Clinical applications of next generation sequencing in cancer: from panels, to exomes, to genomes

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This article will review recent impact of massively parallel next-generation sequencing (NGS) in our understanding and treatment of cancer. While whole exome sequencing (WES) remains popular and effective as a method of genetically profiling different cancers, advances in sequencing technology has enabled an increasing number of whole-genome based studies. Clinically, NGS has been used or is being developed for genetic screening, diagnostics, and clinical assessment. Though challenges remain, clinicians are in the early stages of using genetic data to make treatment decisions for cancer patients. As the integration of NGS in the study and treatment of cancer continues to mature, we believe that the field of cancer genomics will need to move toward more complete 100% genome sequencing. Current technologies and methods are largely limited to coding regions of the genome. A number of recent studies have demonstrated that mutations in non-coding regions may have direct tumorigenic effects or lead to genetic instability. Non-coding regions represent an important frontier in cancer genomics.

Keywords: next-generation sequencing (NGS), exome sequencing, cancer genomics, clinical genomics, non-coding DNA

Introduction

Cancer, in its many forms, accounted for 8.2 million deaths in 2012 (GLOBOCAN, 2012). The rapid development of DNA sequencing technologies has driven a revolution in our understanding of this highly complex and diverse group of diseases (Devita and Rosenberg, 2012). This review fulfills two purposes. First, this article summarizes the history of massively parallel next-generation sequencing (NGS) in the context of cancer genomics and reviews recent research and clinical applications. Second, we highlight the importance and potential of complete or 100% genome sequencing, i.e., the ability to sequence highly repetitive non-coding sequences beyond the reach of current NGS technologies.

Background and History

Sequencing the First Cancer Exomes and Genomes

The first cancer exomes were sequenced soon after the completion of the Human Genome Project in 2001. Compared to whole genome sequencing (WGS), exome sequencing covers only the 1% of the genome that is translated into protein, greatly reducing the technical burden of data collection and analysis. Ley et al. piloted the use of NGS to study the exomes of 140 samples of human acute myeloid leukemia (AML) cells in 2003, identifying 6 previously described and 7 undescribed
mutations relevant for AMP pathogenesis. The investigation searched for mutations capable of altering gene function and identified the FLT3 gene as a distinguishing mutant in AML patients (Ley et al., 2003).

The first solid tumor exomes to be investigated were from 11 breast and 11 colorectal cancer tissue samples. Sjöblom et al. identified 189 frequently mutated genes associated with these cancers, most of which were not previously known. Additionally, the investigators found that the average tumor accumulates an average of ∼90 mutations over its course of development, though only a subset of mutations contributes to the formation of neoplasms (Sjöblom et al., 2006). A follow-up study revealed varying mutation frequencies for individual genes with few but commonly mutated gene “mountains” and numerous but infrequently mutated gene “hills” (Wood et al., 2007). Despite similarities in the number of mutations for each cancer, the types and locations of these mutations result in distinct cancer subtypes (Wood et al., 2007).

Ley et al. performed the first whole-genome sequencing study on AML cells collected from a single patient. The patient’s skin cells were used as a control. The study identified 2 genes known to contribute to tumor progression and 8 known to be present in tumor cells but which have unknown functions. As a proof-of-concept, the study demonstrated the feasibility of WGS as an unbiased tool for the molecular profiling of individual cancers (Ley et al., 2008). Table 1 provides a summary of cancers and gene mutations.

Discoveries

Melanoma

Analyzing genomic data from melanoma samples is uniquely challenging because of the high number of passenger mutations caused by ultraviolet light exposure (Hodis et al., 2012). To overcome this, Hodis et al. controlled for UV-induced mutational load by comparing mutated genes-of-interest against a baseline level of intrinsic mutation. They identified six novel genes: PPP6C, RAC1, SNX31, TACC1, STK19, and ARID2. Of these genes, PPP6C, RAC1, and STK19 are thought to be potentially targetable. In a WES study of 147 melanomas, Krauthammer et al. identified a P29S mutation RAC1 in 9.2% of sun-exposed exposed melanomas. Mutations in the active site of PPP6C, a serine/threonine phosphatase, were found in 12% of sun-exposed melanomas that already possessed BRAF or NRAS mutations (Krauthammer et al., 2012).

Mutations in BRAF, NRAS, and KIT are known to be involved in the pathogenesis of metastatic melanoma. BRAF inhibitors are a class of targeted therapeutics approved for treating metastatic melanoma and have demonstrated significantly improved overall survival (Kunz et al., 2013).

