

METHODS FOR QUANTITATIVE GENETIC ANALYSIS OF CELL FREE DNA

STATEMENT REGARDING SEQUENCE LISTING

The Sequence Listing associated with this application is provided in text format
5 in lieu of a paper copy, and is hereby incorporated by reference into the specification.
The name of the text file containing the Sequence Listing is
CLFK_002_00US_ST25.txt. The text file is 117 KB, was created on August 22, 2014,
and is being submitted electronically via EFS-Web.

BACKGROUND

10 Technical Field

The invention relates generally to compositions and methods for the quantitative genetic analysis of cell free DNA (cfDNA). In particular, the present invention relates to improved targeted sequence capture compositions and methods for the genetic characterization and analysis of cfDNA.

15 Description of the Related Art

It is becoming increasingly clear that most, if not all, of the most common human cancers are diseases of the human genome. The emerging picture is that somatic mutations accumulate during an individual's lifetime, some of which increase the probability that the cell in which they are harbored can develop into a tumor
20 (Vogelstein *et al.*, *Science* 339(6127): 1546–1558 (2013)). With just the wrong combination of accumulated mutational events, a precancerous growth loses constraints that keep uncontrolled proliferation in check and the resulting cell mass becomes a cancer. The constellations of mutations that are necessary and sufficient to cause cancer are often collectively referred to as “driver mutations.” One of the themes that
25 have emerged from recent and intensive molecular analysis is that cancer, once thought of as a single, tissue-specific disease, is in fact a group of related diseases, each with a

unique molecular pathology. The human genome project laid the groundwork for genome-wide analysis of cancers.

For example, the introduction of next-generation sequencing technologies (2004-present) has accelerated the discovery pace of causal genomic factors that
5 underlie the diagnosis of NSCLC, making it clear that NSCLC is really a family of related diseases, each of which may be responsive to a different targeted therapy.

The art lacks reliable and robust molecular analysis methods for the analysis of genetic diseases. Traditionally, molecular diagnostics have consisted of antibody-based tests (immunohistochemistry), in-situ hybridization with DNA probes (fluorescence in
10 situ hybridization), and hybridization or PCR-based tests that query specific nucleotide sequences. Until recently, DNA sequencing as a molecular diagnostic tool has been generally limited to the coding exons of one or two genes. While DNA sequencing has been used in the diagnosis and treatment of solid cancers, one of the most significant drawbacks of these methods is that they require direct access to tumor tissues. Such
15 material is often difficult to obtain from the initial biopsy used to diagnose the disease and virtually impossible to obtain in multiple repetitions over time. Similarly, biopsies are not possible in patients with inaccessible tumors and not practical in individuals suffering from metastatic disease.

Thus, the vast potential of molecular diagnostics for genetic diseases; fetal
20 testing; paternity testing; predicting response to drug treatment; diagnosing or monitoring a medical condition; mendelian disorders; genetic mosaicism; pathogen screening; microbiome profiling; and organ transplant monitoring; has yet to be realized. To date, existing molecular diagnostics approaches lack efficient solutions to clone and amplify individual DNA molecules, as well as solutions to efficiently target
25 sequencing to specific genomic loci, with sensitivity sufficient to discriminate true positive test results from false positive signals that arise during sample processing.

BRIEF SUMMARY

The invention relates generally to compositions and methods for improved compositions and methods for the genetic analysis of cfDNA.

In various embodiments, a method for genetic analysis of cell-free DNA (cfDNA) is provided, comprising: treating cfDNA with one or more end-repair enzymes to generate end-repaired cfDNA; ligating one or more adaptors to each end of the end-repaired cfDNA to generate a cfDNA library; amplifying the cfDNA library to generate
5 cfDNA library clones; determining the number of genome equivalents in the cfDNA clone library; and performing a quantitative genetic analysis of one or more target genetic loci in the cfDNA library clones.

In a particular embodiment, the method further comprises isolating cfDNA from a biological sample of a subject.

10 In an additional embodiment, the cfDNA is isolated from a biological sample selected from the group consisting of: amniotic fluid, blood, plasma, serum, semen, lymphatic fluid, cerebral spinal fluid, ocular fluid, urine, saliva, stool, mucous, and sweat.

In a certain embodiment, the one or more adaptors comprise a plurality of
15 adaptor species.

In a particular embodiment, the one or more adaptors each comprise a primer binding site for amplification of the cfDNA library.

In a further embodiment, the one or more adaptors each comprise one or more unique read codes.

20 In an additional embodiment, the one or more adaptors each comprise one or more sample codes for sample multiplexing.

In another embodiment, the one or more adaptors each comprise one or more sequences for DNA sequencing.

In a particular embodiment, qPCR is performed on the cfDNA clone library and
25 a qPCR measurement is compared to standards of known genome equivalents to determine the genome equivalents of the cfDNA clone library.

In another particular embodiment, qPCR is performed with a primer that binds to an Alu sequence and a primer that binds to a sequence in an adaptor.

In a certain embodiment, the quantitative genetic analysis is performed on a
30 plurality of genetic loci in the cfDNA library clones.

In a further embodiment, the quantitative genetic analysis is performed on a plurality of genetic loci in a plurality of cfDNA clone libraries.

In an additional embodiment, the quantitative genetic analysis comprises hybridizing one or more capture probes to a target genetic locus to form capture probe-
5 cfDNA clone complexes.

In a particular embodiment, the quantitative genetic analysis comprises isolating the capture probe-cfDNA clone complexes.

In a certain embodiment, the quantitative genetic analysis comprises amplification of the cfDNA clone sequence in the isolated hybridized capture probe-
10 cfDNA clone complexes.

In a further embodiment, the quantitative genetic analysis comprises DNA sequencing to generate a plurality of sequencing reads.

In another embodiment, the quantitative genetic analysis comprises bioinformatic analysis of the plurality of sequencing reads.

15 In a particular embodiment, bioinformatics analysis is used: to quantify the number of genome equivalents analyzed in the cfDNA clone library; to detect genetic variants in a target genetic locus; to detect mutations within a target genetic locus; to detect genetic fusions within a target genetic locus; and to measure copy number fluctuations within a target genetic locus.

20 In an additional embodiment, the subject does not have a genetic disease.

In a certain embodiment, the subject has not been diagnosed with a genetic disease.

In another certain embodiment, the subject has been diagnosed with a genetic disease.

25 In another embodiment, the quantitative genetic analysis is used to identify or detect one or more genetic lesions that cause or associated with the genetic disease.

In a certain embodiment, the genetic lesion comprises a nucleotide transition or transversion, a nucleotide insertion or deletion, a genomic rearrangement, a change in copy number, or a gene fusion.

30 In a particular embodiment, the genetic lesion comprises a genomic rearrangement that fuses the 3' coding region of the ALK gene to another gene.

In a particular embodiment, the 3' coding region of the ALK gene is fused to the EML4 gene.

In another embodiment, the genetic disease is cancer.

In a further embodiment, the subject is pregnant.

5 In an additional embodiment, the quantitative genetic analysis is used to identify or detect one or more genetic variants or genetic lesions of one or more target genetic loci in fetal cfDNA.

In a particular embodiment, the subject is a transplant recipient.

In an additional embodiment, the quantitative genetic analysis is used to identify
10 or detect donor cfDNA in the subject.

In various embodiments, a method of predicting, diagnosing, or monitoring a genetic disease in a subject is provided, comprising: isolating or obtaining cfDNA from a biological sample of a subject; treating the cfDNA with one or more end-repair enzymes to generate end-repaired cfDNA; ligating one or more adaptors to each end of
15 the end-repaired cfDNA to generate a cfDNA library; amplifying the cfDNA library to generate a cfDNA clone library; determining the number of genome equivalents in the cfDNA clone library; and performing a quantitative genetic analysis of one or more target genetic loci associated with the genetic disease in the cfDNA clone library, wherein the identification or detection of one or more genetic lesions in the one or more
20 target genetic loci is prognostic for, diagnostic of, or monitors the progression of the genetic disease.

In an additional embodiment, the cfDNA is isolated from a biological sample selected from the group consisting of: amniotic fluid, blood, plasma, serum, semen, lymphatic fluid, cerebral spinal fluid, ocular fluid, urine, saliva, stool, mucous, and
25 sweat.

In a certain embodiment, the genetic lesion comprises a nucleotide transition or transversion, a nucleotide insertion or deletion, a genomic rearrangement, a change in copy number, or a gene fusion.

In a particular embodiment, the genetic lesion comprises a genomic
30 rearrangement that fuses the 3' coding region of the ALK gene to another gene.

In a further embodiment, the 3' coding region of the ALK gene is fused to the EML4 gene.

In a particular embodiment, the genetic disease is cancer.

In various embodiments, a companion diagnostic for a genetic disease is provided comprising: isolating or obtaining cfDNA from a biological sample of a subject; treating the cfDNA with one or more end-repair enzymes to generate end-repaired cfDNA; ligating one or more adaptors to each end of the end-repaired cfDNA to generate a cfDNA library; amplifying the cfDNA library to generate a cfDNA clone library; determining the number of genome equivalents in the cfDNA clone library; and performing a quantitative genetic analysis of one or more biomarkers associated with the genetic disease in the cfDNA clone library, wherein detection of, or failure to detect, at least one of the one or more biomarkers indicates whether the subject should be treated for the genetic disease.

In a particular embodiment, the cfDNA is isolated from a biological sample selected from the group consisting of: amniotic fluid, blood, plasma, serum, semen, lymphatic fluid, cerebral spinal fluid, ocular fluid, urine, saliva, stool, mucous, and sweat.

In an additional embodiment, the biomarker is a genetic lesion.

In a particular embodiment, the genetic lesion comprises a nucleotide transition or transversion, a nucleotide insertion or deletion, a genomic rearrangement, a change in copy number, or a gene fusion.

In an additional embodiment, the genetic lesion comprises a genomic rearrangement that fuses the 3' coding region of the ALK gene to another gene.

In a further embodiment, the 3' coding region of the ALK gene is fused to the EML4 gene.

In a certain embodiment, the genetic disease is cancer.

BRIEF DESCRIPTION OF THE SEVERAL VIEWS OF THE DRAWINGS

Figure 1 shows the expected versus observed variant frequencies as a function of admix dilution in the absence of unique read filtering. In the absence of unique read filtering, random base changes at these four selected positions occurred with

measurable, non-zero frequencies; thus, demonstrating a lack of sensitivity to detect the particular single nucleotide variants (SNV).

Figure 2 shows that unique read filtering performed on the data generated in Figure 1. The left hand panel shows the data from Figure 1 on the BRAF I326T SNV without unique read filtering. The right hand panel shows that using unique read filtering of the same data increased the assay sensitivity and allowed the discrimination of true signal from error-prone noise.

Figure 3 shows capture probe performance as a function of length and wash temperature. The y-axis shows the total number of reads associated with each capture probe. The bars in the bar chart are broken into two categories, where open bars correspond to on-target reads that align to the intended capture probe targets and solid bars show off-target reads that are associated with a capture probe but that map to unintended regions of the genome. Overall, the 40-mer and 60-mer capture probes perform substantially the same with 44° C and 47° C washes. With the 50° C wash, the 40-mer capture probes perform erratically. These data validate the use of 40-mer capture probes at wash temperatures in the range of about 44° C to about 47° C.

Figure 4 shows a schematic for the targeted and oriented sequencing of intron 19 of the ALK gene. A) In the “wild-type” reference sequence, antisense-oriented ALK capture probes identify sequences from intron 19. B) In the case of pathogenic fusion genes, some ALK capture probes will identify junction sequences associated with the gene fusion event.

Figure 5 shows a schematic for high density capture probe placement for complete sequencing of target regions. Each capture probe captures a collection of sequences that provide cumulative coverage at each base position. Here, coverage is represented by a line, and the amplitude of the line denotes depth of coverage derived from a particular capture probe. Overlapping coverage from adjacent capture probes provides complete sequencing of target regions in both possible directions. In addition, the head-to-head placement of opposite strand capture probes ensures that all capture probe binding sites are sequenced.

Figure 6 shows a representative example of the size distribution of fragmented DNA used in library construction.

Figure 7 shows the performance of high-density 40-mer capture probes in a representative experiment. The y-axis shows the total number of reads, which are broken out as on-target reads, off-target reads, and unmappable reads. The x-axis enumerates each of the 105 capture probes used in this experiment for sequence
5 capture.

Figure 8 shows a representative example of the cumulative coverage of a target region using high density 40-mer capture probes. Shown here is the cumulative coverage of TP53 coding exons.

Figure 9A shows a representative example of the size distribution of cell-free
10 DNA (cfDNA) libraries. The dominant band is consistent with a collection of 170 ± 10 bp fragments ligated to 90 bp of adaptors. **Figure 9B** shows a published gel image of cfDNA and a representative cfDNA library generated using the methods disclosed and/or contemplated herein. The qualitative “ladder” appearance is conserved in the library, but the library is shifted to higher mass by the addition of 90 bp of adaptor
15 sequences. **Figure 9C** shows a representative example of genomic, plasma-derived cfDNA libraries from Ovarian cancer patients (OvC) and “healthy donors” (HD).

Figure 10 shows the unique read counts across eight cfDNA libraries derived from four plasma samples. Fragmentation (frag) prior to library construction with this sample 23407 increased the library yield by more than two-fold.

Figure 11 shows the representative read coverage of cfDNA across a region of the TP53 gene. Twenty four 131 bp reads captured by the
20 “TP53_NM_000546_chr17:7579351:region_3:280nt:41:80:r” capture probe (SEQ ID NO:201) were chosen at random and aligned using the BLAT algorithm within the UCSC genome browser. Twenty one reads map to the target region, and they do so in a
25 pattern of overlapping coverage. The probe used to capture these reads is marked with an arrow.

Figure 12 shows an overview of targeted DNA sequencing of the coding regions of the TP53 gene from a cfDNA genomic library. The coverage (horizontal axis) extends across all 10 coding regions and includes intronic regions involved in
30 mRNA splicing. The sequencing depth (vertical axis) reaches a maximum of 4851 and is uniform across all coding exons.

Figure 13 shows a plot of unique read counts versus qPCR estimated genome equivalents in an ACA2-based assay. qPCR measurements are shown on the X-axis versus read counts on the Y-axis. Perfect agreement between these measurements is shown as the diagonal. There is very poor, if any, correlation between measurements, especially at lower genomic inputs. These data show that the ACA2-based qPCR assay chronically underestimates library complexity and is inadequate for measuring genome equivalents.

Figure 14 shows a schematic of the core elements of a qPCR genome equivalent measurement assay that couples an genomic repeat specific primer (*e.g.*, Alu) and a long adaptor-specific primer. (A) Standard library amplification using a single, 25 nt primer named ACA2 (primer 1). (B) Longer, 58 nt versions of the ACA2 primer (primer 2) do not amplify genomic libraries because of stem-loop suppression. (C) Forward and reverse primers directed to a consensus human Alu repeat element (primers 3 and 4) recognize 1000's of loci and readily amplify genomic DNA. (D) A single Alu primer alone, either forward or reverse (primer 3 or primer 4), coupled with the long ACA2 primer (primer 2) do not amplify genomic DNA. (E) The same primer pair as in (D) readily amplifies genomic cfDNA library clones that contain Alu sequences.

Figure 15 shows proof-of-concept data for an Alu plus adaptor-based qPCR assay of genome equivalents. (A) Amplification of 10 pg of a standard genomic library with various PCR primers. The x-axis specifies PCR primers used for amplification and the Y-axis (log scale) indicates the PCR signal measured in units of fg/ μ L. The standard ACA2 primer produced a strong signal, as expected. The ACA2 long primer failed to produce signal owing to PCR suppression. The two Alu primer pairs both produced signal at 1% the amount of ACA2, suggesting that 1% of clones possess an amplifiable Alu sequence. The combination of any Alu primer with the long ACA2 primer also produced signal in ~1% of clones. (B) Validation against 10 pg of genomic DNA (left four samples) or 10 pg of library DNA (right four clones). Alu primer pairs amplify comparable signal from genomic DNA or a genomic library. In contrast, primer pairs consisting of an Alu primer and a long ACA2 primer amplify

genomic DNA poorly (L+A1F) or not at all (L+A1R). These same pairs exhibit amplification of library that slightly exceeds the signal from Alu primer pairs.

Figure 16 shows a direct comparison of ACA2 primer qPCR assay with the Alu-ACA2 long-primer qPCR assay. The Alu ACA2 long-primer qPCR assay shows
5 an 8-fold increase in detectable genome equivalents, which is more consistent with unique read counts derived from sequencing data.

Figure 17 shows a representative example of adaptor structure and function for high sensitivity, quantitative genetic assays that provide accurate determinations of genome equivalents analyzed. (A) Fine structure of the adaptor ligation strand. Details
10 relating to each numbered element are provided in Example 4. (B) The duplex formed between 45 nt ligation strands and 12 nt partner oligo strand creates a blunt-end ligation substrate compatible with end-repaired cfDNA fragments (solid bars). (C) Following ligation, the complement to the ligation strand is created by a DNA polymerase-mediated fill-in reaction.

15 **Figure 18** shows a representative example of the size distribution of two DNA samples (NA06994 & NCI-H2228) processed to mimic cfDNA.

Figure 19 shows a representative example of the sensitivity of detection of the TP53 point mutation Q331* in tumor sample DNA (H2228) admixed with normal
20 genomic DNA (N). The most sensitive detection corresponds to ~ 1 mutant copy of TP53 among 1000 normal copies of the gene.

Figure 20 shows the precise determination of the junction sequence for the EML4-ALK fusion gene harbored in cell line NCI-H2228 using the compositions and methods contemplated herein.

Figure 21 shows the detection of the EML4-ALK fusion gene tumor sample
25 DNA (H2228) admixed with normal genomic DNA (N). Because the fusion is present as a heterozygote in the NCI-H2228 cell line, the most sensitive detection corresponds to one gene fusion among ~100 normal chromosomal copies of the ALK gene (50 genome equivalents).

Figure 22 shows the detection of the MYCN gene amplification in admixtures
30 of cell line NCI-H69 (H69) diluted into normal human DNA (N). The threshold value of two normal diploid copies is shown as a dashed red line.

Figure 23 shows the DNA mutations detected in the TP53 gene of three different cancer patients. The canonical gene model is shown at the top of the figure. The peaks represent DNA sequence coverage (X-axis) and depth (Y-axis). Sequencing depth was >4000 genome equivalents for all sample analyzed. An expanded view of
 5 exon 7 below the gene model shows where all detected mutations were localized. The frequency of mutant detection in cfDNA (plasma), tumor tissue, and normal adjacent tissue is shown, where available (NA – not available). OVA1 and OVA2 are ovarian cancer patients; CRC406 and CRC407 are colorectal cancer patients. No mutations in TP53 were found in any of the OVA1 samples.

10 **Figure 24** shows the DNA sequencing of a larger, thirteen gene panel (boxed). The sequencing identified a KRAS mutation in cfDNA and tumor from ovarian cancer patient OVA1.

Figure 25 shows the DNA sequencing of a larger, twelve gene panel. The sequencing identified an ERBB2 gene amplification in the plasma of colorectal cancer
 15 patient CRC407.

