore topics such as pharmacogenetics and cancer diagnostics; describe the regulatory environments in which clinical laboratories operate; discuss billing and reimbursement, quality control/assurance, and other operational considerations unique to clinical laboratories; delineate how clinical and analytic sensitivity/specificity and clinical utility of genetic tests are assessed; consider how copy-number and sequence variations are evaluated for clinical significance; and introduce ethical and legal issues relevant to medical genetics. Students will also complete an online human subjects training course and participate in two small group discussions focused on cases from biochemical genetics, clinical genetics/genetic counseling, cytogenetics, and molecular genetics*.[16]

The lectures in this course cover all major topics for laboratory genetics specialists. Baylor's reach out effort to medical and graduate students and postdoc fellows to identify individuals interested in medical genetics as a career path may be replicated by other institutions.

SUMMARY

This tertiary education system has contributed to a well-trained workforce for genetics and genomic medicine. As of July 2014, the ABMGG has listed a workforce consisting of 1,509 M.D. clinical geneticists, 734 clinical cytogeneticists, 596 clinical molecular geneticists and 315 clinical biochemical geneticists. There are 3,475 genetic counselors certified by ABGC. There are 3762 certified cytogenetics technologists and 2,515 certified molecular genetics technologists by ASCP statistics for 2013 (**Table 1**). Based on a population size of 314 million and the pool of 1,500 clinical geneticists in the United States, there are about five clinical geneticists per million population. The ratio of clinical geneticists, laboratory specialists, genetic counselors and genetics technologists is estimated to be 1:1:2:4.

As the newest medical specialty, genetics and genomic medicine has experienced rapid application of advanced technologies and accumulation of clinical knowledge since the completion of Human Genome Project in 2003.[17] However, the implementation of genomic medicine in the past decade encounters many challenges including the difficulty in establishing clinical validity and utility of tests, the burden to patients and clinicians of assaying, reporting, intervening and following up genomic findings, the changing regulatory and coverage landscape, the need for education, etc.[17,18] All these challenges from the clinical practice will be fed back to the medical genetics education systems and demand changes to prepare genetics technologists, counselors and specialists for the high throughput genetic technologies and rapidly accumulating knowledge in genomic medicine. As genetics and genomic medicine integrates more into the mainstream health care, it is expected more undergraduates, graduates and medical students are becoming aware about this tertiary education system and seeking a career in medical genetics.

In addition to the United States, a similar medical genetics education system has been developed in Canada. However, in many developing countries including China, there are some institutional based training programs but no systematic efforts from the national level.[19] The structure, organization and curriculum of this tertiary medical genetics education system could serves as a good model for medical genetic educators in other countries.

CONFLICT OF INTEREST
None.

****** Supplemental Tables will be shown online due to limit of space: http://www.najms.net/v07i04p189w

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