Breast Cancer

The Cancer Genome Atlas network sequenced 510 breast cancers exomes, identifying 4 distinct subtypes: luminal A (ER+ and/or PR+, HER2−), luminal B (ER+ and/or PR+, HER2+), HER2-enriched (ER−, PR−, HER2+), and basal-like (ER−, PR−, HER2−). 40% of luminal A tumors possessed a mutated PIK3CA gene. TP53 and PIK3CA were mutated in 29% of luminal B tumors. Compared to luminal A or luminal B subtypes, the basal subtype exhibited a more consistent pattern of mutation, with TP53 mutated in 80% of cases. The HER2-enriched subtype is characterized by HER2 amplification, found in 80% of these tumors (Koboldt et al., 2012). Basal type tumors are characterized by the highest amount of mutations, while luminal A types generally contain the lowest frequencies of mutations (Wang et al., 2014b). Another study investigated CAG repeat lengths of breast cancer tumor samples to determine the significance of intratumor genetic heterogeneity (ITGH) (Gottlieb et al., 2013). The findings between differing repeat lengths showed that shorter CAG repeats may play protective roles against breast cancer, as opposed to longer repeat lengths, which may contribute to cancer development (Gottlieb et al., 2013). The study demonstrates that merely identifying genetic variations does not provide sufficient understanding of cancer etiology; rather it is necessary to determine frequency and distribution of mutations between cancerous and normal tissues (Gottlieb et al., 2013; Riahi et al., 2014).

Clinical Utility

The information generated by next generation sequencing (NGS) technologies enables clinicians to make improved diagnostic and treatment decisions. For example, breast cancers have traditionally been diagnosed by mammogram, physical exam, and histology. The discovery of BRCA1, BRCA2, and other biomarkers introduced genetics as an important consideration (Van De Vijver et al., 2002; Van’t Veer et al., 2002). Today, commercially available micro-array-based tests such as OncoType DX and MammaPrint allow more accurate profiling of breast cancers based on genetic biomarkers such as HER2, ER, and PR, each with their own treatment protocols. In parallel with improved diagnostics, identification of cancer-associated genes has led to the development of molecularly targeted therapies such as trastuzumab, which was among the first therapies specifically targeted to HER2+ breast cancers. Moreover, sequencing of hundreds of breast tumors has also revealed significant intratumor heterogeneity, reflecting an additional level of complexity for the development of new treatments (Desmedt et al., 2012; Shah et al., 2012).

Genetic Screening

As the cost of NGS continues to approach the $1000 threshold, population-wide genomic screening becomes more likely (Bruniciardi et al., 2011). Already, NGS may improve genetic testing in families with histories of high penetrance cancer genes such as BRCA1, BRCA2, APC, and TP53 (Meldrum et al., 2011). Several investigators have tested the Illumina HiSeq platform in detecting BRCA1, BRCA2, and TP53 from a tumor cell line (Morgan et al., 2010; Schroeder et al., 2010). In these studies, NGS analysis identified all known variants in the tumor cell line with sensitivity and specificity greater than traditional diagnostic methods, demonstrating the effectiveness of NGS as a diagnostic tool. More important than the improvement in
TABLE 1 | Summary of genetic mutations associated with selected cancers.

| Cancer type | Somatic mutations | Structural rearrangements | Insertions/Deletions | Hereditary mutations | References |
|-------------|-------------------|---------------------------|----------------------|---------------------|------------|
| Melanoma    | HRAS, BRAF, RAS, CTNNB1, QNA11, QNAO, KIT, MEK1, NRAS, MMAC1, PTEN, GRIN2A, PREX2, RAC1, PPP6C, STK19, SNX31, TACC1, ARID2, CDK4, MITF | CDKN2, HMGI-C, RAF | MMAC1, PTEN, BRAF | MAP2K1, MAP2K2, CDK4 | Brose et al., 2002; Vogelstein and Kinzler, 2004; Garraway et al., 2005; Wei et al., 2011; Hodiis et al., 2012 | Vogelstein et al., 2013 |
| Lung Cancer | TP53, KRAS, STK11, EGFR, ALK, BRAF, RAS, AKT1, DDR2, HER2, MEK1, NRAS, PIK3CA, PTEN | RET, RAS1, ALK, EML4, NTRK1 | EGFR, FHT, FRA3B, FGFR1, HER2 | EGFR, BRAF, RAS, KRAS, TP53 | Brose et al., 2002; Kosaka et al., 2004; Vogelstein and Kinzler, 2004; Suda et al., 2007; Lipson et al., 2012; Vogelstein et al., 2013 |
| Liver Cancer | CTNNB1, GNMT, p57, IN1 | GNMT | E1B, GNMT, p57 | ARID1A, ARID1B, ARID2, MLL, MLL3, TP53, CTNNB1, EGFR, GNMT, IN1 | Biegel et al., 1999; Tseng et al., 2003; Vogelstein and Kinzler, 2004; Vogelstein et al., 2013 |
| Breast Cancer | FBXW7, AKT2, P53KCA, CCND1, ERBB2, NTRK1, SMAD2, MAP2K4, AKT1, ESRI, FGFR1, FGFR2, HER2, PIK3CA, PTEN | BRCA1, BRCA2, TP53, P53KCA, CHEK2 | BRCA1 | TP53, BRCA1, BRCA2, PTEN, AKT1, TP43, TBX3, RUNX1, CBFB | Vogelstein and Kinzler, 2004; Walsh et al., 2006; Stephens et al., 2009; Vogelstein et al., 2013 |
| Colorectal Cancer | CTNNB1, BAX, FBXW7, P53KCA, FES, KRAS, NRAS, SMAD2, SMAD4, TGFBR1, TGFBR2, MAP2K4, PTPN1, AKT1, PTEN, BRAF, PIK3CA | ALK | APC-L1 | FAP, AXIN2, MSH2, MLH1, MSH6, PMS2, HNPPCC, MUTYH, PIK3CA, IRS2, IRS4, PTEN, RHEB | Miki et al., 1992; Vogelstein and Kinzler, 2004; Wood et al., 2007; Lipson et al., 2012; Vogelstein et al., 2013 |
| Ovarian Cancer | FBXW7, AKT2, ERBB2, TGFBR1, TGFBR2, BRAF, KRAS, PIK3CA, PTEN | ARID1A, BRCA1 | MMP-1, BRCA1, BRCA2, MLPA, MAPH | STK11, BRCA1, BRCA2 | Kanamori et al., 1999; Seltner and Taylor, 2004; Vogelstein and Kinzler, 2004; Jones et al., 2008; Vogelstein et al., 2013 |
| Pancreatic Cancer | KRAS2, N-RAS, MAP2K4, CDKN2A, TP53, SMAD4, BRCA2 | TP53, SMAD4, INK4A | CDKN2A, TP53 | STK11, CDKN2A | Bardeesy and Depinho, 2002; Montagna et al., 2003; Vogelstein and Kinzler, 2004; Vogelstein et al., 2013 |
| Thyroid Cancer | NTRK1, BRAF, KRAS, RET | RET/PTC, ELE1, AKAP9, PTEN, BRAF, TRK | PTEN | RET, NTRK1, BRAF | Fugazzola et al., 1996; Dahia et al., 1997; Cheung et al., 2001; Vogelstein and Kinzler, 2004; Vogelstein et al., 2013 |