DETAILED DESCRIPTION

A. OVERVIEW

The present invention contemplates, in part, compositions and methods for the quantitative genetic analysis of the genetic state of an individual using cell-free DNA
 20 (cfDNA). As used herein, the term “genetic state” refers to the sequence of one or more target genome sequences in the genome in relation to a non-causal normal sequence or in relation to a sequence that is causal for a genetic condition or disease. In one embodiment, analyzing the genetic state refers to identifying, quantifying, or monitoring a genetic variant in a target genetic locus, wherein the variant varies with
 25 respect to a reference sequence (*e.g.*, a normal or mutated sequence). The present inventors have provided solutions to the molecular diagnostic problems of genetic conditions or diseases associated with lack of sensitivity to discriminate true positives from false positives, inefficient cloning and amplification of individual DNA molecules, and inefficient targeted sequencing to specific genomic loci. The solutions

contemplated herein comprise compositions and methods for reliable and robust quantitative genetic analysis with sensitivity sufficient to discriminate true positive test results from false positive signals that arise during sample processing.

Next-generation sequencing technology has afforded the opportunity to add
5 broad genomic surveys to molecular diagnosis in a variety of scenarios including cancers, fetal diagnostics, paternity testing, pathogen screening and organ transplant monitoring. In the context of genetic diseases, next-generation sequencing information is being used in a clinical setting to identify mutations within genes that are likely to alter gene function, to identify the gain or loss of genetic material within cells, and to
10 identify genomic rearrangements that are not found in normal, healthy cells. The results of these broad diagnostic surveys are often used to guide patient treatment.

However, the potential benefits of DNA sequencing in diagnosis and treatment of the genetic state of an individual or genetic conditions or diseases is outweighed by the need to directly access affected tissues to obtain samples. Such material is often
15 difficult to obtain from the initial biopsy used to diagnose the disease and virtually impossible to obtain in multiple repetitions over time. Similarly, in cancer patients, biopsies are not possible in patients with inaccessible tumors and not practical in individuals suffering from metastatic disease. In contrast, the present inventors' approach derives from the fact that all tissues require access to the vasculature to
20 survive and as a consequence these masses deposit DNA into bodily fluids. One major depot of bodily fluid in which the DNA of diseased cells is found is the plasma of human blood.

In contrast to testing methods that rely on shallow, genome-wide sequence coverage, molecular diagnostics contemplated herein for the genetic state of an
25 individual; genetic diseases; mendelian disorders; genetic mosaicism; fetal testing; paternity testing; predicting response to drug treatment; diagnosing or monitoring a medical condition; pathogen screening; microbiome profiling; and organ transplant monitoring leverage the availability of cfDNA to provide deep sequence coverage of select target genes. In addition, the cfDNA-based cancer diagnostics contemplated
30 herein possess the ability to detect a variety of genetic changes including somatic sequence variations that alter protein function, large-scale chromosomal rearrangements

that create chimeric gene fusions, and copy number variation that includes loss or gain of gene copies. Using the contemplated compositions and methods, these changes are detectable and quantifiable in the face of significant dilution, or admixture, of normal sequences within cfDNA that are contributed by the normal turnover processes that
5 happen within healthy tissues. The compositions and methods contemplated herein also successfully address the major challenges associated with detecting rare genetic changes causal of disease; namely, that cfDNA is highly fragmented, that cfDNA levels vary substantially between different individuals, and that the degree of admixture of diseased versus normal sequences is highly variable among patients, even within
10 individuals suffering from the same molecular disease and stage.

In various embodiments, compositions and methods for genetic analysis of comprise interrogating the DNA fraction within biological fluid samples and stool samples. The methods contemplated herein provide a novel comprehensive framework address molecular genetic analysis using cfDNA available from a variety of biological
15 sources. Cloning of purified cfDNA introduces tagged cfDNA sequences that inform downstream analysis and enable amplification of the resulting clone libraries. Hybrid capture with target specific oligonucleotides is used to retrieve specific sequences for subsequent analysis. Independent measurements of the number of genomes present in the library are applied to each sample, and these assays provide a means to estimate the
20 assay's sensitivity. The assays contemplated herein provide reliable, reproducible, and robust methods for the analysis, detection, diagnosis, or monitoring of genetic states, conditions, or disease.

The practice of particular embodiments of the invention will employ, unless indicated specifically to the contrary, conventional methods of chemistry, biochemistry,
25 organic chemistry, molecular biology, microbiology, recombinant DNA techniques, genetics, immunology, and cell biology that are within the skill of the art, many of which are described below for the purpose of illustration. Such techniques are explained fully in the literature. See, *e.g.*, Sambrook, *et al.*, *Molecular Cloning: A Laboratory Manual* (3rd Edition, 2001); Sambrook, *et al.*, *Molecular Cloning: A Laboratory Manual* (2nd Edition, 1989); Maniatis *et al.*, *Molecular Cloning: A Laboratory Manual* (1982); Ausubel *et al.*, *Current Protocols in Molecular Biology*
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- (John Wiley and Sons, updated July 2008); *Short Protocols in Molecular Biology: A Compendium of Methods from Current Protocols in Molecular Biology*, Greene Pub. Associates and Wiley-Interscience; Glover, *DNA Cloning: A Practical Approach*, vol. I & II (IRL Press, Oxford, 1985); Anand, *Techniques for the Analysis of Complex*
- 5 *Genomes*, (Academic Press, New York, 1992); *Transcription and Translation* (B. Hames & S. Higgins, Eds., 1984); Perbal, *A Practical Guide to Molecular Cloning* (1984); and Harlow and Lane, *Antibodies*, (Cold Spring Harbor Laboratory Press, Cold Spring Harbor, N.Y., 1998).

B. DEFINITIONS

- 10 Unless defined otherwise, all technical and scientific terms used herein have the same meaning as commonly understood by those of ordinary skill in the art to which the invention belongs. Although any methods and materials similar or equivalent to those described herein can be used in the practice or testing of the present invention, preferred embodiments of compositions, methods and materials are described herein.

- 15 For the purposes of the present invention, the following terms are defined below.

The articles “a,” “an,” and “the” are used herein to refer to one or to more than one (*i.e.* to at least one) of the grammatical object of the article. By way of example, “an element” means one element or more than one element.

- The use of the alternative (*e.g.*, “or”) should be understood to mean either one,
- 20 both, or any combination thereof of the alternatives.

The term “and/or” should be understood to mean either one, or both of the alternatives.

- As used herein, the term “about” or “approximately” refers to a quantity, level, value, number, frequency, percentage, dimension, size, amount, weight or length that
- 25 varies by as much as 15%, 10%, 9%, 8%, 7%, 6%, 5%, 4%, 3%, 2% or 1% to a reference quantity, level, value, number, frequency, percentage, dimension, size, amount, weight or length. In one embodiment, the term “about” or “approximately” refers a range of quantity, level, value, number, frequency, percentage, dimension, size, amount, weight or length $\pm 15\%$, $\pm 10\%$, $\pm 9\%$, $\pm 8\%$, $\pm 7\%$, $\pm 6\%$, $\pm 5\%$, $\pm 4\%$, $\pm 3\%$,

± 2%, or ± 1% about a reference quantity, level, value, number, frequency, percentage, dimension, size, amount, weight or length.

Throughout this specification, unless the context requires otherwise, the words “comprise”, “comprises” and “comprising” will be understood to imply the inclusion of
5 a stated step or element or group of steps or elements but not the exclusion of any other step or element or group of steps or elements. In particular embodiments, the terms “include,” “has,” “contains,” and “comprise” are used synonymously.

By “consisting of” is meant including, and limited to, whatever follows the phrase “consisting of.” Thus, the phrase “consisting of” indicates that the listed
10 elements are required or mandatory, and that no other elements may be present.

By “consisting essentially of” is meant including any elements listed after the phrase, and limited to other elements that do not interfere with or contribute to the activity or action specified in the disclosure for the listed elements. Thus, the phrase “consisting essentially of” indicates that the listed elements are required or mandatory,
15 but that no other elements are optional and may or may not be present depending upon whether or not they affect the activity or action of the listed elements.

Reference throughout this specification to “one embodiment,” “an embodiment,” “a particular embodiment,” “a related embodiment,” “a certain embodiment,” “an additional embodiment,” or “a further embodiment” or combinations
20 thereof means that a particular feature, structure or characteristic described in connection with the embodiment is included in at least one embodiment of the present invention. Thus, the appearances of the foregoing phrases in various places throughout this specification are not necessarily all referring to the same embodiment. Furthermore, the particular features, structures, or characteristics may be combined in
25 any suitable manner in one or more embodiments.

As used herein, the term “isolated” means material that is substantially or essentially free from components that normally accompany it in its native state. In particular embodiments, the term “obtained” or “derived” is used synonymously with isolated.

30 As used herein, the term “DNA” refers to deoxyribonucleic acid. In various embodiments, the term DNA refers to genomic DNA, recombinant DNA, synthetic

DNA, or cDNA. In one embodiment, DNA refers to genomic DNA or cDNA. In particular embodiments, the DNA comprises a “target region.” DNA libraries contemplated herein include genomic DNA libraries and cDNA libraries constructed from RNA, *e.g.*, an RNA expression library. In various embodiments, the DNA
5 libraries comprise one or more additional DNA sequences and/or tags.

A “target genetic locus” or “DNA target region” refers to a region of interest within a DNA sequence. In various embodiments, targeted genetic analyses are performed on the target genetic locus. In particular embodiments, the DNA target region is a region of a gene that is associated with a particular genetic state, genetic
10 condition, genetic diseases; fetal testing; genetic mosaicism, paternity testing; predicting response to drug treatment; diagnosing or monitoring a medical condition; microbiome profiling; pathogen screening; or organ transplant monitoring.

As used herein, the terms “circulating DNA,” “circulating cell-free DNA” and “cell-free DNA” are often used interchangeably and refer to DNA that is extracellular
15 DNA, DNA that has been extruded from cells, or DNA that has been released from necrotic or apoptotic cells.

A “subject,” “individual,” or “patient” as used herein, includes any animal that exhibits a symptom of a condition that can be detected or identified with compositions contemplated herein. Suitable subjects include laboratory animals (such as mouse, rat, rabbit, or guinea pig), farm animals (such as horses, cows, sheep, pigs), and domestic
20 animals or pets (such as a cat or dog). In particular embodiments, the subject is a mammal. In certain embodiments, the subject is a non-human primate and, in preferred embodiments, the subject is a human.

C. METHODS OF GENETIC ANALYSIS OF CELL FREE DNA

25 In various embodiments, a method for genetic analysis of cfDNA is provided.

In particular embodiments, a method for genetic analysis of cfDNA comprises: generating and amplifying a cfDNA library, determining the number of genome equivalents in the cfDNA library; and performing a quantitative genetic analysis of one or more genomic target loci.

A method for genetic analysis of cfDNA comprises treating cfDNA with one or more end-repair enzymes to generate end-repaired cfDNA and ligating one or more adaptors to each end of the end-repaired cfDNA to generate a cfDNA library; amplifying the cfDNA library to generate cfDNA library clones; determining the
5 number of genome equivalents of cfDNA library clones; and performing a quantitative genetic analysis of one or more target genetic loci in the cfDNA library clones.

1. GENERATING A CFDNA LIBRARY

In particular embodiments, methods of genetic analysis contemplated herein comprise generating a cfDNA library comprising treating cfDNA with one or more end-
10 repair enzymes to generate end-repaired cfDNA and ligating one or more adaptors to each end of the end-repaired cfDNA to generate the cfDNA library.

(a) Cell-Free DNA (cfDNA)

The methods and compositions contemplated herein are designed to efficiently analyze, detect, diagnose, and/or monitor genetic states, genetic conditions, genetic
15 diseases, genetic mosaicism, fetal diagnostics, paternity testing, microbiome profiling, pathogen screening, and organ transplant monitoring using cell-free DNA (cfDNA) as an analyte. The size distribution of cfDNA ranges from about 150 bp to about 180 bp fragments. Fragmentation may be the result of endonucleolytic and/or exonucleolytic activity and presents a formidable challenge to the accurate, reliable, and robust
20 analysis of cfDNA. Another challenge for analyzing cfDNA is its short half-life in the blood stream, on the order of about 15 minutes. Without wishing to be bound to any particular theory, the present invention contemplates, in part, that analysis of cfDNA is like a “liquid biopsy” and is a real-time snapshot of current biological processes.

Moreover, because cfDNA is not found within cells and may be obtained from a
25 number of suitable sources including, but not limited to, biological fluids and stool samples, it is not subject to the existing limitations that plague next generation sequencing analysis, such as direct access to the tissues being analyzed. .

Illustrative examples of biological fluids that are suitable sources from which to isolate cfDNA in particular embodiments include, but are not limited to amniotic fluid,

blood, plasma, serum, semen, lymphatic fluid, cerebral spinal fluid, ocular fluid, urine, saliva, mucous, and sweat.

In particular embodiments, the biological fluid is blood or blood plasma.

In certain embodiments, commercially available kits and other methods known
 5 to the skilled artisan can be used to isolate cfDNA directly from the biological fluids of a patient or from a previously obtained and optionally stabilized biological sample, *e.g.*, by freezing and/or addition of enzyme chelating agents including, but not limited to EDTA, EGTA, or other chelating agents specific for divalent cations.

(b) Generating End-Repaired cfDNA

10 In particular embodiments, generating a cfDNA library comprises the end-repair of isolated cfDNA. The fragmented cfDNA is processed by end-repair enzymes to generate end-repaired cfDNA with blunt ends, 5'-overhangs, or 3'-overhangs. In some embodiments, the end-repair enzymes can yield for example. In some embodiments, the end-repaired cfDNA contains blunt ends. In some embodiments, the end-repaired
 15 cfDNA is processed to contain blunt ends. In some embodiments, the blunt ends of the end-repaired cfDNA are further modified to contain a single base pair overhang. In some embodiments, end-repaired cfDNA containing blunt ends can be further processed to contain adenine (A)/thymine (T) overhang. In some embodiments, end-repaired cfDNA containing blunt ends can be further processed to contain adenine
 20 (A)/thymine (T) overhang as the single base pair overhang. In some embodiments, the end-repaired cfDNA has non-templated 3' overhangs. In some embodiments, the end-repaired cfDNA is processed to contain 3' overhangs. In some embodiments, the end-repaired cfDNA is processed with terminal transferase (TdT) to contain 3' overhangs. In some embodiments, a G-tail can be added by TdT. In some embodiments, the end-
 25 repaired cfDNA is processed to contain overhang ends using partial digestion with any known restriction enzymes (*e.g.*, with the enzyme Sau3A, and the like).

(c) Ligating Adaptor Molecules to End-Repaired cfDNA

In particular embodiments, generating a cfDNA library comprises ligating one or more adaptors to each end of the end-repaired cfDNA. The present invention
 30 contemplates, in part, an adaptor module designed to accommodate large numbers of genome equivalents in cfDNA libraries. Adaptor modules are configured to measure

the number of genome equivalents present in cfDNA libraries, and, by extension, the sensitivity of sequencing assays used to identify sequence mutations.

As used herein, the term “adaptor module” refers to a polynucleotide comprising at least five elements: (i) a first element comprising a PCR primer binding site for the
5 single-primer library amplification; (ii) a second element comprising a 5 nucleotide read code that acts to uniquely identified each sequencing read; (iii) a third element comprising a 3 nucleotide sample code to identify different samples and enable sample multiplexing within a sequencing run; (iv) a fourth element comprising a 12 nucleotide anchor sequence that enables calibration of proper base calls in sequencing reads and
10 acts as an anchor for hybridization to a partner oligonucleotide; and (v) a fifth element comprising the two 3' terminal nucleotides of Element 4 (Figure 17 and Tables 12-16). The adaptor module is hybridized to a partner oligonucleotide that is complementary to Element 4 to form an adaptor suitable for ligating to the ends of cfDNA, optionally end-repaired blunt-ended cfDNA.

15 In particular embodiments, an adaptor module comprises one or more PCR primer sequences, one or more read codes, one or more sample codes, one or more anchor sequences, and two or more 3' nucleotides that are efficient ligation substrates. In additional embodiments, the adaptor module further comprises one or more sequencing primer binding sites.

20 In particular embodiments, an adaptor module comprises a first element that comprises one or more PCR primer binding sequences for single-primer amplification of a cfDNA library. In one embodiment, the PCR primer binding sequence is about 12 to about 40 nucleotides, about 18 to about 40 nucleotides, about 20 to about 35 nucleotides, or about 20 to about 30 nucleotides. In another embodiment, the PCR
25 primer binding sequence is about 12 nucleotides, about 13 nucleotides, about 14 nucleotides, about 15 nucleotides, about 16 nucleotides, about 17 nucleotides, about 18 nucleotides, about 19 nucleotides, about 20 nucleotides, about 21 nucleotides, about 22 nucleotides, about 23 nucleotides, about 24 nucleotides, about 25 nucleotides, about 26 nucleotides, about 27 nucleotides, about 28 nucleotides, about 29 nucleotides, about 30
30 nucleotides, about 31 nucleotides, about 32 nucleotides, about 33 nucleotides, about 34

nucleotides, about 35 nucleotides, about 36 nucleotides, about 37 nucleotides, about 38 nucleotides, about 39 nucleotides, or about 40 nucleotides or more.

In one embodiment, the PCR primer binding sequence is about 25 nucleotides.

In particular embodiments, an adaptor module comprises a second element that
5 comprises one or more read code sequences. As used herein, the term “read code”
refers to a polynucleotide that is used to identify unique sequencing reads. In one
embodiment, the read code is a random sequence of nucleotides. In one embodiment,
the read code is about 1 nucleotide, about 2 nucleotides, about 3 nucleotides, about 4
nucleotides, about 5 nucleotides, about 6 nucleotides, about 7 nucleotides, about 8
10 nucleotides, about 9 nucleotides, about 10 nucleotides, or more.

By way of a non-limiting example, a 5 nucleotide codes consists of 256 possible
unique sequences where each code chosen is 2 nucleotides different from every other
code in the set. This feature enables unique and distinct reads to be differentiated from
reads that appear to be unique owing to a sequencing error in the code region. In
15 particular embodiments, codes that have been empirically determined to interfere with
adaptor function, owing to particular sequence combinations, may be excluded from
use, *e.g.*, seven codes of the 256 had an overrepresentation of G nucleotides and were
excluded.

In other embodiments, each read code of 5, 6, 7, 8, 9, 10 or more nucleotides
20 may differ by 2, 3, 4, or 5 nucleotides from every other read code.

In one embodiment, the read code is about 5 nucleotides and differs from every
other read code by 2 nucleotides.

In particular embodiments, an adaptor module comprises a third element that
comprises one or more sample code sequences. As used herein, the term “sample code”
25 refers to a polynucleotide that is used to identify the sample. The sample code is also
useful in establishing multiplex sequencing reactions because each sample code is
unique to the sample and thus, can be used to identify a read from a particular sample
within a multiplexed sequencing reaction.

In one embodiment, the sample code comprises sequence that is about 1, about 2
30 nucleotides, about 3 nucleotides, about 4 nucleotides, or about 5 nucleotides, or more.

In another embodiment, each sample code of 2, 3, 4, 5 or more nucleotides may differ from every other sample code by 2, 3, 4, or 5 nucleotides.

In one embodiment, the sample code is about three nucleotides and differs from every other sample code used in other samples by two nucleotides.