sensitivity/specificity, the data generated by NGS allows for more sophisticated analysis of gene interactions.

Economical NGS screening will also benefit patients with de novo mutations who would not otherwise undergo genetic screening based on family history. In the case of BRCA mutations, family history only accounts for 30–50% of mutations (Moller et al., 2007). Additionally, NGS testing allows for testing of genes with a wide range in frequency (Meldrum et al., 2011). Several companies and institutions offer cancer gene panels that screen for over 70 genes (Washington University in St.
Diagnostics and Assessment
Currently, NGS-based gene panels are regularly used for cancer diagnostics. For example, the 2015 National Comprehensive Cancer Network guidelines recommend NGS gene panels for patients with hereditary and ovarian cancer who have tested negative for high-penetration genes (Park et al., 2014). In a study of 141 patients who tested negative for BRCA1/2, evaluation by an NGS panel of 40 genes identified 16 patients who have pathogenic variants in 9 non-BRCA genes (Kurian et al., 2014). The use of NGS in clinical diagnostics may be separated into three approaches: gene panels, whole exome sequencing (WES), and whole genome sequencing. Among these, gene panels have been in use for the longest period, with more than 16 laboratories in the United States panels for hereditary cancer (Wang et al., 2014a). The diagnostic yields of these panels range from 20 to 51%, which is comparable to that of exome or genome-based methods (Wang et al., 2014a). Recent exome-based diagnostics for mitochondrial respiratory disease and intellectual disability demonstrated diagnostic yields of 60 and 16%, respectively (De Ligt et al., 2012; Taylor et al., 2014). Other evaluations of exome-based diagnostics demonstrated diagnostic yields between 25 and 30% (Yang et al., 2013, 2014; Lee et al., 2014). Genome-based diagnostics are comparatively newer and there are fewer studies that evaluate their use. Studies that evaluated the use of genome sequencing to diagnose intellectual disability and early-onset epilepsy demonstrated a diagnostic yield of 50 and 24%, respectively (Gilissen et al., 2014; Martin et al., 2014). As our understanding of the genome grows, in-depth genome-based diagnostics will have higher diagnostic yield.

Clinical Decision-making and Treatment
NGS has enabled investigators to discover and elucidate hundreds of genes involved in cancer, advances that will inevitably reveal novel therapeutic targets. Targeted therapies, a growing group of therapeutic agents with molecular-level specificity have greatly changed the treatment and management for many cancers. Notable examples include imatinib (BCR-ABL) and trastuzumab (HER2). Targeted therapies have the potential to be more effective and less toxic than traditional chemotherapies for patients suffering from cancer (Tsimberidou et al., 2014). Treatments like EGFR-targeted plasmonic magnetic particles have been shown to be more effective in suppressing lung cancer development and tumor growth by abrogating the G2/M cell cycle phase and inducing apoptosis (Kuroda et al., 2014). Another promising development in targeted cancer therapy is signaling-directed androgen receptor treatment for castration-resistant prostate cancer, which deactivates tumor proliferation pathways and inhibits cancer progression (Bastos et al., 2014). Currently, discoveries on the diagnostics and assessment outpace the development of targeted therapies. As NGS technology matures, the selection of targeted therapies stands to expand greatly as more targets become known.