5 In particular embodiments, an adaptor module comprises a fourth element that comprises one or more anchor sequences. As used herein, an “anchor sequence” refers to a nucleotide sequence of at least 8 nucleotides, at least 10 nucleotides, at least 12 nucleotides, at least 14 nucleotides, or at least 16 nucleotides that hybridizes to a partner oligonucleotide and that comprises the following three properties: (1) each anchor
10 sequence is part of a family of four anchor sequences that collectively represent each of the four possible DNA bases at each site within extension; this feature, balanced base representation, is useful to calibrate proper base calling in sequencing reads in particular embodiments; (2) each anchor sequence is composed of only two of four possible bases, and these are specifically chosen to be either an equal number of A + C
15 or an equal number of G + T; an anchor sequence formed from only two bases reduces the possibility that the anchor sequence will participate in secondary structure formation that would preclude proper adaptor function; and (3) because each anchor sequence is composed of equal numbers of A+C or G+T, each anchor sequence shares roughly the same melting temperature and duplex stability as every other anchor sequence in a set
20 of four.

In particular embodiments, an adaptor module comprises a fifth element that is comprised of the two 3' terminal nucleotides of Element 4. These two bases at the 3' end of each anchor are chosen based on an empirical determination that shows that these two nucleotides are efficient substrates for ligation to the cfDNA. In particular
25 embodiments, Element 5 comprises the sequences selected from the group consisting of: AA, CC, TT and GG. In particular embodiments, Element 5 does not comprise the dinucleotide combination CG or TG as the inventors have determined that these combinations are not efficient ligation substrates.

In particular embodiments, a ligation step comprises ligating an adaptor module
30 to the end-repaired cfDNA to generate a “tagged” cfDNA library. In some embodiments, a single adaptor module is employed. In some embodiments, two, three,

four or five adaptor modules are employed. In some embodiments, an adaptor module of identical sequence is ligated to each end of the fragmented end-repaired DNA.

In one embodiment, a plurality of adaptor species is ligated to an end-repaired cfDNA library. Each of the plurality of adaptors may comprise one or more primer
5 binding site for amplification of the cfDNA library, one or more read code sequences, one or more sequences for sample multiplexing, and one or more sequences for DNA sequencing.

Ligation of one or more adaptors contemplated herein may be carried out by methods known to those of ordinary skill in the art. In particular embodiments, one or
10 more adaptors contemplated herein are ligated to end-repaired cfDNA that comprises blunt ends. In certain embodiments, one or more adaptors contemplated herein are ligated to end-repaired cfDNA that comprises complementary ends appropriate for the ligation method employed. In certain embodiments, one or more adaptors contemplated herein are ligated to end-repaired cfDNA that comprises a 3' overhang.

15 **2. cfdNA LIBRARY AMPLIFICATION**

In particular embodiments, methods of genetic analysis contemplated herein comprise amplification of a cfDNA library to generate a cfDNA clone library or a library of cfDNA clones. Each molecule of the cfDNA library comprises an adaptor ligated to each end of an end-repaired cfDNA, and each adaptor comprises one or more
20 PCR primer binding sites. In one embodiment, different adaptors are ligated to different ends of the end-repaired cfDNA.

In a preferred embodiment, the same adaptor is ligated to both ends of the cfDNA. Ligation of the same adaptor to both ends of end-repaired cfDNA allows for PCR amplification with a single primer sequence. In particular embodiments, a portion
25 of the adaptor ligated-cfDNA library will be amplified using standard PCR techniques with a single primer sequence driving amplification. In one embodiment, the single primer sequence is about 25 nucleotides, optionally with a projected T_m of $\geq 55^\circ \text{C}$ under standard ionic strength conditions.

In particular embodiments, picograms of the initial cfDNA library are amplified
30 into micrograms of cfDNA clones, implying a 10,000-fold amplification. The amount

of amplified product can be measured using methods known in the art, *e.g.*, quantification on a Qubit 2.0 or Nanodrop instrument.

3. DETERMINING THE NUMBER OF GENOME EQUIVALENTS

In various embodiments, a method for genetic analysis of cfDNA comprises
5 determining the number of genome equivalents in the cfDNA clone library. As used herein, the term “genome equivalent” refers to the number of genome copies in each library. An important challenge met by the compositions and methods contemplated herein is achieving sufficient assay sensitivity to detect and analysis rare genetic mutations or differences in genetic sequence. To determine assay sensitivity value on a
10 sample-by-sample basis, the numbers of different and distinct sequences that are present in each sample are measured, by measuring the number of genome equivalents that are present in a sequencing library. To establish sensitivity, the number of genome equivalents must be measured for each sample library.

The number of genome equivalents can be determined by qPCR assay or by
15 using bioinformatics-based counting after sequencing is performed. In the process flow of clinical samples, qPCR measurement of genome equivalents is used as a QC step for cfDNA libraries. It establishes an expectation for assay sensitivity prior to sequence analysis and allows a sample to be excluded from analysis if its corresponding cfDNA clone library lacks the required depth of genome equivalents. Ultimately, the
20 bioinformatics-based counting of genome equivalents is also used to identify the genome equivalents – and hence the assay sensitivity and false negative estimates – for each given cfDNA clone library.

The empirical qPCR assay and statistical counting assays should be well correlated. In cases where sequencing fails to reveal the sequence depth in a cfDNA
25 clone library, reprocessing of the cfDNA clone library and/or additional sequencing may be required.

In one embodiment, the genome equivalents in a cfDNA clone library are determined using a quantitative PCR (qPCR) assay. In a particular embodiment, a standard library of known concentration is used to construct a standard curve and the
30 measurements from the qPCR assay are fit to the resulting standard curve and a value

for genome equivalents is derived from the fit. Surprisingly, the present inventors have discovered that a qPCR “repeat-based” assay comprising one primer that specifically hybridizes to a common sequence in the genome, *e.g.*, a repeat sequence, and another primer that binds to the primer binding site in the adaptor, measured an 8-fold increase
5 in genome equivalents compared to methods using just the adaptor specific primer (present on both ends of the cfDNA clone). The number of genome equivalents measured by the repeat-based assays provides a more consistent library-to-library performance and a better alignment between qPCR estimates of genome equivalents and bioinformatically counted tag equivalents in sequencing runs.

10 Illustrative examples of repeats suitable for use in the repeat-based genome equivalent assays contemplated herein include, but not limited to: short interspersed nuclear elements (SINEs), *e.g.*, Alu repeats; long interspersed nuclear elements (LINEs), *e.g.*, LINE1, LINE2, LINE3; microsatellite repeat elements, *e.g.*, short tandem repeats (STRs), simple sequence repeats (SSRs); and mammalian-wide interspersed
15 repeats (MIRs).

In one embodiment, the repeat is an Alu repeat.

4. QUANTITATIVE GENETIC ANALYSIS

In various embodiments, a method for genetic analysis of cfDNA comprises quantitative genetic analysis of one or more target genetic loci of the cfDNA library
20 clones. Quantitative genetic analysis comprises one or more of, or all of, the following steps: capturing cfDNA clones comprising a target genetic locus; amplification of the captured targeted genetic locus; sequencing of the amplified captured targeted genetic locus; and bioinformatic analysis of the resulting sequence reads.

(a) Capture of Target Genetic Locus

25 The present invention contemplates, in part, a capture probe module designed to retain the efficiency and reliability of larger probes but that minimizes uninformative sequence generation in a cfDNA clone library. A “capture probe module” refers to a polynucleotide that comprises a capture probe sequence and a tail sequence. In particular embodiments, the capture probe module sequence or a portion thereof serves
30 as a primer binding site for one or more sequencing primers.

In particular embodiments, a capture probe module comprises a capture probe. As used herein a “capture probe” refers to a region capable of hybridizing to a specific DNA target region. Because the average size of cfDNA is about 150 to about 170 bp and is highly fragmented the compositions and methods contemplated herein comprise the use of high density and relatively short capture probes to interrogate DNA target regions of interest.

One particular concern with using high density capture probes is that generally capture probes are designed using specific “sequence rules.” For example, regions of redundant sequence or that exhibit extreme base composition biases are generally excluded in designing capture probes. However, the present inventors have discovered that the lack of flexibility in capture probe design rules does not substantially impact probe performance. In contrast, capture probes chosen strictly by positional constraint provided on-target sequence information; exhibit very little off-target and unmappable read capture; and yield uniform, useful, on-target reads with only few exceptions. Moreover, the high redundancy at close probe spacing more than compensates for occasional poor-performing capture probes.

In particular embodiments, a target region is targeted by a plurality of capture probes, wherein any two or more capture probes are designed to bind to the target region within 10 nucleotides of each other, within 15 nucleotides of each other, within 20 nucleotides of each other, within 25 nucleotides of each other, within 30 nucleotides of each other, within 35 nucleotides of each other, within 40 nucleotides of each other, within 45 nucleotides of each other, or within 50 nucleotides or more of each other, as well as all intervening nucleotide lengths.

In one embodiment, the capture probe is about 25 nucleotides, about 26 nucleotides, about 27 nucleotides, about 28 nucleotides, about 29 nucleotides, about 30 nucleotides, about 31 nucleotides, about 32 nucleotides, about 33 nucleotides, about 34 nucleotides, about 35 nucleotides, about 36 nucleotides, about 37 nucleotides, about 38 nucleotides, about 39 nucleotides, about 40 nucleotides, about 41 nucleotides, about 42 nucleotides, about 43 nucleotides, about 44 nucleotides, or about 45 nucleotides.

In one embodiment, the capture probe is about 100 nucleotides, about 200 nucleotides, about 300 nucleotides, about 400 nucleotides, or about 100 nucleotides. In

another embodiment, the capture probe is from about 100 nucleotides to about 500 nucleotides, about 200 nucleotides to about 500 nucleotides, about 300 nucleotides to about 500 nucleotides, or about 400 nucleotides to about 500 nucleotides, or any intervening range thereof.

5 In a particular embodiment, the capture probe is not 60 nucleotides.

 In another embodiment, the capture probe is substantially smaller than 60 nucleotides but hybridizes comparably, as well as, or better than a 60 nucleotide capture probe targeting the same DNA target region.

 In a certain embodiment, the capture probe is 40 nucleotides.

10 In certain embodiments, a capture probe module comprises a tail sequence. As used herein, the term “tail sequence” refers to a polynucleotide at the 5' end of the capture probe module, which in particular embodiments can serve as a primer binding site. In particular embodiments, a sequencing primer binds to the primer binding site in the tail region.

15 In particular embodiments, the tail sequence is about 5 to about 100 nucleotides, about 10 to about 100 nucleotides, about 5 to about 75 nucleotides, about 5 to about 50 nucleotides, about 5 to about 25 nucleotides, or about 5 to about 20 nucleotides. In certain embodiments, the third region is from about 10 to about 50 nucleotides, about 15 to about 40 nucleotides, about 20 to about 30 nucleotides or about 20 nucleotides, or
20 any intervening number of nucleotides.

 In particular embodiments, the tail sequence is about 30 nucleotides, about 31 nucleotides, about 32 nucleotides, about 33 nucleotides, about 34 nucleotides, about 35 nucleotides, about 36 nucleotides, about 37 nucleotides, about 38 nucleotides, about 39 nucleotides, or about 40 nucleotides.

25 In various embodiments, the capture probe module comprises a specific member of a binding pair to enable isolation and/or purification of one or more captured fragments of a tagged and or amplified cfDNA library that hybridizes to the capture probe. In particular embodiments, the capture probe module is conjugate to biotin or another suitable hapten, *e.g.*, dinitrophenol, digoxigenin.

30 In various embodiments, the capture probe module is hybridized to a tagged and optionally amplified cfDNA library to form a complex. In some embodiments, the

multifunctional capture probe module substantially hybridizes to a specific genomic target region in the cfDNA library.

Hybridization or hybridizing conditions can include any reaction conditions where two nucleotide sequences form a stable complex; for example, the tagged cfDNA library and capture probe module forming a stable tagged cfDNA library—capture probe module complex. Such reaction conditions are well known in the art and those of skill in the art will appreciate that such conditions can be modified as appropriate, *e.g.*, decreased annealing temperatures with shorter length capture probes, and within the scope of the present invention. Substantial hybridization can occur when the second region of the capture probe complex exhibits 100%, 99%, 98%, 97%, 96%, 95%, 94%, 93%, 92%, 91%, 90%, 89%, 88%, 85%, 80%, 75%, or 70% sequence identity, homology or complementarity to a region of the tagged cfDNA library.

In particular embodiments, the capture probe is about 40 nucleotides and has an optimal annealing temperature of about 44° C or about 47° C.

In certain embodiments, the methods contemplated herein comprise isolating a tagged cfDNA library—capture probe module complex. In particular embodiments, methods for isolating DNA complexes are well known to those skilled in the art and any methods deemed appropriate by one of skill in the art can be employed with the methods of the present invention (Ausubel *et al.*, *Current Protocols in Molecular Biology*, 2007-2012). In particular embodiments, the complexes are isolated using biotin—streptavidin isolation techniques.

In particular embodiments, removal of the single stranded 3'-ends from the isolated tagged cfDNA library-capture probe module complex is contemplated. In certain embodiments, the methods comprise 3'-5' exonuclease enzymatic processing of the isolated tagged DNA library-multifunctional capture probe module complex to remove the single stranded 3' ends.

In certain other embodiments, the methods comprise performing 5'-3' DNA polymerase extension of multifunctional capture probe utilizing the isolated tagged DNA library fragments as template.

In certain other embodiments, the methods comprise creating a hybrid capture probe-isolated tagged cfDNA target molecule through the concerted action of a 5' FLAP endonuclease, DNA polymerization and nick closure by a DNA ligase.

A variety of enzymes can be employed for the 3'-5' exonuclease enzymatic processing of the isolated tagged cfDNA library-multifunctional capture probe module complex. Illustrative examples of suitable enzymes, which exhibit 3'-5' exonuclease enzymatic activity, that can be employed in particular embodiments include, but are not limited to: T4 or Exonucleases I, III, V (*see also*, Shevelev IV, Hübscher U., "The 3' 5' exonucleases," *Nat Rev Mol Cell Biol.* 3(5):364-76 (2002)). In particular embodiments, the enzyme comprising 3'-5' exonuclease activity is T4 polymerase. In particular embodiments, an enzyme which exhibits 3'-5' exonuclease enzymatic activity and is capable of primer template extension can be employed, including for example T4 or Exonucleases I, III, V. *Id.*

In some embodiments, the methods contemplated herein comprise performing sequencing and/or PCR on the 3'-5' exonuclease enzymatically processed complex discussed *supra* and elsewhere herein. In particular embodiments, a tail portion of a capture probe molecule is copied in order to generate a hybrid nucleic acid molecule. In one embodiment, the hybrid nucleic acid molecule generated comprises the target region capable of hybridizing to the capture probe module and the complement of the capture probe module tail sequence.

In a particular embodiment, genetic analysis comprises a) hybridizing one or more capture probe modules to one or more target genetic loci in a plurality of cfDNA library clones to form one or more capture probe module-cfDNA library clone complexes; b) isolating the one or more capture probe module-cfDNA library clone complexes from a); c) enzymatically processing the one or more isolated capture probe module-cfDNA library clone complexes from step b); d) performing PCR on the enzymatically processed complex from c) wherein the tail portion of the capture probe molecule is copied in order to generate amplified hybrid nucleic acid molecules, wherein the amplified hybrid nucleic acid molecules comprise a target sequence in the target genomic locus capable of hybridizing to the capture probe and the complement of

the capture probe module tail sequence; and e) performing quantitative genetic analysis on the amplified hybrid nucleic acid molecules from d).

In a particular embodiment, methods for determining copy number of a specific target genetic locus are contemplated comprising: a) hybridizing one or more capture
 5 probe modules to one or more target genetic loci in a plurality of cfDNA library clones to form one or more capture probe module-cfDNA library clone complexes; b) isolating the one or more capture probe module-cfDNA library clone complexes from a); c) enzymatically processing the one or more isolated capture probe module-cfDNA library clone complexes from step b); d) performing PCR on the enzymatically processed
 10 complex from c) wherein the tail portion of the capture probe molecule is copied in order to generate amplified hybrid nucleic acid molecules, wherein the amplified hybrid nucleic acid molecules comprise a target sequence in the the target genetic locus capable of hybridizing to the capture probe and the complement of the capture probe module tail sequence; e) performing PCR amplification of the amplified hybrid nucleic
 15 acid molecules in d); and f) quantitating the PCR reaction in e), wherein the quantitation allows for a determination of copy number of the specific target region.

In one embodiment, the enzymatic processing of step c) comprises performing 3'-5' exonuclease enzymatic processing on the one or more capture probe module-cfDNA library clone complexes from b) using an enzyme with 3'-5' exonuclease
 20 activity to remove the single stranded 3' ends; creating one or more hybrid capture probe module-cfDNA library clone molecules through the concerted action of a 5' FLAP endonuclease, DNA polymerization and nick closure by a DNA ligase; or performing 5'-3' DNA polymerase extension of the capture probe using the isolated cfDNA clone in the complex as a template.

25 In one embodiment, the enzymatic processing of step c) comprises performing 5'-3' DNA polymerase extension of the capture probe using the isolated cfDNA clone in the complex as a template.

In particular embodiments, PCR can be performed using any standard PCR reaction conditions well known to those of skill in the art. In certain embodiments, the
 30 PCR reaction in e) employs two PCR primers. In one embodiment, the PCR reaction in e) employs a first PCR primer that hybridizes to a repeat within the target genetic locus.

In a particular embodiment, the PCR reaction in e) employs a second PCR primer that hybridizes to the hybrid nucleic acid molecules at the target genetic locus/tail junction.

In certain embodiments, the PCR reaction in e) employs a first PCR primer that hybridizes to the target genetic locus and a second PCR primer hybridizes to the

5 amplified hybrid nucleic acid molecules at the target genetic locus/tail junction. In particular embodiments, the second primer hybridizes to the target genetic locus/tail junction such that at least one or more nucleotides of the primer hybridize to the target genetic locus and at least one or more nucleotides of the primer hybridize to the tail sequence.

10 In certain embodiments, the amplified hybrid nucleic acid molecules obtained from step e) are sequenced and the sequences aligned horizontally, *i.e.*, aligned to one another but not aligned to a reference sequence. In particular embodiments, steps a) through e) are repeated one or more times with one or more capture probe modules. The capture probe modules can be the same or different and designed to target either
15 cfDNA strand of a target genetic locus. In some embodiments, when the capture probes are different, they hybridize at overlapping or adjacent target sequences within a target genetic locus in the tagged cfDNA clone library. In one embodiment, a high density capture probe strategy is used wherein a plurality of capture probes hybridize to a target genetic locus, and wherein each of the plurality of capture probes hybridizes to the
20 target genetic locus within about 5, 10, 15, 20, 25, 30, 35, 40, 45, 50, 100, 200, bp of any other capture probe that hybridizes to the target genetic locus in a tagged cfDNA clone library, including all intervening distances.

In some embodiments, the method can be performed using two capture probe modules per target genetic locus, wherein one hybridizes to the “Watson” strand (non-
25 coding or template strand) upstream of the target region and one hybridizes to the “Crick” strand (coding or non-template strand) downstream of the target region.