Due to the easy accessibility of circulating tumor DNA (ctDNA), sequencing ctDNA is another attractive method for analyzing tumor load and treatment effectiveness (Wang and Wheeler, 2014). The mechanism by which ctDNA enters the bloodstream is not well understood, though Gormally et al. propose two mechanisms: release of whole cells followed by lysis and apoptosis (Gormally et al., 2007). Diehl et al. demonstrated that ctDNA measurements in 18 patients with colorectal cancer were a reliable indicator of tumor dynamics (Diehl et al., 2007). In 2014, Lohr et al. developed computational methods to isolate ctDNA sequences from serum. A comparison of their ctDNA sequences to previously sequenced tumor samples revealed 90% of early trunk mutations and 73% of metastatic trunk mutations in the tumor were also found in ctDNA (Lohr et al., 2014). In another study by Murtaza et al. sequencing of ctDNA from patients with breast, lung, and ovarian cancers allowed investigators to track mutations in the tumor genome in a non-invasive manner (Murtaza et al., 2013). Additionally, Dawson et al. demonstrated that the sensitivity of ctDNA surpassed that of other circulating biomarkers (Dawson et al., 2013). These studies suggest that NGS analysis of ctDNA holds great potential for screening, diagnosis, and clinical decision-making.

There remain many challenges for investigators and clinicians. With massive amounts of data generated, healthcare infrastructure needs new strategies for data curation. Additionally, the economic implications of widespread sequencing are not yet known given the complex interplay between healthcare providers, the biomedical industry, insurance companies, and academic research (Buchanan et al., 2013).

Commercialization
Today, patients may choose between many services and technologies offered by gene sequencing companies for assistance in patient diagnosis and treatment decision processes. Some companies, such as Foundation Medicine and Personal Genome Diagnostics, offer clinical tests like FoundationOne and CancerComplete to help identify the genetic variants in a patient’s DNA sample that may be contributing to cancer development.

A number of companies and institutions provide individual gene panel tests for different types of cancers. Cancer-specific kits such as AmbryGen’s OvaNext and ColoNext selectively enrich genes-of-interest for ovarian and colorectal cancers, respectively. Other companies and institutions offer similar cancer-specific testing, such as Neogenomics Laboratories, GPS@WUSTL, Emory Genetics Laboratory, ARUP Laboratories, Myriad Genetics, and GeneDx. WES-based tests such as the FoundationOne or FoundationOne-Heme have been developed to be highly sensitive and specific (Frampton et al., 2013). Table 2 provides a summary of commercial services using NGS.

Future Directions
Single Molecule Sequencing
While NGS has undoubtedly driven a revolution in genetics, current technologies face certain limitations. First, the
| Company                     | Product                          | Disease                  | Scope of coverage       | No. of Genes analyzed | Investigates                                                                 |
|----------------------------|----------------------------------|--------------------------|-------------------------|-----------------------|-------------------------------------------------------------------------------|
| Foundation Medicine        | Foundation One Cancer Panel      | Cancer                   | Panel                   | 236 genes, 47 introns from 19 genes associated with rearrangement             | Solid tumors–gene alterations, alteration frequency                          |
| Foundation Medicine        | Foundation One Heme Cancer Panel | Cancer                   | Panel                   | 405 genes from DNA including 31 introns associated with rearrangement, 265 genes from RNA, fusion genes | Hematologic tumors–gene alteration, alteration frequency, fusion genes       |
| Personal Genome Diagnostics | Cancer Complete Cancer Panel     | Cancer                   | Full exome              | ~20,000               | Gene point mutations, copy number alterations (indels), rearrangements        |
| PGDX                       | Cancer Select cancer Panel       | Cancer                   | 120 cancer gene panel   | 120                   | Point mutations, copy number alterations, rearrangements                      |
| Ambry Genetics             | Exome Next                       | Cancer                   | Exome                   | ~20,000               | Mitochondrial genome mutations, sequence variants                            |
| Ambry Genetics             | BRCA1 and BRCA2 gene sequencing  | Breast Cancer            | Full exome              | ~20,000               | Exon analysis                                                                 |
| GeneDx                     | XomeDx                           | Cancer                   | Full exome              | ~20,000               | Exon analysis                                                                 |
| GeneDx                     | XomeDx Plus                      | Cancer                   | Exome                   | 20,000 plus mitochondrial sequencing | Combined test, mitochondrial genome sequencing and deletions                  |
| GeneDx                     | XomeDx Slice                     | Cancer                   | Exome                   | targeted test          | Targets regions of the exome or specific genes–variant search                |
| GeneDx                     | Comprehensive cancer panel Cancer| Cancer                   | Panel                   | 29                    | Gene sequence, deletions/duplications, gene mutations, nucleotide substitutions |
| NeoGenomics Laboratories   | EGFR Mutation Analysis NSCLC     | NSCLC                    | EGFR exons 18-21        | 1                     | Mutations on target exons, duplications/deletions                            |
| NeoGenomics Laboratories   | NeoSITE Melanoma Cancer          | Cancer                   | Panel                   | 5                     | Copy number variants, duplications/deletions                                 |
| NeoGenomics Laboratories   | FISH for non-small cell lung cancer | NSCLC                 | Panel                   | 2                     | Rearrangements, fusions                                                     |
| NeoGenomics Laboratories   | Colorectal Cancer panel          | Colorectal Cancer        | Panel                   | 2                     | KRAS and BRAF mutations, mismatch repair defects, microsatellite instability at 5 target loci |
| Caris                      | MI Profile                       | Cancer                   | Panel                   | 47                    | Somatic mutations in solid tumors                                           |
| Myriad Genetics            | BRCA Analysis                    | Breast and Ovarian Cancer| BRCA1, BRCA2            | 2                     | Gene mutations                                                               |
| Quest Diagnostics          | OncoVantage                      | Solid tumors             | Panel                   | 34                    | Point mutations, indels                                                      |
| GPS@WUSTL                  | Comprehensive Cancer Gene Set Analysis | Cancer                | Panel                   | 42                    | Point mutations, indels                                                      |
| Arup Laboratories          | Gastrointestinal hereditary cancer panel | Gastrointestinal cancer | Panel                   | 15                    | Targeted capture of coding exons and intron/exon junctions–sequenced for mutation detection, deletion/duplication analysis |
amplification of DNA libraries may result in differential expansion of certain regions of the genome. This introduces the problem of biased reads. Second, epigenetic modifications are lost during amplification. Third, the short read lengths generated from current NGS platforms requires a reliance on a reference genome and robust alignment algorithms to produce sequences from raw NGS data (Mardis, 2013). Lastly, the entire sequencing process from sample preparation to computational construction of the sequence takes days to weeks (Liu et al., 2012).