In particular embodiments, the methods contemplated herein can further be performed multiple times with any number of capture probe modules, for example 2, 3, 4, 5, 6, 7, 8, 9, or 10 or more capture probe modules per target genetic locus any
30 number of which hybridize to the Watson or Crick strand in any combination. In some

embodiments, the sequences obtained can be aligned to one another in order to identify any of a number of differences.

In certain embodiments, a plurality of target genetic loci are interrogated, *e.g.*, 100, 200, 300, 400, 500, 600, 700, 800, 900, 1000, 1500, 2000, 2500, 3000, 3500, 4000,
 5 4500, 5000, 10000, 50000, 100000, 500000 or more in a single reaction, using one or more capture probe modules.

(b) Sequencing

In particular embodiments, the quantitative genetic analysis comprises sequencing a plurality of hybrid nucleic acid molecules, as discussed elsewhere herein,
 10 *supra*, to generate sufficient sequencing depths to obtain a plurality of unique sequencing reads. A unique read is defined as the single consensus read from a “family” of reads that all share the same read code and sequence start point within cfDNA. Each capture probe yields a set of unique reads that are computationally distilled from total reads by grouping into families. The unique reads for a given
 15 sample are then computed as the average of all the unique reads observed on a probe-by-probe basis. Cases where there is an obvious copy number change are excluded from the data set used to compute the average. Unique reads are important because each unique read must be derived from a unique cfDNA clone. Each unique read represents the input and analysis of a haploid equivalent of genomic DNA. The sum of
 20 unique reads is the sum of haploid genomes analyzed. The number of genomes analyzed, in turn, defines the sensitivity of the sequencing assay. By way of a non-limiting example, if the average unique read count is 100 genome equivalents, then that particular assay has a sensitivity of being able to detect one mutant read in 100, or 1%. Any observation less than this is not defensible.

25 In particular embodiments, the quantitative genetic analysis comprises multiplex sequencing of hybrid nucleic acid molecules derived from a plurality of samples.

In various embodiments, the quantitative genetic analysis comprises obtaining one or more or a plurality of tagged DNA library clones, each clone comprising a first DNA sequence and a second DNA sequence, wherein the first DNA sequence
 30 comprises a sequence in a targeted genetic locus and the second DNA sequence comprises a capture probe sequence; performing a paired end sequencing reaction on

the one or more clones and obtaining one or more sequencing reads or performing a sequencing reaction on the one or more clones in which a single long sequencing read of greater than about 100, 200, 300, 400, 500 or more nucleotides is obtained, wherein the read is sufficient to identify both the first DNA sequence and the second DNA
5 sequence; and ordering or clustering the sequencing reads of the one or more clones according to the probe sequences of the sequencing reads.

(c) Bioinformatics Analysis

In various embodiments, the quantitative genetic analysis further comprises bioinformatic analysis of the sequencing reads. Bioinformatic analysis excludes any
10 purely mental analysis performed in the absence of a composition or method for sequencing. In certain embodiments, bioinformatics analysis includes, but is not limited to: sequence alignments; genome equivalents analysis; single nucleotide variant (SNV) analysis; gene copy number variation (CNV) analysis; and detection of genetic lesions. In particular embodiments, bioinformatics analysis is useful to quantify the
15 number of genome equivalents analyzed in the cfDNA clone library; to detect the genetic state of a target genetic locus; to detect genetic lesions in a target genetic locus; and to measure copy number fluctuations within a target genetic locus.

Sequence alignments may be performed between the sequence reads and one or more human reference DNA sequences. In particular embodiments, sequencing
20 alignments can be used to detect genetic lesions in a target genetic locus including, but not limited to detection of a nucleotide transition or transversion, a nucleotide insertion or deletion, a genomic rearrangement, a change in copy number, or a gene fusion. Detection of genetic lesions that are causal or prognostic indicators may be useful in the diagnosis, prognosis, treatment, and/or monitoring of a particular genetic condition or
25 disease.

Also contemplated herein, are methods for sequence alignment analysis that can be performed without the need for alignment to a reference sequence, referred to herein as horizontal sequence analysis. Such analysis can be performed on any sequences generated by the methods contemplated herein or any other methods. In particular
30 embodiments, the sequence analysis comprises performing sequence alignments on the reads obtained by the methods contemplated herein.

In one embodiment, the genome equivalents in a cfDNA clone library are determined using bioinformatics-based counting after sequencing is performed. Each sequencing read is associated with a particular capture probe, and the collection of reads assigned to each capture probe is parsed into groups. Within a group, sets of individual
5 reads share the same read code and the same DNA sequence start position within genomic sequence. These individual reads are grouped into a “family” and a single consensus representative of this family is carried forward as a “unique read.” All of the individual reads that constituted a family are derived from a single ligation event and thus, they are amplification-derived “siblings” of one another. Each unique read is
10 considered a unique ligation event and the sum of unique reads is considered equivalent to the number of genome equivalents analyzed.

As the number of unique clones approaches the total number of possible sequence combinations, probability dictates that the same code and start site combinations will be created by independent events and that these independent events
15 will be inappropriately grouped within single families. The net result will be an underestimate of genome equivalents analyzed, and rare mutant reads may be discarded as sequencing errors because they overlap with wild-type reads bearing the same identifiers.

In particular embodiments, to provide an accurate analysis for cfDNA clone
20 libraries, the number of genome equivalents analyzed is about 1/10, about 1/12, about 1/14, about 1/16, about 1/18, about 1/20, about 1/25 or less the the number of possible unique clones. It should be understood that the procedure outlined above is merely illustrative and not limiting.

In some embodiments, the number of genome equivalents to be analyzed may
25 need to be increased. To expand the depth of genome equivalents, at least two solutions are contemplated. The first solution is to use more than one adaptor set per sample. By combining adaptors, it is possible to multiplicatively expand the total number of possible clones and therefore, expand the comfortable limits of genomic input. The second solution is to expand the read code by 1, 2, 3, 4, or 5 or more bases. The
30 number of possible read codes that differ by at least 2 bases from every other read code scales as $4^{(n-1)}$ where n is the number of bases within a read code. Thus, in a non-

limiting example, if a read code is 5 nucleotides and $4^{(5-1)} = 256$; therefore, the inclusion of additional bases expands the available repertoire by a factor of four for each additional base.

In one embodiment, quantitative genetic analysis comprises bioinformatic
5 analysis of sequencing reads to identify rare single nucleotide variants (SNV).

Next-generation sequencing has an inherent error rate of roughly 0.02-0.02%, meaning that anywhere from 1/200 to 1/500 base calls are incorrect. To detect variants and other mutations that occur at frequencies lower than this, for example at frequencies of 1 per 1000 sequences, it is necessary to invoke molecular annotation strategies. By
10 way of a non-limiting example, analysis of 5000 unique molecules using targeted sequence capture technology would generate – at sufficient sequencing depths of >50,000 reads – a collection of 5000 unique reads, with each unique read belonging to a “family” of reads that all possess the same read code. A SNV that occurs within a family is a candidate for being a rare variant. When this same variant is observed in
15 more than one family, it becomes a very strong candidate for being a rare variant that exists within the starting sample. In contrast, variants that occur sporadically within families are likely to be sequencing errors and variants that occur within one and only one family are either rare or the result of a base alteration that occurred *ex vivo* (e.g., oxidation of a DNA base or PCR-introduced errors).

20 In one embodiment, the methods of detecting SNVs comprise introducing 10-fold more genomic input (genomes or genome equivalents) as the desired target sensitivity of the assay. In one non-limiting example, if the desired sensitivity is 2% (2 in 100), then the experimental target is an input of 2000 genomes.

In particular embodiments, bioinformatics analysis of sequencing data is used to
25 detect or identify SNV associated with a genetic state, condition or disease, genetic mosaicism, fetal testing, paternity testing, predicting response to drug treatment, diagnosing or monitoring a medical condition, microbiome profiling, pathogen screening, and monitoring organ transplants.

In various embodiments, a method for copy number determination analysis is
30 provided comprising obtaining one or more or a plurality of clones, each clone comprising a first DNA sequence and a second DNA sequence, wherein the first DNA

sequence comprises a sequence in a targeted genetic locus and the second DNA sequence comprises a capture probe sequence. In related embodiments, a paired end sequencing reaction on the one or more clones is performed and one or more sequencing reads are obtained. In another embodiment, a sequencing reaction on the one or more clones is performed in which a single long sequencing read of greater than about 100 nucleotides is obtained, wherein the read is sufficient to identify both the first DNA sequence and the second DNA sequence. The sequencing reads of the one or more clones can be ordered or clustered according to the probe sequence of the sequencing reads.

Copy number analyses include, but are not limited to analyses, that examine the number of copies of a particular gene or mutation that occurs in a given genomic DNA sample and can further include quantitative determination of the number of copies of a given gene or sequence differences in a given sample. In particular embodiments, copy number analysis is used to detect or identify gene amplification associated with genetic states, conditions, or diseases, fetal testing, genetic mosaicism, paternity testing, predicting response to drug treatment, diagnosing or monitoring a medical condition, microbiome profiling, pathogen screening, and monitoring organ transplants.

In particular embodiments, bioinformatics analysis of sequencing data is used to detect or identify one or more sequences or genetic lesions in a target locus including, but not limited to detection of a nucleotide transition or transversion, a nucleotide insertion or deletion, a genomic rearrangement, a change in copy number, or a gene fusion. Detection of genetic lesions that are causal or prognostic indicators may be useful in the diagnosis, prognosis, treatment, and/or monitoring of a particular genetic condition or disease. In one embodiment, genetic lesions are associated with genetic states, conditions, or diseases, fetal testing, genetic mosaicism, paternity testing, predicting response to drug treatment, diagnosing or monitoring a medical condition, microbiome profiling, pathogen screening, and monitoring organ transplants.

D. CLINICAL APPLICATIONS OF QUANTITATIVE GENETIC ANALYSIS

In various embodiments, the present invention contemplates a method of detecting, identifying, predicting, diagnosing, or monitoring a condition or disease in a subject.

5 In particular embodiments, a method of detecting, identifying, predicting, diagnosing, or monitoring a genetic state, condition or disease in a subject comprises performing a quantitative genetic analysis of one or more target genetic loci in a cfDNA clone library to detect or identify a change in the sequence at the one or more target genetic loci.

10 In one embodiment, a method of detecting, identifying, predicting, diagnosing, or monitoring a genetic state, condition or disease comprises isolating or obtaining cfDNA from a biological sample of a subject; treating the cfDNA with one or more end-repair enzymes to generate end-repaired cfDNA; ligating one or more adaptors to each end of the end-repaired cfDNA to generate a cfDNA library; amplifying the
15 cfDNA library to generate a cfDNA clone library; determining the number of genome equivalents in the cfDNA clone library; and performing a quantitative genetic analysis of one or more target genetic loci in a cfDNA clone library to detect or identify a change in the sequence at the one or more target genetic loci.

In particular embodiments, a method of detecting, identifying, predicting,
20 diagnosing, or monitoring a genetic state, or genetic condition or disease selected from the group consisting of: genetic diseases; genetic mosaicism; fetal testing; paternity testing; paternity testing; predicting response to drug treatment; diagnosing or monitoring a medical condition; microbiome profiling; pathogen screening; and organ transplant monitoring comprising isolating or obtaining cfDNA from a biological
25 sample of a subject; treating the cfDNA with one or more end-repair enzymes to generate end-repaired cfDNA; ligating one or more adaptors to each end of the end-repaired cfDNA to generate a cfDNA library; amplifying the cfDNA library to generate a cfDNA clone library; determining the number of genome equivalents in the cfDNA clone library; and performing a quantitative genetic analysis of one or more target
30 genetic loci in a cfDNA clone library to detect or identify a nucleotide transition or

transversion, a nucleotide insertion or deletion, a genomic rearrangement, a change in copy number, or a gene fusion in the sequence at the one or more target genetic loci.

Illustrative examples of genetic diseases that can be detected, identified, predicted, diagnosed, or monitored with the compositions and methods contemplated herein include, but are not limited to cancer, Alzheimer's disease (APOE1), Charcot-Marie-Tooth disease, Leber hereditary optic neuropathy (LHON), Angelman syndrome (UBE3A, ubiquitin-protein ligase E3A), Prader-Willi syndrome (region in chromosome 15), β -Thalassaemia (HBB, β -Globin), Gaucher disease (type I) (GBA, Glucocerebrosidase), Cystic fibrosis (CFTR Epithelial chloride channel), Sickle cell disease (HBB, β -Globin), Tay-Sachs disease (HEXA, Hexosaminidase A), Phenylketonuria (PAH, Phenylalanine hydrolyase), Familial hypercholesterolaemia (LDLR, Low density lipoprotein receptor), Adult polycystic kidney disease (PKD1, Polycystin), Huntington disease (HDD, Huntingtin), Neurofibromatosis type I (NF1, NF1 tumour suppressor gene), Myotonic dystrophy (DM, Myotonin), Tuberous sclerosis (TSC1, Tuberin), Achondroplasia (FGFR3, Fibroblast growth factor receptor), Fragile X syndrome (FMR1, RNA-binding protein), Duchenne muscular dystrophy (DMD, Dystrophin), Haemophilia A (F8C, Blood coagulation factor VIII), Lesch-Nyhan syndrome (HPRT1, Hypoxanthine guanine ribosyltransferase 1), and Adrenoleukodystrophy (ABCD1).

Illustrative examples of cancers that can be detected, identified, predicted, diagnosed, or monitored with the compositions and methods contemplated herein include, but are not limited to: B cell cancer, e.g., multiple myeloma, melanomas, breast cancer, lung cancer (such as non-small cell lung carcinoma or NSCLC), bronchus cancer, colorectal cancer, prostate cancer, pancreatic cancer, stomach cancer, ovarian cancer, urinary bladder cancer, brain or central nervous system cancer, peripheral nervous system cancer, esophageal cancer, cervical cancer, uterine or endometrial cancer, cancer of the oral cavity or pharynx, liver cancer, kidney cancer, testicular cancer, biliary tract cancer, small bowel or appendix cancer, salivary gland cancer, thyroid gland cancer, adrenal gland cancer, osteosarcoma, chondrosarcoma, cancer of hematological tissues, adenocarcinomas, inflammatory myofibroblastic tumors, gastrointestinal stromal tumor (GIST), colon cancer, multiple myeloma (MM),

myelodysplastic syndrome (MDS), myeloproliferative disorder (MPD), acute lymphocytic leukemia (ALL), acute myelocytic leukemia (AML), chronic myelocytic leukemia (CML), chronic lymphocytic leukemia (CLL), polycythemia Vera, Hodgkin lymphoma, non-Hodgkin lymphoma (NHL), soft-tissue sarcoma, fibrosarcoma, myxosarcoma, liposarcoma, osteogenic sarcoma, chordoma, angiosarcoma, endotheliosarcoma, lymphangiosarcoma, lymphangioendotheliosarcoma, synovioma, mesothelioma, Ewing's tumor, leiomyosarcoma, rhabdomyosarcoma, squamous cell carcinoma, basal cell carcinoma, adenocarcinoma, sweat gland carcinoma, sebaceous gland carcinoma, papillary carcinoma, papillary adenocarcinomas, medullary carcinoma, bronchogenic carcinoma, renal cell carcinoma, hepatoma, bile duct carcinoma, choriocarcinoma, seminoma, embryonal carcinoma, Wilms' tumor, bladder carcinoma, epithelial carcinoma, glioma, astrocytoma, medulloblastoma, craniopharyngioma, ependymoma, pinealoma, hemangioblastoma, acoustic neuroma, oligodendroglioma, meningioma, neuroblastoma, retinoblastoma, follicular lymphoma, diffuse large B-cell lymphoma, mantle cell lymphoma, hepatocellular carcinoma, thyroid cancer, gastric cancer, head and neck cancer, small cell cancers, essential thrombocythemia, agnogenic myeloid metaplasia, hypereosinophilic syndrome, systemic mastocytosis, familial hypereosinophilia, chronic eosinophilic leukemia, neuroendocrine cancers, carcinoid tumors, and the like.

In one embodiment, the genetic lesion is a lesion annotated in the Cosmic database (the lesions and sequence data can be downloaded from cancer.sanger.ac.uk/cosmic/census) or a lesion annotated in the Cancer Genome Atlas (the lesions and sequence data can be downloaded from tcga-data.nci.nih.gov/tcga/tcgaDownload.jsp).

Illustrative examples of genes that harbor one or more genetic lesions associated with cancer that can be detected, identified, predicted, diagnosed, or monitored with the compositions and methods contemplated herein include, but are not limited to ABCB1, ABCC2, ABCC4, ABCG2, ABL1, ABL2, AKT1, AKT2, AKT3, ALDH4A1, ALK, APC, AR, ARAF, ARFRP1, ARID1A, ATM, ATR, AURKA, AURKB, BCL2, BCL2A1, BCL2L1, BCL2L2, BCL6, BRAF, BRCA1, BRCA2, Clorf144, CARD11, CBL, CCND1, CCND2, CCND3, CCNE1, CDH1, CDH2, CDH20, CDH5, CDK4,

CDK6, CDK8, CDKN2A, CDKN2B, CDKN2C, CEBPA, CHEK1, CHEK2, CRKL, CRLF2, CTNNB1, CYP1B1, CYP2C19, CYP2C8, CYP2D6, CYP3A4, CYP3A5, DNMT3A, DOT1L, DPYD, EGFR, EPHA3, EPHA5, EPHA6, EPHA7, EPHB1, EPHB4, EPHB6, EPHX1, ERBB2, ERBB3, ERBB4, ERCC2, ERG, ESR1, ESR2, ETV1, ETV4, ETV5, ETV6, EWSR1, EZH2, FANCA, FBXW7, FCGR3A, FGFR1, FGFR2, FGFR3, FGFR4, FLT1, FLT3, FLT4, FOXP4, GATA1, GNA11, GNAQ, GNAS, GPR124, GSTP1, GUCY1A2, HOXA3, HRAS, HSP90AA1, IDH1, IDH2, IGF1R, IGF2R, IKBKE, IKZF1, INHBA, IRS2, ITPA, JAK1, JAK2, JAK3, JUN, KDR, KIT, KRAS, LRP1B, LRP2, LTK, MAN1B1, MAP2K1, MAP2K2, MAP2K4, MCL1, MDM2, MDM4, MEN1, MET, MITF, MLH1, MLL, MPL, MRE11A, MSH2, MSH6, MTHFR, MTOR, MUTYH, MYC, MYCL1, MYCN, NF1, NF2, NKX2-1, NOTCH1, NPM1, NQO1, NRAS, NRP2, NTRK1, NTRK3, PAK3, PAX5, PDGFRA, PDGFRB, PIK3CA, PIK3R1, PKHD1, PLCG1, PRKDC, PTCH1, PTEN, PTPN11, PTPRD, RAF1, RARA, RB1, RET, RICTOR, RPTOR, RUNX1, SLC19A1, SLC22A2, SLCO1B3, SMAD2, SMAD3, SMAD4, SMARCA4, SMARCB1, SMO, SOD2, SOX10, SOX2, SRC, STK11, SULT1A1, TBX22, TET2, TGFBR2, TMPRSS2, TNFRSF14, TOP1, TP53, TPMT, TSC1, TSC2, TYMS, UGT1A1, UMPS, USP9X, VHL, and WT1.

In particular embodiments, the genetic lesion comprises a nucleotide transition or transversion, a nucleotide insertion or deletion, a genomic rearrangement, a change in copy number, or a gene fusion.