Single molecule or third generation sequencing systems address shortcomings present in current NGS platforms. Single-molecule real-time sequencing (SMRT, Pacific Biosciences) and nanopore sequencing (Oxford Nanopore) are perhaps the most well-known. Conceptually, both of these systems detect nucleotide incorporation onto a single DNA strand in real time. SMRT uses a system of fluorescent signals to monitor nucleotide incorporation while nanopore detects voltage across a lipid bilayer as a DNA is ratcheted across an α-hemolysin nanopore (Eid et al., 2009; Liu et al., 2012). Sequencing a single strand eliminates the need for amplification, reducing sequencing bias present in NGS platforms. Monitoring systems can also be tuned to detect epigenetic changes. Read lengths are also significantly longer compared to current NGS systems, with SMRT reads in the range of ~5000–6000 bp (English et al., 2012; Chin et al., 2013). Long read lengths allow for rapid de novo sequencing of organisms without reference genomes as well as the sequencing of highly repetitive regions. Additionally, simplified preparation and sequencing in real time with nucleotide incorporation significantly shortens run times. SMRT runs can be completed in just 1 day (Liu et al., 2012).

Single molecule sequencing systems are beginning to make an impact in cancer genomics and are poised to play a larger role moving forward. While SMRT has been available since 2011, nanopore sequencing has yet to see widespread use. SMRT has been used to resequence AML patients to identify a marker (FLT3 with internal tandem duplication) associated with poor prognosis (Smith et al., 2012). Kleinman et al. used SMRT to elucidate a distinct DNA methylation pattern and epigenetic alteration program in embryonal brain tumors (Kleinman et al., 2014). In addition to the ability to study genetic and epigenetic changes undetectable by NGS, single molecule sequencing also holds great potential for sensitive diagnostics. Sequencing results comparable to NGS reads may be obtained from as little as 500 pg of starting DNA (Raley et al., 2014). In late 2013, Pacific Biosciences announced a large-scale collaboration with Roche to produce diagnostics tools based on SMRT (Pacific Biosciences Investor Relations, 2013).

Diagnostic Yield

As the field moves forward to understand a wider range of genetic abnormalities, there must be a concurrent shift toward 100% genome sequencing for diagnostics. However, current genome-based diagnostics still face several challenges. Dewey et al. analyzed 12 healthy genomes for 56 clinically significant genes and found that the best platform (Illumina) was only able to sequence 51 out of 56 genes with adequate coverage (Dewey et al., 2014). This is a technical hurdle that we hope will be overcome with improved technologies and bioinformatics. Genome-based diagnostics are also inherently limited by the inability to sequence the whole genome, with approximately 8% of the genome not sequenced. This challenge may only be overcome with 100% genome sequencing. Improvement in the diagnostic yield of genetic testing can only occur given a solid foundation of complete gene coverage. Given that the relatively low diagnostic yields of current strategies, we submit that the goal of 100% genome sequencing will be clinically significant.

100% Genome Sequencing

Current findings suggest that a variety of defects in non-coding regions can contribute to neoplastic pathogenesis (Chmielecki and Meyerson, 2014). Huang et al. identified a pattern of mutations in the promoter region of telomerase reverse transcriptase, demonstrating that somatic mutations in non-coding regions can have a direct tumorigenic effect (Huang et al., 2013). Zhu et al. demonstrated that genomic instability following the loss of Brca1 in mice may be due to de-repression of satellite DNA transcription. The authors propose that tumor suppressor functions of BRCA1 primarily stem from its role as a regulator of heterochromatin (Zhu et al., 2011). Ting et al. identified a pattern of satellite transcript overexpression in epithelial cancers of the lung, kidney, ovary, colon, and prostate, proposing that heterochromatric alterations may serve as a biomarker for cancer (Ting et al., 2011). These findings suggest that non-coding regions may be a rich source of new insights into tumorigenesis.