In one embodiment, the genetic lesion is a gene fusion that fuses the 3' coding region of the ALK gene to another gene.

In one embodiment, the genetic lesion is a gene fusion that fuses the 3' coding region of the ALK gene to the EML4 gene.

Illustrative examples of conditions suitable for fetal testing that can be detected, identified, predicted, diagnosed, or monitored with the compositions and methods contemplated herein include but are not limited to: Down Syndrome (Trisomy 21), Edwards Syndrome (Trisomy 18), Patau Syndrome (Trisomy 13), Klinefelter's Syndrome (XXY), Triple X syndrome, XYY syndrome, Trisomy 8, Trisomy 16, Turner

Syndrome (XO), Robertsonian translocation, DiGeorge Syndrome and Wolf-Hirschhorn Syndrome.

Illustrative examples of alleles suitable for paternity testing that can be detected, identified, predicted, diagnosed, or monitored with the compositions and methods

5 contemplated herein include but are not limited to 16 or more of: D20S1082, D6S474, D12ATA63, D22S1045, D10S1248, D1S1677, D11S4463, D4S2364, D9S1122, D2S1776, D10S1425, D3S3053, D5S2500, D1S1627, D3S4529, D2S441, D17S974, D6S1017, D4S2408, D9S2157, Amelogenin, D17S1301, D1GATA113, D18S853, D20S482, and D14S1434.

10 Illustrative examples of genes suitable for predicting the response to drug treatment that can be detected, identified, predicted, diagnosed, or monitored with the compositions and methods contemplated herein include, but are not limited to, one or more of the following genes: ABCB1 (ATP-binding cassette, sub-family B (MDR/TAP), member 1), ACE (angiotensin I converting enzyme), ADH1A (alcohol
15 dehydrogenase 1A (class I), alpha polypeptide), ADH1B (alcohol dehydrogenase IB (class I), beta polypeptide), ADH1C (alcohol dehydrogenase 1C (class I), gamma polypeptide), ADRB1 (adrenergic, beta-1-, receptor), ADRB2 (adrenergic, beta-2-, receptor, surface), AHR (aryl hydrocarbon receptor), ALDH1A1 (aldehyde
dehydrogenase 1 family, member A1), ALOX5 (arachidonate 5-lipoxygenase), BRCA1
20 (breast cancer 1, early onset), COMT (catechol-O-methyltransferase), CYP2A6 (cytochrome P450, family 2, subfamily A, polypeptide 6), CYP2B6 (cytochrome P450, family 2, subfamily B, polypeptide 6), CYP2C9 (cytochrome P450, family 2, subfamily C, polypeptide 9), CYP2C19 (cytochrome P450, family 2, subfamily C, polypeptide 19), CYP2D6 (cytochrome P450, family 2, subfamily D, polypeptide 6), CYP2J2
25 (cytochrome P450, family 2, subfamily J, polypeptide 2), CYP3A4 (cytochrome P450, family 3, subfamily A, polypeptide 4), CYP3A5 (cytochrome P450, family 3, subfamily A, polypeptide 5), DPYD (dihydropyrimidine dehydrogenase), DRD2 (dopamine receptor D2), F5 (coagulation factor V), GSTP1 (glutathione S-transferase pi), HMGCR (3-hydroxy-3-methylglutaryl-Coenzyme A reductase), KCNH2 (potassium voltage-
30 gated channel, subfamily H (eag-related), member 2), KCNJ11 (potassium inwardly-rectifying channel, subfamily J, member 11), MTHFR (5,10-methylenetetrahydrofolate

reductase (NADPH)), NQO1 (NAD(P)H dehydrogenase, quinone 1), P2RY1 (purinergic receptor P2Y, G-protein coupled, 1), P2RY12 (purinergic receptor P2Y, G-protein coupled, 12), PTGIS (prostaglandin I2 (prostacyclin) synthase), SCN5A (sodium channel, voltage-gated, type V, alpha (long QT syndrome 3)), SLC19A1 (solute carrier family 19 (folate transporter), member 1), SLCO1B1 (solute carrier organic anion transporter family, member 1B1), SULT1A1 (sulfotransferase family, cytosolic, 1A, phenol-preferring, member 1), TPMT (thiopurine S-methyltransferase), TYMS (thymidylate synthetase), UGT1A1 (UDP glucuronosyltransferase 1 family, polypeptide A1), VDR (vitamin D (1,25-dihydroxyvitamin D3) receptor), VKORC1 (vitamin K epoxide reductase complex, subunit 1).

Illustrative examples of medical conditions that can be detected, identified, predicted, diagnosed, or monitored with the compositions and methods contemplated herein include, but are not limited to: stroke, transient ischemic attack, traumatic brain injury, heart disease, heart attack, angina, atherosclerosis, and high blood pressure.

Illustrative examples of pathogens that can be screened for with the compositions and methods contemplated herein include, but are not limited to: bacteria, fungi, and viruses.

Illustrative examples of bacterial species that can be screened for with the compositions and methods contemplated herein include, but are not limited to: a *Mycobacterium* spp., a *Pneumococcus* spp., an *Escherichia* spp., a *Campylobacter* spp., a *Corynebacterium* spp., a *Clostridium* spp., a *Streptococcus* spp., a *Staphylococcus* spp., a *Pseudomonas* spp., a *Shigella* spp., a *Treponema* spp., or a *Salmonella* spp.

Illustrative examples of fungal species that can be screened for with the compositions and methods contemplated herein include, but are not limited to: an *Aspergillus* spp., a *Blastomyces* spp., a *Candida* spp., a *Coccidioides* spp., a *Cryptococcus* spp., dermatophytes, a *Tinea* spp., a *Trichophyton* spp., a *Microsporum* spp., a *Fusarium* spp., a *Histoplasma* spp., a *Mucoromycotina* spp., a *Pneumocystis* spp., a *Sporothrix* spp., an *Exserophilum* spp., or a *Cladosporium* spp.

Illustrative examples of viruses that can be screened for with the compositions and methods contemplated herein include, but are not limited to: Influenza A such as H1N1, H1N2, H3N2 and H5N1 (bird flu), Influenza B, Influenza C virus, Hepatitis A

- virus, Hepatitis B virus, Hepatitis C virus, Hepatitis D virus, Hepatitis E virus, Rotavirus, any virus of the Norwalk virus group, enteric adenoviruses, parvovirus, Dengue fever virus, Monkey pox, Mononegavirales, Lyssavirus such as rabies virus, Lagos bat virus, Mokola virus, Duvenhage virus, European bat virus 1 & 2 and
- 5 Australian bat virus, Ephemero virus, Vesiculovirus, Vesicular Stomatitis Virus (VSV), Herpesviruses such as Herpes simplex virus types 1 and 2, varicella zoster, cytomegalovirus, Epstein-Bar virus (EBV), human herpesviruses (HHV), human herpesvirus type 6 and 8, Moloney murine leukemia virus (M-MuLV), Moloney murine sarcoma virus (MoMSV), Harvey murine sarcoma virus (HaMuSV), murine mammary
- 10 tumor virus (MuMTV), gibbon ape leukemia virus (GaLV), feline leukemia virus (FLV), spumavirus, Friend murine leukemia virus, Murine Stem Cell Virus (MSCV) and Rous Sarcoma Virus (RSV), HIV (human immunodeficiency virus; including HIV type 1, and HIV type 2), visna-maedi virus (VMV) virus, the caprine arthritis-encephalitis virus (CAEV), equine infectious anemia virus (EIAV), feline
- 15 immunodeficiency virus (FIV), bovine immune deficiency virus (BIV), and simian immunodeficiency virus (SIV), papilloma virus, murine gammaherpesvirus, Arenaviruses such as Argentine hemorrhagic fever virus, Bolivian hemorrhagic fever virus, Sabia-associated hemorrhagic fever virus, Venezuelan hemorrhagic fever virus, Lassa fever virus, Machupo virus, Lymphocytic choriomeningitis virus (LCMV),
- 20 Bunyaviridae such as Crimean-Congo hemorrhagic fever virus, Hantavirus, hemorrhagic fever with renal syndrome causing virus, Rift Valley fever virus, Filoviridae (filovirus) including Ebola hemorrhagic fever and Marburg hemorrhagic fever, Flaviviridae including Kaysanur Forest disease virus, Omsk hemorrhagic fever virus, Tick-borne encephalitis causing virus and Paramyxoviridae such as Hendra virus
- 25 and Nipah virus, variola major and variola minor (smallpox), alphaviruses such as Venezuelan equine encephalitis virus, eastern equine encephalitis virus, western equine encephalitis virus, SARS-associated coronavirus (SARS-CoV), West Nile virus, and any encephalitis causing virus.

- Illustrative examples of genes suitable for monitoring an organ transplant in a
- 30 transplant recipient that can be detected, identified, predicted, diagnosed, or monitored with the compositions and methods contemplated herein include, but are not limited to,

one or more of the following genes: HLA-A, HLA-B, HLA-C, HLA-DR, HLA-DP, and HLA-DQ.

In particular embodiments, a bioinformatic analysis is used to quantify the number of genome equivalents analyzed in the cfDNA clone library; detect genetic
5 variants in a target genetic locus; detect mutations within a target genetic locus; detect genetic fusions within a target genetic locus; or measure copy number fluctuations within a target genetic locus.

E. COMPANION DIAGNOSTICS

In various embodiments, a companion diagnostic for a genetic disease is
10 provided, comprising: isolating or obtaining cfDNA from a biological sample of a subject; treating the cfDNA with one or more end-repair enzymes to generate end-repaired cfDNA; ligating one or more adaptors to each end of the end-repaired cfDNA to generate a cfDNA library; amplifying the cfDNA library to generate a cfDNA clone library; determining the number of genome equivalents in the cfDNA clone library; and
15 performing a quantitative genetic analysis of one or more biomarkers associated with the genetic disease in the cfDNA clone library, wherein detection of, or failure to detect, at least one of the one or more biomarkers indicates whether the subject should be treated for the genetic disease.

As used herein, the term “companion diagnostic” refers to a diagnostic test that
20 is linked to a particular anti-cancer therapy. In a particular embodiment, the diagnostic methods comprise detection of genetic lesion in a biomarker associated with in a biological sample, thereby allowing for prompt identification of patients should or should not be treated with the anti-cancer therapy.

Anti-cancer therapy includes, but is not limited to surgery, radiation,
25 chemotherapeutics, anti-cancer drugs, and immunomodulators.

Illustrative examples of anti-cancer drugs include, but are not limited to: alkylating agents such as thiotepa and cyclophosphamide (CYTOXAN™); alkyl sulfonates such as busulfan, improsulfan and piposulfan; aziridines such as benzodopa, carboquone, meturedopa, and uredopa; ethylenimines and methylamelamines including
30 altretamine, triethylenemelamine, trietylenephosphoramide,

triethylenethiophosphaoramide and trimethylolomelamine resins; nitrogen mustards such as chlorambucil, chlornaphazine, cholophosphamide, estramustine, ifosfamide, mechlorethamine, mechlorethamine oxide hydrochloride, melphalan, novembichin, phenesterine, prednimustine, trofosfamide, uracil mustard; nitrosoureas such as

5 carmustine, chlorozotocin, fotemustine, lomustine, nimustine, ranimustine; antibiotics such as aclacinomysins, actinomycin, anthramycin, azaserine, bleomycins, cactinomycin, calicheamicin, carabycin, carminomycin, carzinophilin, chromomycins, dactinomycin, daunorubicin, detorubicin, 6-diazo-5-oxo-L-norleucine, doxorubicin and its pegylated formulations, epirubicin, esorubicin, idarubicin, marcellomycin,

10 mitomycins, mycophenolic acid, nogalamycin, olivomycins, peplomycin, potfiromycin, puromycin, quelamycin, rodorubicin, streptonigrin, streptozocin, tubercidin, ubenimex, zinostatin, zorubicin; anti-metabolites such as methotrexate and 5-fluorouracil (5-FU); folic acid analogues such as denopterin, methotrexate, pteropterin, trimetrexate; purine analogs such as fludarabine, 6-mercaptopurine, thiamiprine, thioguanine; pyrimidine

15 analogs such as ancitabine, azacitidine, 6-azauridine, carmofur, cytarabine, dideoxyuridine, doxifluridine, enocitabine, floxuridine, 5-FU; androgens such as calusterone, dromostanolone propionate, epitiostanol, mepitiothane, testolactone; anti-adrenals such as aminogluthethimide, mitotane, trilostane; folic acid replenisher such as frolinic acid; aceglatone; aldophosphamide glycoside; aminolevulinic acid; amsacrine;

20 bestrabucil; bisantrene; edatraxate; defofamine; demecolcine; diaziquone; elformithine; elliptinium acetate; etoglucid; gallium nitrate; hydroxyurea; lentinan; lonidamine; mitoguazone; mitoxantrone; mopidamol; nitracrine; pentostatin; phenamet; pirarubicin; podophyllinic acid; 2-ethylhydrazide; procarbazine; PSK®; razoxane; sizofiran; spirogermanium; tenuazonic acid; triaziquone; 2, 2',2''-trichlorotriethylamine; urethan;

25 vindesine; dacarbazine; mannomustine; mitobronitol; mitolactol; pipobroman; gacytosine; arabinoside ("Ara-C"); cyclophosphamide; thiotepa; taxoids, *e.g.*, paclitaxel (TAXOL®, Bristol-Myers Squibb Oncology, Princeton, N.J.) and doxetaxel (TAXOTERE®, Rhne-Poulenc Rorer, Antony, France); chlorambucil; gemcitabine; 6-thioguanine; mercaptopurine; methotrexate; platinum analogs such as cisplatin and

30 carboplatin; vinblastine; platinum; etoposide (VP-16); ifosfamide; mitomycin C; mitoxantrone; vincristine; vinorelbine; navelbine; novantrone; teniposide; aminopterin;

xeloda; ibandronate; CPT-11; topoisomerase inhibitor RFS 2000; difluoromethylomithine (DMFO); retinoic acid derivatives such as Targretin™ (bexarotene), Panretin™ (alitretinoin); ONTAK™ (denileukin diftitox); esperamicins; capecitabine; and pharmaceutically acceptable salts, acids or derivatives of any of the above. Also included in this definition are anti-hormonal agents that act to regulate or inhibit hormone action on cancers such as anti-estrogens including for example tamoxifen, raloxifene, aromatase inhibiting 4(5)-imidazoles, 4-hydroxytamoxifen, trioxifene, keoxifene, LY117018, onapristone, and toremifene (Fareston); and anti-androgens such as flutamide, nilutamide, bicalutamide, leuprolide, and goserelin; and pharmaceutically acceptable salts, acids or derivatives of any of the above.

Illustrative examples of immunomodulators include, but are not limited to: cyclosporine, tacrolimus, tresperimus, pimecrolimus, sirolimus, verolimus, laflunimus, laquinimod and imiquimod, as well as analogs, derivatives, salts, ions and complexes thereof.

15

All publications, patent applications, and issued patents cited in this specification are herein incorporated by reference as if each individual publication, patent application, or issued patent were specifically and individually indicated to be incorporated by reference.

20

Although the foregoing invention has been described in some detail by way of illustration and example for purposes of clarity of understanding, it will be readily apparent to one of ordinary skill in the art in light of the teachings of this invention that certain changes and modifications may be made thereto without departing from the spirit or scope of the appended claims. The following examples are provided by way of illustration only and not by way of limitation. Those of skill in the art will readily recognize a variety of noncritical parameters that could be changed or modified to yield essentially similar results.

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EXAMPLES

EXAMPLE 1ACCURATE DETECTION OF RARE MUTATIONS USING
TARGETED SEQUENCE CAPTURE TECHNOLOGY5 *PURPOSE*

The purpose of this experiment was to provide a direct proof-of-principle demonstration of rare variant detection using targeted sequence capture technology.

BACKGROUND

10 Target sequence capture technology provides quantitative, sequence-based genetic analysis of nucleic acids and can be exploited to perform a combined mutational and copy number analysis of drug metabolism genes. The present inventors used targeted sequence capture technology and subsequence genetic analysis to detect rare sequence variants.

Genomic DNA inputs play a central role in rare variant detection, but
15 quantitative analysis and control of genomic inputs places bounds on the estimated sensitivity of rare variant analysis. A genomic qPCR assay was used by the present inventors to estimate genomic inputs.

One experimental goal for rare variant analysis is to introduce 10-fold more genomic input as the target sensitivity of the assay. In other words, to measure variants
20 with a sensitivity of 1% (1 in 100), then the experimental target is to input 1000 genomes. Downstream of sequencing, bioinformatics analysis reveals the number of unique reads, and this has the desirable quality of being both an orthogonal and a more direct measure of genomic inputs.

SUMMARY

25 A cell line (ZR75-30) with known SNVs was admixed with a germ line DNA sample (NA12878) in a dilution series ranging from 1-to-1 through 1-to-1000. Target regions corresponding to known sequence differences were retrieved using targeted

sequence capture technology and sequenced. Sequence variants that occur at a frequency of less than 1 per 1000 sequences were detected.

METHODS

Capture probes

- 5 The following table shows a collection of 62 capture probes that were used in this experiment.

Table 1. 60 base probe sequences used in the admix proof-of-concept study

Target	SEQ ID NO:	Probe Sequence
BRAF	1	TAAACATTGGAAAGGTTTCTAATTAACCAGGAGATCCAAAAGA AAGCGGTTCAAGTAGCA
	2	GATCTCAGTTTTTTTGGTTAACTATGTATTTTGGTATATGAAGCT TCTGGGTTTTGCACA
MYCN	3	GACAGATAAGCATACATATTAACATGGATATATATGTGAATTC ATTCAAATGGTTCTCA
	4	AGCTCTTAGCCTTTGGGGGGATGACACTCTTGAGCGGACGTGGG GACGCCTCGCTCTTTA
BRAF	5	AAGCCCCCACC GCCGCCTCTTTCCAAAATAAACACCAGCCAGC CGCCGAGCCCGGAGTCG
	6	GCCTCCCTTCCCCCTCCCCGCCCCGACAGCGGCCGCTCGGGCCCC GGCTCTCGGTTATAAG
CDH1	7	GGTGTGGCAGCCAGGGGGGCGCACTCTGCTCTGGCTGGGCCCC TTCTCCCATGTTTTCTT
	8	TTACACAACCTTTGGGCTTGACAACTTTGGGGTCCAAAGAA CCTAAGAGTCTTTCTG
EPHX2	9	TGATGAAACTTGGGCTGGATGGGGCACAGGTAGGGTGCTTGTT GCTTTCAGTCAGATGAA
	10	AATGAAAGAAAAGGAGGCCAGATTGCTACTCCTGGTCCCTGCC ACACACTAGGTACCCTA
BRCA1	11	ATTGACAATACCTACATAAACTCTTTCCAGAATGTTGTTAAGT CTTAGTCATTAGGGAG
	12	GGATTTCCACCAACACTGTATTCATGTACCCATTTTTCTCTTAAC CTAACTTTATTGGTC
BRCA2	13	CAAAGGGGGGAAAACCATCAGGACATTATTTAACAACGGAAATA TCTAACTGAAAGGCAAA
	14	CAGGCAGACCAACCAAAGTCTTTGTTCCACCTTTTAAAACTAAA TCACATTTTCACAGAG
MYCN	15	CCCCAGCCAGCGGTCCGCAACCCTTGCCGCATCCACGAACTTT GCCCATAGCAGCGGGC
MYC_r1_F1	16	CGACTCATCTCAGCATTAAGTGATAAAAAAATAAATTAAG GCAAGTGGACTTCGGTG
MYC_r1_R1	17	CTGTGGCGCGCACTGCGCGCTGCGCCAGGTTTCCGCACCAAGA CCCCTTTAACTCAAGAC
MYC_r2_F1	18	TTCTACTGCGACGAGGAGGAGAACTTCTACCAGCAGCAGCAGC AGAGCGAGCTGCAGCCC
MYC_r2_F2	19	ACCGAGCTGCTGGGAGGAGACATGGTGAACCAGAGTTTCATCT GCGACCCGGACGACGAG
MYC_r2_F3	20	GCCGCCGCTCAGAGTGCATCGACCCCTCGGTGGTCTTCCCCTA CCCTCTCAACGACAGC

MYC_r2_F4	21	GGCGGCTAGGGGACAGGGGCGGGGTGGGCAGCAGCTCGAATTT CTTCCAGATATCCTCGC
MYC_r2_R1	22	AGACGAGCTTGGCGGCGGCCGAGAAGCCGCTCCACATACAGTC CTGGATGATGATGTTTT
MYC_r2_R2	23	AGGAGAGCAGAGAATCCGAGGACGGAGAGAAGGCGCTGGAGT CTTGCGAGGCGCAGGACT
MYC_r2_R3	24	TAAGAGTGGCCCGTTAAATAAGCTGCCAATGAAAATGGGAAAG GTATCCAGCCGCCCACT
MYC_r2_R4	25	TTGTATTTGTACAGCATTAATCTGGTAATTGATTATTTTAATGTA ACCTTGCTAAAGGAG
MYC_r3_F1	26	GAGGCCACAGCAAACCTCCTCACAGCCCACTGGTCCTCAAGAG GTGCCACGTCTCCACAC
MYC_r3_F2	27	AGAGGAGGAACGAGCTAAAACGGAGCTTTTTTGCCCTGCGTGA CCAGATCCCGGAGTTGG
MYC_r3_F3	28	TCCAACTTGACCCTCTTGGCAGCAGGATAGTCCTTCCGAGTGGA GGGAGGCGCTGCGTAG
MYC_r3_R1	29	GCTTGGACGGACAGGATGTATGCTGTGGCTTTTTTAAGGATAAC TACCTTGGGGGCCTTT
MYC_r3_R2	30	GCATTTGATCATGCATTTGAAACAAGTTCATAGGTGATTGCTCA GGACATTTCTGTTAGA
MYC_r3_R3	31	CGCCCCGCGCCCTCCAGCCGGGTCCAGCCGGAGCCATGGGGC CGGAGCCGCAGTGAGCA
ERBB2r1r	32	CTCTGGCCCCGCGCGCCGCGGGACCTCGGCGGGGCATCCACAG GGCAGGGTCCCCGCCGCT
ERBB2r2f	33	GGCATGACTTGGAGTGAGTTTGATGGGGTGGCCAGGTCTGAG AAGGTCCCCCGCCAGTG
ERBB2r2r	34	GCAGGGCACCTTCTTCTGCCACCCACCTGTAAACAGAGGGCTCA GCCAGCTGGAGGCAG
ERBB2r3f	35	CCCAAGATCTCCAAGTACTGGGGAACCCAGGGAGGCCCTGGG GGGTGGCAGTGTTCCTA
ERBB2r3r	36	CTAATGCACACAAAGCCTCCCCCTGGTTAGCAGTGGCCCTGGTC AGCTCTGAATAACCAA
ERBB2r4f	37	CTGCTCCTCTTTTAGAAGGCAGGAGGGCCCCAAGGGAAGCAGA AGGTGACAGAAGGGGAA
ERBB2r4r	38	TGGGGCAGTGGCGGGCAGGCACTGGGTTGTAAGTTGGGAGTTT GCGGCTGGGGTCAGGCT
ERBB2r5f	39	TCTGCTGCTGTTTGTGCCTCTCTCTGTTACTAACCCGTCCTCTCG CTGTTAGACATCTCT
ERBB2r5r	40	CCCACCCCTCCCATGTACCTGTATGACACCTGCATTCCACCCG GCCCCAGCCCTCCCT
ERBB2r6f	41	TGGGCCAGGTAGTCTCCCTAGAAGGTGATGCTGATGAGGGTCT GGTGCCAGGGCGCCAC
ERBB2r6r	42	GGTGCCACCCCTTGCATCCTGGGGGTAGAGCACATTGGGCA CAAAGCAGAGGCACATA
ERBB2r7f	43	CACCCTGCCTGGTACTGCCCTATTGCCCCTGGCACACCAGGGCA AAACAGCACAGTGAAA
ERBB2r7r	44	CCATTTACAGAAACAAACCTCCCCACCAAAATGAGAAAAGTGT GTTTCTCCCTGGCACTC
ERBB2r8f	45	TTATTCTTCTTGTGCCTGGGCACGGTAATGCTGCTCATGGTGGT GCACGAAGGGCCAGGG
ERBB2r8r	46	GAAGGATAGGACAGGGTGGGCTGGGCCAGGCTGCATGCGCAG AGGGACAGGAACTGCAGC
ERBB2r9f	47	GGGCCCCGACCCTGATGCTCATGTGGCTGTTGACCTGTCCCGGT ATGAAGGCTGAGACGG
ERBB2r9r	48	TCTGTCTCCTGCCATCCCCAAGAGATGCTGCCACATCTGGATCC TCAGGACTCTGTCTGC

TYMSr2f	49	TCACGTCCCAGGGCAGTTTCTTCCCTGAAGAAAGTTGGATGGC ATGATCTGTCTTCCCA
TYMSr2r	50	GTGTTGAGAACAGACTACTGACTTCTAATAGCAGCGACTTCTTT ACCTTGATAAACCACA
TYMSr3f	51	AAAAAAAGGATGGGTTCATATGGGTGGTGTCAAGTGCCCACC TCCTAGCAAGTCAGCAG
TYMSr3r	52	CCCTCACAAGGTCAAAGCTATACATCAGCTCCTGTGACATTGAC TCATCCCCCAGACCTT
TYMSr4f	53	AACCCACCGAGATCTGCAAACTTTGCAGGATGCACCAGATGTC TTGTAGCCATGGGTCAA
TYMSr4r	54	TGCCTCCCTCAGGTGCCTCTGCACAAAACCAGATTGCTTCCCTC TAAGAGTATGGTTAGT
TYMSr5f	55	GTTTTACTTTGCCTTTAGCTGTGGTCTTTCAAACCACCATCCCTC CTTATCTTCTCTG
TYMSr5r	56	CTCTGCAATTTGTTTTCCCATATTAAAGAACTGAAGAGCTCAGT GTGGTAGGCTGGCAAG
TYMSr6f	57	TTTTAAATGATGTTTTAAAGAATTGAACTAACATACTGTTCTG CTTCTCCCCCGGGTT
TYMSr6r	58	CCTGCCCCACCTTCTCCCTAAACTGAAGCCCCACATTTGGAGC AGTCATCTTTATCTTG
TYMSr7f	59	GGTTGCGCTCCAATCATGTTACATAACCTACGGCAAGGTATCGA CAGGATCATACTCCTG
TYMSr7r	60	GCACAGTTACATTTGCCAGTGGCAACATCCTTAAAAATTAATAA CTGATAGGTCACGGAC
TYMSr1f	61	CGTCCCCGCCGCCCACTTGGCCTGCCTCCGTCCCGCCGCCAC TTCGCCTGCCTCCGTC
TYMSr1r	62	CTGTAAGGCGAGGAGGACGATGCGTCCCCTCCCTCGCAGGATT GAGGTTAGGACTAAACG

Capture probe modules were pooled from stock plates, combined with partner oligo # 138 (SEQ ID NO:63)
(GTGAAAACCAGGATCAACTCCCGTGCCAGTCACAT/3BioTEG/) and diluted to a final working concentration of 1 nM.

5 Genomic samples

Commercially-purchased genomic DNA from germ line sample NA12878 and cell line ZR75-30 was fragmented at a concentration of 10-20 ng/μl to a target fragment size of 500 bp on a Covaris sonication instrument. The DNA was purified with a 1:1 concentration of DNA purification beads and end-repaired using the New England Biolabs (NEB) Quick blunt kit at a final concentration of 15 – 30 ng/μL. The germ line and cell line DNAs were blended at ratios of 1:1, 10:1, 100:1 and 1000:1, respectively. Libraries were constructed, purified and quantified. The sample codes, library quantitation and inputs used for library construction are shown in Table 2.

Table 2. Adaptors and genomic analysis of libraries used as inputs

Admix	Adaptor code	genomes/ μ l	# desired genomes	μ l into PCR
1:1	NNNNNNNNCATGGCCGCAGG (SEQ ID NO:64)	55	200	4
10:1	NNNNNNNNATCTTAGTGGCA (SEQ ID NO:65)	66	200	3
100:1	NNNNNNNNCGGAACTCGGAG (SEQ ID NO:66)	64	1000	16
1000:1	NNNNNNNNGACTCCGATCCC (SEQ ID NO:67)	77	10000	130

Genomic libraries were pooled, denatured, combined with probe, hybridized and washed. The washed capture probe-tagged genomic library **complexes** were amplified with **forward and reverse full-length primers**, purified, and size-selected for 225-600 5 bp fragments on a Pippin-prep instrument. Finally, the captured material was sequenced using a 150-V3 Illumina sequencing kit.

RESULTS

The paired capture probes that target BRAF (in two loci), MYCN and CDH1 were used to analyze the SNVs in these loci. The results are shown in Table 3.

10 Table 3. Bioinformatic summary

Mutation	Sample NA:ZR	Unique reads by tag and position					No unique filtering				
		Total # reads	change to A	change to C	change to G	change to T	Total # reads	change to A	change to C	change to G	change to T
BRAF-I326T-A-G	1to1	186		0	55	0	34728		6	11308	10
BRAF-I326T-A-G	10to1	171		0	10	0	46464		6	2615	2
BRAF-I326T-A-G	100to1	733		0	3	0	51540		10	89	2
BRAF-I326T-A-G	1000to1	3020		0	3	0	54565		6	19	7
BRAF-E26D-C-A	1to1	171	66		0	0	29192	12388		5	2
BRAF-E26D-C-A	10to1	183	12		0	1	38085	2573		1	4
BRAF-E26D-C-A	100to1	631	3		0	0	38913	110		1	2
BRAF-E26D-C-A	1000to1	2367	1		0	0	46623	13		2	2

CDH1-E243*-G-T	1to1	180	0	0		54	23846	2	1		8556
CDH1-E243*-G-T	10to1	208	0	0		12	42307	1	2		2658
CDH1-E243*-G-T	100to1	728	0	0		4	42440	6	0		129
CDH1-E243*-G-T	1000to1	2727	0	0		0	53632	5	1		7
MYCN-E270Q-G-C	1to1	158	0	47		0	20302	0	5587		0
MYCN-E270Q-G-C	10to1	186	0	14		0	35733	1	2663		2
MYCN-E270Q-G-C	100to1	566	0	3		0	35393	0	247		5
MYCN-E270Q-G-C	1000to1	2101	0	2		0	37223	0	15		2

Column 3 shows the total number unique read counts, which in turn provide bounds on the sensitivity of the assay. The estimated and measured genomic inputs were well within range of one another. The lightly shaded boxes highlight the SNV where the cell line sequence differed from the germ line sequence. In the absence of unique read filtering – shown on the right portion of the table – random base changes at these four selected positions occurred with measurable, non-zero frequencies. Figure 1.

By requiring that changes occur within unique read families, it became possible to sort true signal from error-prone noise. Figure 2.

EXAMPLE 2

10 A NOVEL PROBE DESIGN EFFECTIVE FOR COMPREHENSIVE SEQUENCING OF TARGET REGIONS IN HIGHLY FRAGMENTED GDNA

PURPOSE

The purpose of these experiments is to develop an assay system to reliably and reproducibly interrogate circulating DNAs.

15 BACKGROUND

Analysis of circulating DNA from body fluids represents an exciting, but as yet, unrealized opportunity in molecular diagnostics. Genomic DNA is highly intact.

Literature suggest that the average size of circulating DNA is about 150 bp, which correlates well to the size of DNAs wrapped around a single nucleosomal histone complex.

SUMMARY

5 The technical parameters of targeted sequence capture technology contemplated herein were designed to accommodate highly fragmented DNA and to retain the ability to generate comprehensive sequence coverage of targeted DNA. Capture probe density was increased and the length of capture probe sequences was reduced from 60 nucleotide to 40 nucleotide to minimize uninformative sequence generation in the clone
10 library. The human genome is littered with repetitive sequences and drastic fluctuations in base composition, thus, the suitability of implementing higher capture probe densities and shorter capture probes could not be conceded but required empirical validation of the new assay.

 Conditions were established in which the shorter 40 mer capture probe
15 sequences exhibit reliable and robust assay performance. In a first set of experiments, the assays were used to query two large regions – the coding regions for the tumor suppressor gene TP53 and the long, contiguous, intron 19 of the ALK oncogene, both of which are central to cancer diagnostics. In a second set of experiments, several high density pairwise capture probes that possess shorter 40 nucleotide capture probe
20 sequences were used to interrogate known SNVs that reside in the NCI-H69 cell line.

 The new high density shorter capture probes were successfully used to query short fragmented DNAs and the results indicated that the assay design is well suited to sequencing of circulating DNAs that are found in the plasma fraction of blood.

METHODS - MODIFIED 40 MER CAPTURE PROBES

25 The capture probe sequences used to empirically validate the performance of the 40 mer capture probes are shown in Table 4.

60 mer Capture Probes		
Name	SEQ ID NO:	Sequence
PLP1_ex2_F	68	ATGTGACTGGCACGGGAGTTGATCCTGGTTTTACGGGTTTGAGT GGCATGAGCTACCTACTGGATGTGCCTGACTGTTCCCCTTCTTCT TCCC

PLP1_ex2_R	69	ATGTGACTGGCACGGGAGTTGATCCTGGTTTTTCACCTATCTCCAG GATGGAGAGAGGGAAAAAAGATGGGTCTGTGTGGGAGGGCA7 0GGTACTT
PLP1_ex3_F	70	ATGTGACTGGCACGGGAGTTGATCCTGGTTTTTCACGAAAGAAGCC AGGTCTTCAATTAATAAGATTCCCTGGTCTCGTTTGTCTACCTGTT AATG
PLP1_ex3_M	71	ATGTGACTGGCACGGGAGTTGATCCTGGTTTTTCACCAGACTCGCG CCCAATTTTCCCCACCCCTTGTATTGCCACAAAATCCTGAGGAT GATC
CYP2D6_F	72	ATGTGACTGGCACGGGAGTTGATCCTGGTTTTTCACAAGCACCTAG CCCCATTCCTGCTGAGCAGGAGGTGGCAGGTACCCAGACTGGGA GGTAA
CYP2D6_R	73	ATGTGACTGGCACGGGAGTTGATCCTGGTTTTTCACAGTCGGTGGG GCCAGGATGAGGCCAGTCTGTTACACATGGCTGCTGCCTCTCA GCTCT
chrX_15_F	74	ATGTGACTGGCACGGGAGTTGATCCTGGTTTTTCACCCTGGCCCTC AGCCAGTACAGAAAGTCATTTGTCAAGGCCTTCAGTTGGCAGACG TGCTC
chrX_15_R	75	ATGTGACTGGCACGGGAGTTGATCCTGGTTTTTCACAGAATTCATT GCCAGCTATAAATCTGTGGAAACGCTGCCACACAATCTTAGCACA CAAGA
chrX_69_F	76	ATGTGACTGGCACGGGAGTTGATCCTGGTTTTTCACTTACTTCCCTC CAGTTTGTGTGCTTGCAAACAACAGAATCTTCTCTCCATGAAATC ATG
chrX_69_R	77	ATGTGACTGGCACGGGAGTTGATCCTGGTTTTTCACCAGGGGTATC TATTATCCCCATTTTCTCACAAAGGAAACCAAGATAAAAGGTTTA AATGG
KRAS_ex1_F	78	ATGTGACTGGCACGGGAGTTGATCCTGGTTTTTCACTGTTACCTTTA AAAGACATCTGCTTTCTGCCAAAATTAATGTGCTGAACTTAACT TACC
KRAS_ex1_R	79	ATGTGACTGGCACGGGAGTTGATCCTGGTTTTTCACTTCCCAGTAA ATTACTCTTACCAATGCAACAGACTTTAAAGAAGTTGTGTTTTAC AATGC
KRAS_ex2_F	80	ATGTGACTGGCACGGGAGTTGATCCTGGTTTTTCACTAAATGACAT AACAGTTATGATTTTGCAGAAAACAGATCTGTATTTATTTCACTGT TACT
KRAS_ex2_R	81	ATGTGACTGGCACGGGAGTTGATCCTGGTTTTTCACGACAGGTTTT GAAAGATATTTGTGTTACTAATGACTGTGCTATAACTTTTTTTTCT TTCC
MYC_r2_F1	82	ATGTGACTGGCACGGGAGTTGATCCTGGTTTTTCACCTGTGGCGCG CACTGCGCGCTGCGCCAGGTTTCCGCACCAAGACCCCTTTAACTC AAGAC
MYC_r2_R1	83	ATGTGACTGGCACGGGAGTTGATCCTGGTTTTTCACGGCGGCTAGG GGACAGGGGCGGGGTGGGCAGCAGCTCGAATTTCTTCCAGATATC CTCGC
MYC_r2_F3	84	ATGTGACTGGCACGGGAGTTGATCCTGGTTTTTCACACCGAGCTGC TGGGAGGAGACATGGTGAACCAGAGTTTCATCTGCGACCCGGAC GACGAG
MYC_r2_R3	85	ATGTGACTGGCACGGGAGTTGATCCTGGTTTTTCACAGGAGAGCAG AGAATCCGAGGACGGAGAGAAAGGCGCTGGAGTCTTGCGAGGCGC AGGACT
SRY_r1_F	86	ATGTGACTGGCACGGGAGTTGATCCTGGTTTTTCACCTGTAAGTTA TCGTAAAAAGGAGCATCTAGGTAGGTCTTTGTAGCCAATGTTACC CGATT
SRY_r1_M3	87	ATGTGACTGGCACGGGAGTTGATCCTGGTTTTTCACAATGGCCATT CTTCCAGGAGGCACAGAAATTACAGGCCATGCACAGAGAGAAAT ACCCGA