Complete genomic sequencing may also reveal epigenetic changes in cancer that were previously inaccessible due to limitations in the coverage and resolution of last-generation technologies. The epigenetics of nucleosomes for example, have eluded investigation in the past, but new protocols utilizing NGS which enable genome-wide studies of nucleosome positioning at high sensitivity might allow networks of chromatin modulation to finally be probed (Wei et al., 2012). Using NGS, Kim et al. characterized the instability of microsatellite regions in colorectal and endometrial cancers, showing that this genetic instability affects nucleosome positioning (Kim et al., 2013). Studies of the epigenetics of cancer have already produced surprising findings, such as the discovery that regions of DNA hypomethylation in breast cancer cells are paradoxically silenced by the formation of repressive chromatin domains (Hon et al., 2012), and the discovery that histone modifications drive pediatric glioblastoma (Rheinbay et al., 2012). Still more protocols that utilize NGS for studying epigenetic changes are in the pipeline: A recently published method of deciphering histone post-translational modifications (PTMs) using DNA-barcoded nucleosome libraries, is enabled in large part by the speed and low-cost of high throughput DNA sequencing (Nguyen et al., 2014). A thorough understanding of chromatin regulation however, will require not just knowledge of DNA base sequences, but also an understanding of how DNA segments interact with histones and their regulatory elements. To this end, biophysical models, such as a recently published model by Cherstvy and Teif on the electrostatics of histone-DNA interactions (Cherstvy and Teif, 2014), are essential. In another modeling study, Beshnova...
et al. demonstrate that although major satellite repeats in mice encode preferences for nucleosome positioning, nucleosome positioning is not rigid, and can alternate between two separate types of positioning (Beshnova et al., 2014).

Final Comments

In this article, we discussed the past, present, and future of DNA sequencing in cancer genomics. As advancements in sequencing technology enabled investigators to study cancer genomes in greater breadth and depth, the field has produced novel insights into tumor pathogenesis, identified clinically useful biomarkers, and developed increasingly precise diagnostics and targeted therapeutics. However, it is important to note that our understanding of the genome is limited, with <5000 of 23,000 known (Park et al., 2014). The clinical usefulness of genomic sequencing requires advancement in our knowledge of the genome and bioinformatic systems to process genetic data—advancements that would be built on a foundation of 100% genome sequencing.

References

Bardeesy, N., and Depinho, R. A. (2002). Pancreatic cancer biology and genetics. Nat. Rev. Cancer 2, 897–909. doi: 10.1038/nrc949

Bastos, D. A., Daik, C., Rathkopf, D., and Scher, H. I. (2014). Expanding androgen- and androgen receptor signaling-directed therapies for castration-resistant prostate cancer. Oncology (Williston Park, NY) 28, 693–699.

Beshnova, D. A., Cherstvy, A. G., Vainshtein, Y., and Teif, V. B. (2014). Regulation binding on nucleosome repeat length. Phys. Biol. 11:044001. doi: 10.1088/1478-3975/11/4/044001

Chmielecki, J., and Meyerson, M. (2014). DNA sequencing of cancer: what have we learned? Annu. Rev. Med. 65, 63–79. doi: 10.1146/annurev-med-060712-200152

Dahia, P. L. M., Marsh, D. J., Zheng, Z., Zedenius, J., Komminoth, P., Frisk, T., et al. (1997). Somatic deletions and mutations in the coden disease gene, PTEN, in sporadic thyroid tumors. Cancer Res. 57, 4710–4713.

Dawson, S.-J., Tsui, D. W., Murtaza, M., Biggs, H., Rueda, O. M., Chin, S.-F., et al. (2013). Analysis of circulating tumor DNA to monitor metastatic breast cancer. N. Engl. J. Med. 368, 1199–1209. doi: 10.1056/NEJMoa1213261

De Ligt, J., Willemsen, M. H., Van Bon, B. W., Kleefstra, T., Yntema, H. G., Groes, T., et al. (2012). Diagnostic exome sequencing in persons with severe intellectual disability. N. Engl. J. Med. 367, 1921–1929. doi: 10.1056/NEJMoa1205624

Dewey, F. E., Grove, M. E., Pan, C., Goldstein, B. A., Bernstein, J. A., Chab, H., et al. (2014). Clinical interpretation and implications of whole-genome sequencing. JAMA 311, 1035–1045. doi: 10.1001/jama.2014.1717

Dhiel, F., Schmidt, K., Choti, M. A., Romans, K., Goodman, S., Li, Y., et al. (2007). Circulating mutant DNA to assess tumor dynamics. Nat. Med. 14, 985–990. doi: 10.1038/nm.1789

Eid, J., Fehr, A., Gray, J., Luong, K., Lyle, J., Otto, G., et al. (2009). Real-time DNA sequencing from single polymerase molecules. Science 323, 133–138. doi: 10.1126/science.1162986

English, A. C., Richards, S., Han, W., Yang, M., Vee, V., Qu, J., et al. (2012). Mind the gap: upgrading genomes with Pacific Biosciences RS long-read sequencing technology. PLoS ONE 7:e47768. doi: 10.1371/journal.pone.0047768

Frampton, G. M., Fichtenholz, A., Otto, G. A., Wang, K., Downing, S. R., He, J., et al. (2013). Development and validation of a clinical cancer genomic profiling test based on massively parallel DNA sequencing. Nat. Biotechnol. 31, 1023–1031. doi: 10.1038/nbt.2696

Fugazzola, L., Pierotti, M. A., Viganò, E., Pacini, F., Vontosovska, T. V., and Bonzarzone, I. (1996). Molecular and biochemical analysis of RET/PTC4, a novel oncogenic rearrangement between RET and ELE1 genes, in a post-Chernobyl papillary thyroid cancer. Oncogene 13, 1093–1097.