VHL_r3_F	88	ATGTGACTGGCACGGGAGTTGATCCTGGTTTTACCTTGTTTCGTTCTTGTACTGAGACCCTAGTCTGCCACTGAGGATTTGGTTTTTGCCCTTC
VHL_r3_R	89	ATGTGACTGGCACGGGAGTTGATCCTGGTTTTACATCAAGACTCATCAGTACCATCAAAAGCTGAGATGAAACAGTGTAAGTTTCAACAGAAAT
UGT1A1_r_4F	90	ATGTGACTGGCACGGGAGTTGATCCTGGTTTTACTGTGTCCAGCTGTGAAACTCAGAGATGTAAGTCTGACATCCTCCCTATTTTGCATCTCA
UGT1A1_r_4R	91	ATGTGACTGGCACGGGAGTTGATCCTGGTTTTACATTTGAAACAATTTTATCATGAATGCCATGACCAAAGTATTCTTCTGTATCTTCTTCTT
TNFRSF1_4_r3_F	92	ATGTGACTGGCACGGGAGTTGATCCTGGTTTTACTGATGGGTGGGCTCCCGAAGGGGCTCCCGCAGACTTGCGAAGTTCCCACTCTCTGGGCG
TNFRSF1_4_r3_R	93	ATGTGACTGGCACGGGAGTTGATCCTGGTTTTACCAGGGTGCGGGGGCATCCAGGCTGCCAAGCGGAGGCTGGGCCGGCTGTGCTGGCCTCTT
RUNX1_r_4_F	94	ATGTGACTGGCACGGGAGTTGATCCTGGTTTTACTTTTGAAATGTGGGTTTGTGGCATGAAACGTGTTTCAAGCATAGTTTGACAGATAACG
RUNX1_r_4_R	95	ATGTGACTGGCACGGGAGTTGATCCTGGTTTTACTGCCCTAAAA GTGTATGTATAACATCCCTGATGTCTGCATTGTCTTTGACTGGTGTTT
RHD_r5_F	96	ATGTGACTGGCACGGGAGTTGATCCTGGTTTTACAACCCCTCGAGGCTCAGACCTTTGGAGCAGGAGTGTGATTCTGGCCAACCACCTCTCTG
RHD_r5_R	97	ATGTGACTGGCACGGGAGTTGATCCTGGTTTTACCATAAATATGTGTGCTAGTCCTGTTAGACCCAAGTGCTGCCCAAGGGCAGCGCCCTGCTC
PTEN_r5_F	98	ATGTGACTGGCACGGGAGTTGATCCTGGTTTTACTACTTGTTAATTAAAAATTCAAGAGTTTTTTTTCTTATTCTGAGGTTATCTTTTTACCA
PTEN_r5_R	99	ATGTGACTGGCACGGGAGTTGATCCTGGTTTTACCCAAAAATCTGTTTTCCAATAAATTCTCAGATCCAGGAAGAGGAAAGGAAAAACATCAAAA
EP300_r1_8_F	100	ATGTGACTGGCACGGGAGTTGATCCTGGTTTTACATACTCCATCTCCCGTAAAAATAGTGAGACTTGAGTAATGTTTGATGTCACTTGTC TTTC
EP300_r1_8_R	101	ATGTGACTGGCACGGGAGTTGATCCTGGTTTTACCAGTCACCACATATATTATTCTAGGTATCCCAGAAAAGTTAAAGTCAAATCTGAAACACAT
VHL_r1_F	102	ATGTGACTGGCACGGGAGTTGATCCTGGTTTTACCGCCCCGCGTCCGACCCGCGGATCCCGCGGCGTCCGGCCCCGGGTGGTCTGGATCGCGGAG
VHL_r1_R	103	ATGTGACTGGCACGGGAGTTGATCCTGGTTTTACCCATACGGGCAGCACGACGCGCGGACTGCGATTGCAGAAGATGACCTGGGAGGGCTCGCG
VHL_r1_M1	104	ATGTGACTGGCACGGGAGTTGATCCTGGTTTTACTAGAGGGGCTTCAGACCGTGCTATCGTCCCTGCTGGGTCGGGCCTAAGCGCCGGGCCCGT
VHL_r1_M2	105	ATGTGACTGGCACGGGAGTTGATCCTGGTTTTACGGCGCCGAGGAGGAGATGGAGGCCGGGCGGCCGCGGCCCGTGCTGCGCTCGGTGAACTCG
VHL_r2_F	106	ATGTGACTGGCACGGGAGTTGATCCTGGTTTTACGGTGTGGGCCACCGTGCCCAGCCACCGGTGTGGCTCTTAACAACCTTTGCTTGTC CCGA

VHL_r2_ R	107	ATGTGACTGGCACGGGAGTTGATCCTGGTTTTTACAAGTGGTCTA TCCTGTACTTACCACAACAACCTTATCTTTTTTAAAAAGTAAAACGT CAGT
VHL_r3_F	108	ATGTGACTGGCACGGGAGTTGATCCTGGTTTTTACCTTGTTCGTTT CTTGACTGAGACCCTAGTCTGCCACTGAGGATTTGGTTTTTGGCC TTC
VHL_r3_ R	109	ATGTGACTGGCACGGGAGTTGATCCTGGTTTTTACATCAAGACTC ATCAGTACCATCAAAAGCTGAGATGAAACAGTGTAAGTTTCAACA GAAAT
40 mers		
Name	SEQ ID NO.	Sequence
PLP1_ex2 F 40	110	ATGTGACTGGCACGGGAGTTGATCCTGGTTTTTACACCTACTGGA TGTGCCTGACTGTTTCCCCCTTCTTCTTCCC
PLP1_ex2 R 40	111	ATGTGACTGGCACGGGAGTTGATCCTGGTTTTTACGGGAAAAAAA AGATGGGTCTGTGTGGGAGGGCAGGTACTT
PLP1_ex3 F 40	112	ATGTGACTGGCACGGGAGTTGATCCTGGTTTTTACTTAATAAGAT TCCCTGGTCTCGTTTGTCTACCTGTAAATG
PLP1_ex3 M 40	113	ATGTGACTGGCACGGGAGTTGATCCTGGTTTTTACCCCCACCCCTT GTTATTGCCACAAAATCCTGAGGATGATC
CYP2D6_ F 40	114	ATGTGACTGGCACGGGAGTTGATCCTGGTTTTTACGCTGAGCAGG AGGTGGCAGGTACCCCAGACTGGGAGGTAA
CYP2D6_ R 40	115	ATGTGACTGGCACGGGAGTTGATCCTGGTTTTTACGGCCAGTCT GTTACACATGGCTGCTGCCTCTCAGCTCT
chrX_15_ F 40	116	ATGTGACTGGCACGGGAGTTGATCCTGGTTTTTACGAAAGTCATT TGTCAGGCCTTCAGTTGGCAGACGTGCTC
chrX_15_ R 40	117	ATGTGACTGGCACGGGAGTTGATCCTGGTTTTTACAATCTGTGGA AACGCTGCCACACAATCTTAGCACACAAGA
chrX_69_ F 40	118	ATGTGACTGGCACGGGAGTTGATCCTGGTTTTTACTGCTTGCAAA ACAACAGAATCTTCTCTCCATGAAATCATG
chrX_69_ R 40	119	ATGTGACTGGCACGGGAGTTGATCCTGGTTTTTACATTTTCTCACA AAGGAAACCAAGATAAAAGGTTTAAATGG
KRAS_ex 1 F 40	120	ATGTGACTGGCACGGGAGTTGATCCTGGTTTTTACTGCTTTCTGCC AAAATTAATGTGCTGAACTTAACTTACC
KRAS_ex 1 R 40	121	ATGTGACTGGCACGGGAGTTGATCCTGGTTTTTACCCAATGCAAC AGACTTTAAAGAAGTTGTGTTTTACAATGC
KRAS_ex 2 F 40	122	ATGTGACTGGCACGGGAGTTGATCCTGGTTTTTACATTTTGCAGA AAACAGATCTGTATTTATTTCAGTGTTACT
KRAS_ex 2 R 40	123	ATGTGACTGGCACGGGAGTTGATCCTGGTTTTTACTGTGTTACTA ATGACTGTGCTATAACTTTTTTTCTTCC
MYC_r2_ F1 40	124	ATGTGACTGGCACGGGAGTTGATCCTGGTTTTTACTGCGCCAGGT TTCCGCACCAAGACCCCTTAACTCAAGAC
MYC_r2_ R1 40	125	ATGTGACTGGCACGGGAGTTGATCCTGGTTTTTACGGGGTGGGCA GCAGCTCGAATTCTTCCAGATATCCTCGC
MYC_r2_ F3 40	126	ATGTGACTGGCACGGGAGTTGATCCTGGTTTTTACCATGGTGAAC CAGAGTTTCATCTGCGACCCGACGACGAG
MYC_r2_ R3 40	127	ATGTGACTGGCACGGGAGTTGATCCTGGTTTTTACGACGGAGAGA AGGCGCTGGAGTCTTGCGAGGCGCAGGACT
SRY_r1_F 40	128	ATGTGACTGGCACGGGAGTTGATCCTGGTTTTTACGAGCATCTAG GTAGGTCTTTGTAGCCAATGTTACCCGATT
SRY_r1_ M3 40	129	ATGTGACTGGCACGGGAGTTGATCCTGGTTTTTACGCACAGAAAT TACAGGCCATGCACAGAGAGAAATACCCGA
VHL_r3_F 40	130	ATGTGACTGGCACGGGAGTTGATCCTGGTTTTTACAGACCCTAGT CTGCCACTGAGGATTTGGTTTTTGGCCCTTC
VHL_r3_ R 40	131	ATGTGACTGGCACGGGAGTTGATCCTGGTTTTTACTCAAAAGCTG AGATGAAACAGTGTAAGTTTCAACAGAAAT
UGT1A1_	132	ATGTGACTGGCACGGGAGTTGATCCTGGTTTTTACAGAGATGTAA

r_4F_40		CTGCTGACATCCTCCCTATTTTGCATCTCA
UGT1A1_r_4R_40	133	ATGTGACTGGCACGGGAGTTGATCCTGGTTTTTCACGAATGCCATGACCAAAGTATTCTTCTGTATCTTCTTTCTT
TNFRSF1_4_r3_F_40	134	ATGTGACTGGCACGGGAGTTGATCCTGGTTTTTCACGGGCCTCCCGCAGACTTGCGAAGTTCCCACTCTCTGGGCG
TNFRSF1_4_r3_R_40	135	ATGTGACTGGCACGGGAGTTGATCCTGGTTTTTCACGCTGCCAAGCGGAGGCTGGGCGGCTGTGCTGGCCTCTT
RUNX1_r_4_F_40	136	ATGTGACTGGCACGGGAGTTGATCCTGGTTTTTCACGCCATGAAACGTGTTTCAAGCATAGTTTTGACAGATAACG
RUNX1_r_4_R_40	137	ATGTGACTGGCACGGGAGTTGATCCTGGTTTTTCACAACATCCCTGATGTCTGCATTTGTCTTTGACTGGTGTTT
RHD_r5_F_40	138	ATGTGACTGGCACGGGAGTTGATCCTGGTTTTTCACTTTGGAGCAGGAGTGTGATTCTGGCCAACCACCCTCTCTG
RHD_r5_R_40	139	ATGTGACTGGCACGGGAGTTGATCCTGGTTTTTCACTGTTAGACCCAAGTGCTGCCCAAGGGCAGCGCCCTGCTC
PTEN_r5_F_40	140	ATGTGACTGGCACGGGAGTTGATCCTGGTTTTTCACAAGAGTTTTTTTCTTATTCTGAGGTTATCTTTTTACCA
PTEN_r5_R_40	141	ATGTGACTGGCACGGGAGTTGATCCTGGTTTTTCACAATTCTCAGATCCAGGAAGAGGAAAGGAAAAACATCAAAA
EP300_r1_8_F_40	142	ATGTGACTGGCACGGGAGTTGATCCTGGTTTTTCACATAGTGAGACTTGAGTAATGTTTGATGTCACTTGTCTTTC
EP300_r1_8_R_40	143	ATGTGACTGGCACGGGAGTTGATCCTGGTTTTTCACTAGGTATCCAGAAAAGTTAAAGTCAAATCTGAAACACAT
VHL_r1_F_40	144	ATGTGACTGGCACGGGAGTTGATCCTGGTTTTTCACGATCCCGCGCGTCCGGCCCCGGGTGGTCTGGATCGCGGAG
VHL_r1_R_40	145	ATGTGACTGGCACGGGAGTTGATCCTGGTTTTTCACGCGGACTGCGATTGCAGAAGATGACCTGGGAGGGCTCGCG
VHL_r1_M1_40	146	ATGTGACTGGCACGGGAGTTGATCCTGGTTTTTCACTATCGTCCCTGCTGGGTCTGGGCTAAGCGCCGGGCCCCGT
VHL_r1_M2_40	147	ATGTGACTGGCACGGGAGTTGATCCTGGTTTTTCACGGCCGGGCGGCCGCGGCCGTGCTGCGCTCGGTGAACCTCG
VHL_r2_F_40	148	ATGTGACTGGCACGGGAGTTGATCCTGGTTTTTCACGCCACCGGTGTGGCTCTTTAACAACCTTTGCTTGTCCTCA
VHL_r2_R_40	149	ATGTGACTGGCACGGGAGTTGATCCTGGTTTTTCACACCACAACAACCTTATCTTTTTAAAAAGTAAAACGTCAGT
VHL_r3_F_40	150	ATGTGACTGGCACGGGAGTTGATCCTGGTTTTTCACAGACCCTAGTCTGCCACTGAGGATTTGGTTTTTGCCCTTC
VHL_r3_R_40	151	ATGTGACTGGCACGGGAGTTGATCCTGGTTTTTCACTCAAAAGCTGAGATGAAACAGTGTAAGTTTCAACAGAAAT

The performance of 40 mer capture probes was compared to that of 60 mer capture probes. The 40 mer was designed from the 60 mer by removing 20 nucleotides from the 5' end of the 60 mer. Although the 3' end of both capture probe sets are identical with respect to the sequences that are copied from captured genomic clones,

5 the probe sequence signature (Read 2 of the paired end read) is different between the 60 mer and 40 mer probe sets. This design is useful because it allows the capture probes to be multiplexed during sequencing and their performance subsequently analyzed during downstream bioinformatics deconvolution.

Genomic samples

A pool of 12 genomic DNA samples (chosen from a Coriell human panel of 112 human genomic DNAs) was used as the target DNA. The 12 samples were broken into four sets of four samples each, as shown in detail in Table 5.

Capture probes	Wash temp.	Sample Code	Samples			
60mer	50C	AAT	GM20291	M	Americas	AFRICAN ANCESTRY IN SOUTHWEST USA
		CTA	GM19373	M	WAfrican	LUHYA IN WEBUYE, KENYA
		GGG	HG00428	F	AsianE	HAN CHINESE SOUTH
		TCC	HG01624	M	Euro	IBERIAN POPULATIONS IN SPAIN

40mer	50C	AAT	GM20291	M	Americas	AFRICAN ANCESTRY IN SOUTHWEST USA
		CTA	GM19373	M	WAfrican	LUHYA IN WEBUYE, KENYA
		GGG	HG00428	F	AsianE	HAN CHINESE SOUTH
		TCC	HG01624	M	Euro	IBERIAN POPULATIONS IN SPAIN

60mer	47C	AGA	HG02489	M	Americas	AFRICAN CARIBBEAN IN BARBADOS
		CCT	HG01108	F	Americas	PUERTO RICAN IN PUERTO RICO
		GAC	GM19011	F	AsianE	JAPANESE IN TOKYO, JAPAN
		TTG	GM18946	F	AsianE	JAPANESE IN TOKYO, JAPAN

40mer	47C	AGA	HG02489	M	Americas	AFRICAN CARIBBEAN IN BARBADOS
		CCT	HG01108	F	Americas	PUERTO RICAN IN PUERTO RICO
		GAC	GM19011	F	AsianE	JAPANESE IN TOKYO, JAPAN
		TTG	GM18946	F	AsianE	JAPANESE IN TOKYO, JAPAN

60mer	44C	ATC	NA13783	F	NA13783	GM13783
		CAG	HG03700	F	AsianS	PUNJABI IN LAHORE, PAKISTAN
		GCA	HG03367	M	WAfrican	ESAN FROM NIGERIA
		TGT	NA22991	F	NA22991	GM22991

40mer	44C	ATC	NA13783	F	NA13783	GM13783
		CAG	HG03700	F	AsianS	PUNJABI IN LAHORE, PAKISTAN
		GCA	HG03367	M	WAfrican	ESAN FROM NIGERIA
		TGT	NA22991	F	NA22991	GM22991

5 *Hybridization, washing and sequencing*

Six different hybridization conditions were used to hybridize the 60 mer and 40 mer probes to the genomic target DNA:

- 1) 60mer probes washed at 50° C.
- 2) 40mer probes washed at 50° C.
- 3) 60mer probes washed at 47° C.
- 4) 40mer probes washed at 47° C.
- 5) 60mer probes washed at 44° C.
- 6) 40mer probes washed at 44° C.

For each experiment, the capture probe oligos were combined with partner oligo; the final concentration of duplex capture probe was 1 nM for each capture probe.

Each hybridization reaction had ~ 2.5 µg of genomic library in 40 µl total volume. Each sample was heated to 98° C for 2 min then cooled on ice. 20 µl of capture probe and 90 µl of hybridization buffer were added and the hybridization mix was incubated for 24 hours starting at 80° C and decreasing one degree every 48 minutes to 50° C. The complexes were bound to 20 µl of streptavidin beads in 1 mL total volume of TEzero buffer + 0.05% Tween20 (TT). The beads were washed 3 times, 5 min each with 200 µl of TT, and once at 45° C for 5 min in wash buffer. The beads were then washed with TEzero and each reaction was resuspended in 20 µl TEzero. The complexes were then PCR amplified with full length forward (ACA2_FLFP; SEQ ID NO:152; AATGATACGGCGACCACCGAGATCTACACGTCATGCAGGACCAGAGAATTC GAATACA) and full length reverse (CAC3_FLRP; SEQ ID NO:153; CAAGCAGAAGACGGCATAACGAGATGTGACTGGCACGAGGAGTTGATCCTGGT TTTCAC) primers.

Following amplification and purification, the resulting product masses were measured and equal masses were pooled for sequencing.

25 RESULTS - MODIFIED 40MER PRIMERS

The capture probe performance as a function of length and wash temperature is shown graphically in Figure 3. Overall, the 40 mer capture probes performed as well as the 60 mer capture probes with 44° C and 47° C washes. With the 50° C wash, the 40 mer capture probes exhibit sporadic behavior. These data empirically validate the use

of 40 mer capture probes and wash temperatures in the 44° C to 47° C range when using these reagents.

METHODS – HIGH DENSITY 40 MERS

In general, sequence capture probes are designed using specific “rules.” For example, regions of redundant sequence or that exhibit extreme base composition biases are generally avoided. One key implication of the requirement for high probe density and close spacing of probes along target regions is that there is little or no latitude to move probes in order to accommodate any such probe design rules. In this study, probes were designed based solely on their position relative to one another with no consideration of probe binding sequences; thus, use of this high density approach required empirically validating that the hybridization and processing methods would accommodate such a collection of probes.

The human ALK gene encodes a protein kinase important in early development, but normal ALK gene expression is essentially undetectable in normal adults. Oncogenic ALK fusions are created when intron 19 of ALK undergoes illegitimate recombination to fuse the kinase encoding portion of ALK to the 5′ end of another gene. Such gene fusions often cause ectopic expression of the ALK kinase, which in turn is important in driving the inappropriate cell proliferation observed in pulmonary tumors. In lung cancer, this “other gene” is often EML4, but other fusion partners have also been detected. To create an assay that can detect any possible ALK gene fusion event, 40 nucleotide probes were designed that were placed at 80 nucleotide intervals in intron 19 of ALK. These probes were oriented such that they are antisense relative to the gene (Figure 4). This means that their 3′ terminus extends and copies genic regions that are 5′ to their hybridization site. When fusion genes are present, probe extension from probes positioned near the fusion junction copy junction sequences. The DNA sequences resulting from these junction clones have fusion partner sequences at their 5′ end, the fusion junction sequence, and ALK intron 19 sequences at their 3′ ends (Figure 4B).