Garraway, L. A., Widlund, H. R., Rubin, M. A., Getz, G., Berger, A. J., Ramaswamy, S., et al. (2005). Integrative genomic analyses identify MITF as a lineage survival oncogene amplified in malignant melanoma. Nature 436, 117–122. doi: 10.1038/nature3664

Gilissen, C., Hehir-Kwa, J. Y., Thung, D. T., van der Vorst, M., van Bon, B. W. M., Willemsen, M. H., et al. (2014). Genome sequencing identifies major causes of severe intellectual disability. Nature 511, 344–347. doi: 10.1038/nature13394

GLOBOCAN (2012). Estimated Cancer Incidence, Mortality and Prevalence Worldwide in 2012. Available online at: http://globocan.iarc.fr/Pages/fact_sheets_population.aspx

Hodis, E., Watson, I. R., Kryukov, G. V., Arnold, S. T., Imleri, M., Theurillat, J. P., et al. (2012). A landscape of driver mutations in melanoma. Cell 150, 251–263. doi: 10.1016/j.cell.2012.06.024

Huang, F. W., Hodis, E., Xu, M. J., Kryukov, G. V., Chin, L., and Garraway, L. A. (2013). Highly recurrent TERT promoter mutations in human melanoma. Science 339, 957–959. doi: 10.1126/science.1229259

Jones, S., Zhang, X., Parsons, D. W., Lin, J. C.-H., Leary, R. J., Angenendt, P., et al. (2008). Core signaling pathways in human pancreatic cancers revealed by global genomic analyses. Science 321, 1801–1806. doi: 10.1126/science.1164368

Kanamori, Y., Matsushima, M., Minaguchi, T., Kobayashi, K., Sage, S., Kudo, R., et al. (1999). Correlation between expression of the matrix metalloproteinase-1
gene in ovarian cancers and an insertion/deletion polymorphism in its promoter region. Cancer Res. 59, 4225–4227.

Kim, T.-M., Laird, P. W., and Park, P. J. (2013). The landscape of microsatellite instability in colorectal and endometrial cancer genomes. Cell 155, 858–868. doi: 10.1016/j.cell.2013.09.015

Kleinman, C. L., Greges, N., Papillon-Cavanagh, S., Sin-Chan, P., Pramatarova, A., Quang, D.-A. K., et al. (2014). Fusion of TTYTH1 with the C19MC microRNA cluster drives expression of a brain-specific DNM1T3 isoform in the embryonic brain tumor EMTMR. Nat. Genet. 46, 39–44. doi: 10.1038/ng.2849

Koboldt, D. C., Fulton, R. S., Mcclellan, M. D., Schmidt, H., Kalicki-veizer, J. P., et al. (2012). Comprehensive molecular portraits of human breast tumours. Nature 490, 61–70. doi: 10.1038/nature11412

Kosaka, T., Yatabe, Y., Kuwano, H., Takahashi, T., and Mitsudomi, T. (2004). Mutations of the epidermal growth factor receptor gene in lung cancer: biological and clinical implications. Cancer Res. 64, 8919–8923. doi: 10.1158/0008-5472.CAN-04-2818

Krauthammer, M., Kong, Y., Ha, B.-H., Evans, P., Bacchiocchi, A., Mccusker, J. P., et al. (2012). Exome sequencing identifies recurrent somatic RAC1 mutations in melanoma. Nat. Genet. 44, 1006–1014. doi: 10.1038/ng.2359

Kunz, M., Dannemann, M., and Kelso, J. (2013). High-throughput sequencing of the melanoma genome. Exp. Dermatol. 22, 10–17. doi: 10.1111/exd.12054

Kurian, A. W., Hare, E. E., Mills, M. A., Kingham, K. E., Mepsherson, L., Whittemore, A. S., et al. (2014). Clinical evaluation of a multi-genome sequencing panel for hereditary cancer risk assessment. J. Clin. Oncol. 32, 2001–2009. doi: 10.1200/JCO.2013.53.6607

Kuroda, S., Tani, J., Roth, J. A., Sokolov, K., and Ramesh, R. (2014). EGFR-targeted plasmatic magnetic nanoparticles suppress lung tumor growth by abrogating G2/M cell cycle arrest and inducing DNA damage. Int. J. Nanomed. 9, 3825. doi: 10.2147/IJN.S69990

Lee, H., Deignan, J. L., Dorrani, N., Strom, S. P., Kantarci, S., Quintero-Rivera, E., et al. (2014). Validation of ITD mutations in FLT3 as a therapeutic target in human acute myeloid leukaemia. Nature 486, 395–399. doi: 10.1038/nature10933

Selvendiran, J., Jones, S., Wood, L. D., Parsons, D. W., Lin, J., Barber, T. D., et al. (2006). The consensus coding sequences of human breast and colorectal cancers. Science 314, 268–274. doi: 10.1126/science.1133427

Smith, C. C., Wang, Q., Chin, C.-S., Salerno, S., Levis, M. J., et al. (2012). Validation of ITD mutations in FLT3 as a therapeutic target in human acute myeloid leukaemia. Nature 485, 260–263. doi: 10.1038/nature11016

Taylor, R. W., Pyle, A., Griffin, B., Blakely, E. L., Duff, J., He, L., et al. (2014). Aberrant overexpression of satellite repeats in pancreatic and other epithelial cancers. Science 331, 593–596. doi: 10.1126/science.1231784

Ti, T.-T., Lipson, D., Paul, S., Brannigan, B. W., Akhavanfard, S., Coffman, E. J., et al. (2011). A gene-expression signature as a predictor of survival in breast cancer. Nat. Genet. 43, 287–303. doi: 10.1038/ng.2857

Stephens, P. J., Mclatchie, D. B., Beecroft, J., Varela, I., Pleasance, E. D., Pandolfo, M., et al. (2014). Next-generation sequencing systems. Nature 485, 647–654. doi: 10.1038/nature10945

Van De Vijver, M. J., He, Y. D., van ’t Veer, L. J., Dai, H., Basheer, M. A., et al. (2000). A gene-expression signature as a predictor of survival in breast cancer. Nat. Med. 6, 899–904. doi: 10.1038/75248

Van De Vijver, M. J., Darmstadt, G. L., Mcmichael, J. F., et al. (2012). Exome sequencing identifies recurrent somatic RAC1 mutations in melanoma. Nat. Genet. 44, 1006–1014. doi: 10.1038/ng.2359

Weinstein, J., Johnson, B., Mclatchie, D. B., et al. (2011). Pacific Biosciences announces rapid enrichment system. BioTechniques 51, 152–154. doi: 10.2144/0005954109

Whittemore, A. S., et al. (2014). Clinical evaluation of a multiple-gene sequencing panel for hereditary cancer risk assessment. J. Clin. Oncol. 32, 2001–2009. doi: 10.1200/JCO.2013.53.6607

Wong, S. L., et al. (2012). Exome sequencing identifies recurrent somatic RAC1 mutations in melanoma. Nat. Genet. 34, 39–44. doi: 10.1038/ng.2625

Xu, Y., et al. (2009). Complex landscapes of somatic rearrangement in human breast cancer. Hum. Mutat. 31, 4225–4227. doi: 10.1002/humu.21216

Yamakawa, T., et al. (2010). Genetic diagnosis of familial breast cancer using cloning sequencing. Cancer Res. 70, 108–112. doi: 10.1128/clinres.19279

Yamashita, Y., et al. (2013). Exome sequencing identifies recurrent somatic RAC1 mutations in melanoma. Nat. Genet. 44, 1006–1014. doi: 10.1038/ng.2359

Yin, L., et al. (2014). Next-generation sequencing systems. Nature 485, 647–654. doi: 10.1038/nature10945

Yun, J., et al. (2012). Accelerated chromatin biochemistry using DNA-barcoded nuclease libraries. Nat. Methods 9, 834–840. doi: 10.1038/nm.3022

Pacific Biosciences Investor Relations. (2013). Pacific Biosciences Announces Agreement With Roche Diagnostics to Develop and Supply DNA Sequencing-Based Products for Clinical Diagnostics. Available online at: http://investor.pacificbiosciences.com/releasedetail.cfm?ReleaseID=739199
Van’t Veer, L. J., Dai, H., Van De Vijver, M. J., He, Y. D., Hart, A. A., Mao, M., et al. (2002). Gene expression profiling predicts clinical outcome of breast cancer. *Nature* 415, 530–536. doi: 10.1038/415530a

Vogelstein, B., and Kinzler, K. W. (2004). Cancer genes and the pathways they control. *Nat. Med.* 10, 789–799. doi: 10.1038/nm1087

Vogelstein, B., Papadopoulos, N., Velculescu, V. E., Zhou, S., Diaz, L. A., and Kinzler, K. W. (2013). Cancer genome landscapes. *Science* 339, 1546–1558. doi: 10.1126/science.1235122

Walsh, T., Casadei, S., Coats, K., Swisher, E., Stray, S. M., Higgins, J., et al. (2006). Spectrum of mutations in *BRCA1, BRCA2, CHEK2,* and *TP53* in families at high risk of breast cancer. *JAMA* 295, 1379–1388. doi: 10.1001/jama.295.12.1379

Wang, J., Gotway, G., Pascual, J. M., and Park, J. Y. (2014a). Diagnostic yield of clinical next-generation sequencing panels for epilepsy. *JAMA Neurol.* 71, 650–651. doi: 10.1001/jamaneurol.2014.405

Wang, L., and Wheeler, D.A. (2014). Genomic sequencing for cancer diagnosis and therapy. *Annu. Rev. Med.* 65, 33–48. doi: 10.1146/annurev-med-120811-171056

Wei, X., Walia, V., Lin, J. C., Teer, J. K., Prickett, T. D., Gartner, J., et al. (2011). Exome sequencing identifies GRIN2A as frequently mutated in melanoma. *Nat. Genet.* 43, 442–446. doi: 10.1038/ng.810

Wood, L. D., Parsons, D. W., Jones, S., Lin, J., Sjöblom, T., Leary, R. J., et al. (2007). The genomic landscapes of human breast and colorectal cancers. *Science* 318, 1108–1113. doi: 10.1126/science.1145720

Conflict of Interest Statement: The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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