Another important diagnostic target in cancer is the TP53 gene. It encodes a tumor suppressor, and it is often inactivated by mutations in cancers. Mutations that

can inactivate gene function are scattered throughout the gene, and hence conclusive sequence-based assays for TP53 inactivating mutations must address the entire coding region and untranslated regions (UTRs) of the gene. Because circulating DNA fragments are short, high density probes were used to interrogate all target regions of the TP53 gene. Unlike ALK, probes for TP53 are placed in both possible orientations (Figure 5). At high probe densities, the cumulative coverage from multiple probes provides uniform deep sequencing coverage of target regions.

The collection of 105 probes used in this study is shown in Table 6. In addition to probes that target the fusion-prone region of ALK and the coding regions of TP53, probes that cover known SNVs in the cell line DNA were also included.

Table 6.

Name_target region	SEQ ID NO:	Probe sequence
ALK_chr2:29446208_fusion_f	154	ATGTGACTGGCACGGGAGTTGATCCTGGTTTTACCGAATGAGGGTGATGTTTTCCGCGGCACCTCCTTCAGGT
ALK_chr2:29446288_fusion_f	155	ATGTGACTGGCACGGGAGTTGATCCTGGTTTTACGTTGTAGTCGGTCATGATGGTCGAGGTGCGGAGCTTGCTC
ALK_chr2:29446368_fusion_f	156	ATGTGACTGGCACGGGAGTTGATCCTGGTTTTACGCAGCTCCTGGTGCTTCCGGCGGTACACTGCAGGTGGGTG
ALK_chr2:29446448_fusion_f	157	ATGTGACTGGCACGGGAGTTGATCCTGGTTTTACCTACACAGGCCACTTCCTACAGGAAGCCTCCCTGGATCTC
ALK_chr2:29446528_fusion_f	158	ATGTGACTGGCACGGGAGTTGATCCTGGTTTTACGAAATACTAATAAAATGATTAAAGAAGGTGTGTCTTTAAT
ALK_chr2:29446608_fusion_f	159	ATGTGACTGGCACGGGAGTTGATCCTGGTTTTCACTATATGGAAAATAATTATTTGTATTATATAGGGCAGAGTC
ALK_chr2:29446688_fusion_f	160	ATGTGACTGGCACGGGAGTTGATCCTGGTTTTCACTATTAGACCCAATATGGTCTGCAGATTTTATTAGAAGAAAT
ALK_chr2:29446768_fusion_f	161	ATGTGACTGGCACGGGAGTTGATCCTGGTTTTCACGTGAACAGCAGACTGTGTTGCAAGTATAACCCACGTGA
ALK_chr2:29446848_fusion_f	162	ATGTGACTGGCACGGGAGTTGATCCTGGTTTTCACGCCATGGAGCCTAAGGAAGTTTCAGCAAGGCCCTAAGGGG
ALK_chr2:29446928_fusion_f	163	ATGTGACTGGCACGGGAGTTGATCCTGGTTTTACCCAGGAATTGGCCTGCCTTAGTATTTCTGCTGTGCTCAG
ALK_chr2:29447008_fusion_f	164	ATGTGACTGGCACGGGAGTTGATCCTGGTTTTCACTTTGAGGGTGACGTGGGATCTTGGTCAGTTGTGTTTCCT
ALK_chr2:29447088_fusion_f	165	ATGTGACTGGCACGGGAGTTGATCCTGGTTTTCACCACATCATGAAAAGATCTCTGAATTGGTGTCTGGGGATCT
ALK_chr2:29447168_fusion_f	166	ATGTGACTGGCACGGGAGTTGATCCTGGTTTTCACTGAGGACCAGGTCACAGGACCTCTTTGGACTGCAGTTTCC
ALK_chr2:29447248_fusion_f	167	ATGTGACTGGCACGGGAGTTGATCCTGGTTTTCACTAACCCTGCCACTCCCCACCCTCTAGGGTTGTCAATGAA
ALK_chr2:29447328_fusion_f	168	ATGTGACTGGCACGGGAGTTGATCCTGGTTTTCACGAGCTCTACCAATGTGAGTGACCATTATCACTCCTACATG
ALK_chr2:29447408_fusion_f	169	ATGTGACTGGCACGGGAGTTGATCCTGGTTTTCACAAATGTGATTCAAGTGGGTAGATTCTGTGTGTAAAGCCC
ALK_chr2:29447488_fusion_f	170	ATGTGACTGGCACGGGAGTTGATCCTGGTTTTCACTATGTGCTCAGTTCCCTCCTCTATGCAATGGACCGACCGT
ALK_chr2:29447568_fusion_f	171	ATGTGACTGGCACGGGAGTTGATCCTGGTTTTCACGTGTA

fusion_f		AATTGCCGAGCACGTAGTAACCATGCAACAAGTGT
ALK_chr2:29447648_fusion_f	172	ATGTGACTGGCACGGGAGTTGATCCTGGTTTTCACTGGGGACACAGTGTGTGCTGCCATCTCCCTTCTACCGGCA
ALK_chr2:29447728_fusion_f	173	ATGTGACTGGCACGGGAGTTGATCCTGGTTTTCACAAGAGCCTTTCCCTCTGCCCTTTTCAAGCCTCTGCCCATC
ALK_chr2:29447808_fusion_f	174	ATGTGACTGGCACGGGAGTTGATCCTGGTTTTCACGACCACTAGTTCCTCTGTGACCTGCAGGTCAGCTCACC
ALK_chr2:29447888_fusion_f	175	ATGTGACTGGCACGGGAGTTGATCCTGGTTTTCACTTTTCCTATCTCTCTGCCTGGAGGGTGGTGGAGGGCTGGTT
ALK_chr2:29447968_fusion_f	176	ATGTGACTGGCACGGGAGTTGATCCTGGTTTTCACAAACAGGAGCTGCGCCGGTGGAAAGCATGTGGGAGCTAGAA
ALK_chr2:29448048_fusion_f	177	ATGTGACTGGCACGGGAGTTGATCCTGGTTTTCACGGACACTGAAGGAGCTCCCCACCCCTGATCAGCCAGGAG
ALK_chr2:29448128_fusion_f	178	ATGTGACTGGCACGGGAGTTGATCCTGGTTTTCACGGGAACCTGCAGCTGCTCTGGTGGGGGGAAGGTTGGGAGCT
ALK_chr2:29448208_fusion_f	179	ATGTGACTGGCACGGGAGTTGATCCTGGTTTTCACACCCAATTCCAGGACTAGCATAACGAAGTGACACCTTGG
ALK_chr2:29448288_fusion_f	180	ATGTGACTGGCACGGGAGTTGATCCTGGTTTTCACCTGCCTCCCTTGGGAGTCCCTGGGGCTCTGTGCACTCACC
MYCNr1f_40	181	ATGTGACTGGCACGGGAGTTGATCCTGGTTTTCACGGAAGCACCCCCGGTATTAAACGAACGGGGCGGAAAGAA
MYCNr1r_40	182	ATGTGACTGGCACGGGAGTTGATCCTGGTTTTCACCTAACAAAGGGGACGCGACCCGGGTCCAGTGCCCCAGGG
MYCNr1f2_40	183	ATGTGACTGGCACGGGAGTTGATCCTGGTTTTCACCTGGGGGACTGGGTGGCCTCACCCCCAACCCGGTCATC
MYCNr1r2_40	184	ATGTGACTGGCACGGGAGTTGATCCTGGTTTTCACCGCGCTCCAGCTTCTCGCGGGCGGAGAAGCCGCTCCACAT
MYCNr1f3_40	185	ATGTGACTGGCACGGGAGTTGATCCTGGTTTTCACCCACCCGGCCCGAGTGCGTGGATCCCGCCGTGGTCTT
MYCNr1r3_40	186	ATGTGACTGGCACGGGAGTTGATCCTGGTTTTCACGGGACCGGGCGCTGGCTCGCGCTTGTTACGGGAAGGGG
MYCNr2f_40	187	ATGTGACTGGCACGGGAGTTGATCCTGGTTTTCACAAATGGATATATATGTGAATTTCAATCAAATGGTTCTCA
MYCNr2r_40	188	ATGTGACTGGCACGGGAGTTGATCCTGGTTTTCACTAAACCAACATTCTTAATGTCAACACAATGTTTGTAAAA
MYCNr2f2_40	189	ATGTGACTGGCACGGGAGTTGATCCTGGTTTTCACCCCTACGTGGAGAGTGAGGATGCACCCCCACAGAAGAAGA
MYCNr2r2_40	190	ATGTGACTGGCACGGGAGTTGATCCTGGTTTTCATATGACACTCTTGAGCGGACGTGGGGACGCCTCGCTCTTA
MYCNr2f3_40	191	ATGTGACTGGCACGGGAGTTGATCCTGGTTTTCACTCTCACGCTCAGGGACCACGTGCCGGAGTTGGTAAAGAAT
MYCNr2r3_40	192	ATGTGACTGGCACGGGAGTTGATCCTGGTTTTCACCAGTGGCCTTTTCAAAATGACCACCTTGGCGGCCTCTC
TP53_chr17:7579779:region_1:75nt:-59:-20:f	193	ATGTGACTGGCACGGGAGTTGATCCTGGTTTTACGCTAGGGGCTGGGGTGGGGTGGGGTGGTGGGCCTGCC
TP53_chr17:7579838:region_1:75nt:1:40:f	194	ATGTGACTGGCACGGGAGTTGATCCTGGTTTTACCAAGTTTCCATAGGTCTGAAAATGTTTCCTGACTCAGAGGG
TP53_chr17:7579878:region_1:75nt:41:+5:r	195	ATGTGACTGGCACGGGAGTTGATCCTGGTTTTACCTGCCATGGAGGAGCCGAGTCAGATCCTAGCGTCGAGCC
TP53_chr17:7579932:region_1:75nt:+20:+59:r	196	ATGTGACTGGCACGGGAGTTGATCCTGGTTTTCACTCATGCTGGATCCCCACTTTTCTCTTGCAGCAGCCAGAC
TP53_chr17:7579640:region_2:23nt:-59:-20:f	197	ATGTGACTGGCACGGGAGTTGATCCTGGTTTTCACAGCCCAGAGCCCTCCAGGTCCCCAGCCCTCCAGGTCCCC
TP53_chr17:7579741:	198	ATGTGACTGGCACGGGAGTTGATCCTGGTTTTCACGCAGA

region_2:23nt:+20:+59 :r		GACCTGTGGGAAGCGAAAATTCCATGGGACTGACT
TP53_chr17:7579252: region_3:280nt:-59:- 20:f	199	ATGTGACTGGCACGGGAGTTGATCCTGGTTTTACGCAGG GGGATACGGCCAGGCATTGAAGTCTCATGGAAGCC
TP53_chr17:7579311: region_3:280nt:1:40:f	200	ATGTGACTGGCACGGGAGTTGATCCTGGTTTTACCCCGTG CAAGTCACAGACTTGGCTGTCCCAGAATGCAAGAA
TP53_chr17:7579351: region_3:280nt:41:80:r	201	ATGTGACTGGCACGGGAGTTGATCCTGGTTTTACCCAGA AAACCTACCAGGGCAGCTACGGTTTCCGTCTGGGC
TP53_chr17:7579391: region_3:280nt:81:120 :f	202	ATGTGACTGGCACGGGAGTTGATCCTGGTTTTACGAAGG GACAGAAGATGACAGGGGCCAGGAGGGGGCTGGTG
TP53_chr17:7579431: region_3:280nt:121:16 0:r	203	ATGTGACTGGCACGGGAGTTGATCCTGGTTTTACGTGGC CCCTGCACCAGCAGCTCCTACACCGGCGGCCCTG
TP53_chr17:7579471: region_3:280nt:161:20 0:f	204	ATGTGACTGGCACGGGAGTTGATCCTGGTTTTACGGGGG GAGCAGCCTCTGGCATTCTGGGAGCTTCATCTGGA
TP53_chr17:7579511: region_3:280nt:201:24 0:r	205	ATGTGACTGGCACGGGAGTTGATCCTGGTTTTACCCCCG GACGATATTGAACAATGGTTCACTGAAGACCCAGG
TP53_chr17:7579610: region_3:280nt:+20:+5 9:r	206	ATGTGACTGGCACGGGAGTTGATCCTGGTTTTACCTGGG GGGCTGGGGGGCTGAGGACCTGGTCCTCTGACTGC
TP53_chr17:7578327: region_4:185nt:-43:- 4:f	207	ATGTGACTGGCACGGGAGTTGATCCTGGTTTTACCCTGG GCAACCAGCCCTGTCGTCTCTCCAGCCCCAGCTGC
TP53_chr17:7578370: region_4:185nt:1:40:f	208	ATGTGACTGGCACGGGAGTTGATCCTGGTTTTACCCATC GCTATCTGAGCAGCGCTCATGGTGGGGGCAGCGCC
TP53_chr17:7578410: region_4:185nt:41:80:r	209	ATGTGACTGGCACGGGAGTTGATCCTGGTTTTACGCCAT CTACAAGCAGTCACAGCACATGACGGAGGTTGTGA
TP53_chr17:7578450: region_4:185nt:81:120 :f	210	ATGTGACTGGCACGGGAGTTGATCCTGGTTTTACCATGG CGCGGACGCGGGTGCCGGGCGGGGGTGTGGAATCA
TP53_chr17:7578490: region_4:185nt:121:16 0:r	211	ATGTGACTGGCACGGGAGTTGATCCTGGTTTTCACTTTGC CAACTGGCCAAGACCTGCCCTGTGCAGCTGTGGGT
TP53_chr17:7578574: region_4:185nt:+20:+5 9:r	212	ATGTGACTGGCACGGGAGTTGATCCTGGTTTTCACTGCTTT ATCTGTTCACTTGTGCCCTGACTTTCAACTCTGT
TP53_chr17:7578117: region_5:114nt:-59:- 20:f	213	ATGTGACTGGCACGGGAGTTGATCCTGGTTTTACGAGGG CCACTGACAACCACCCTTAACCCCTCCTCCCAGAG
TP53_chr17:7578176: region_5:114nt:1:40:f	214	ATGTGACTGGCACGGGAGTTGATCCTGGTTTTACCCTCA GGCGGCTCATAGGGCACCACCACACTATGTCGAAA
TP53_chr17:7578216: region_5:114nt:41:80:r	215	ATGTGACTGGCACGGGAGTTGATCCTGGTTTTACAGGAA ATTTGCGTGTGGAGTATTTGGATGACAGAAACACT
TP53_chr17:7578292: region_5:114nt:+3:+42 :r	216	ATGTGACTGGCACGGGAGTTGATCCTGGTTTTACCCAGG GTCCCCAGGCCTCTGATTCTCACTGATTGCTCTT
TP53_chr17:7577439: region_6:111nt:-59:- 20:f	217	ATGTGACTGGCACGGGAGTTGATCCTGGTTTTACGAGGC AAGCAGAGGCTGGGGCACAGCAGGCCAGTGTGCAG
TP53_chr17:7577498: region_6:111nt:1:40:f	218	ATGTGACTGGCACGGGAGTTGATCCTGGTTTTACCCTGG AGTCTTCCAGTGTGATGATGGTGAGGATGGGCCTC
TP53_chr17:7577538: region_6:111nt:41:80:r	219	ATGTGACTGGCACGGGAGTTGATCCTGGTTTTCACTAC ATGTGTAACAGTTCCTGCATGGGCGGCATGAACCG

TP53_chr17:7577628: region_6:111nt:+20:+5 9:r	220	ATGTGACTGGCACGGGAGTTGATCCTGGTTTTACCTTGC CACAGGTCTCCCCAAGGCGCACTGGCCTCATCTTG
TP53_chr17:7576974: region_7:138nt:-44:- 5:f	221	ATGTGACTGGCACGGGAGTTGATCCTGGTTTTACCTGCA CCCTTGGTCTCCTCCACCGCTTCTTGTCTGCTTG
TP53_chr17:7577018: region_7:138nt:1:40:f	222	ATGTGACTGGCACGGGAGTTGATCCTGGTTTTACCCTCG CTTAGTGCTCCCTGGGGGCAGCTCGTGGTGAGGCT
TP53_chr17:7577058: region_7:138nt:41:80:r	223	ATGTGACTGGCACGGGAGTTGATCCTGGTTTTACGACCG GCGCACAGAGGAAGAGAATCTCCGCAAGAAAGGGG
TP53_chr17:7577098: region_7:138nt:81:120 :f	224	ATGTGACTGGCACGGGAGTTGATCCTGGTTTTCACTCTCC CAGGACAGGCACAAACACGCACCTCAAAGCTGTTC
TP53_chr17:7577138: region_7:138nt:121:+2 2:r	225	ATGTGACTGGCACGGGAGTTGATCCTGGTTTTCACTCTCTT TTCCTATCCTGAGTAGTGGAATCTACTGGGACG
TP53_chr17:7577175: region_7:138nt:+20:+5 9:r	226	ATGTGACTGGCACGGGAGTTGATCCTGGTTTTACGGACA GGTAGGACCTGATTTTCCTTACTGCCTCTTGCTTCT
TP53_chr17:7576793: region_8:75nt:-59:- 20:f	227	ATGTGACTGGCACGGGAGTTGATCCTGGTTTTACGGCAT TTTGAGTGTTAGACTGGAACTTTCCACTTGATAA
TP53_chr17:7576852: region_8:75nt:1:40:f	228	ATGTGACTGGCACGGGAGTTGATCCTGGTTTTACCCTGA AGGGTGAAATATTCTCCATCCAGTGGTTTCTTCTT
TP53_chr17:7576892: region_8:75nt:41:+5:r	229	ATGTGACTGGCACGGGAGTTGATCCTGGTTTTACCCTAG CACTGCCCAACAACACCAGCTCCTCTCCCCAGCCA
TP53_chr17:7576931: region_8:75nt:+5:+44: r	230	ATGTGACTGGCACGGGAGTTGATCCTGGTTTTCACTGCCT CAGATTCACTTTTATCACCTTTCCTTGCCCTCTTTC
TP53_chr17:7573867: region_9:108nt:-59:- 20:f	231	ATGTGACTGGCACGGGAGTTGATCCTGGTTTTCACATGGC TTTCCAACCTAGGAAGGCAGGGGAGTAGGGCCAGG
TP53_chr17:7573926: region_9:108nt:1:40:f	232	ATGTGACTGGCACGGGAGTTGATCCTGGTTTTACCCTGG AGTGAGCCCTGCTCCCCCTGGCTCCTTCCCAGCC
TP53_chr17:7573966: region_9:108nt:41:80:r	233	ATGTGACTGGCACGGGAGTTGATCCTGGTTTTCACTCCGA GAGCTGAATGAGGCCTTGAACCTCAAGGATGCCCA
TP53_chr17:7574053: region_9:108nt:+20:+5 9:r	234	ATGTGACTGGCACGGGAGTTGATCCTGGTTTTACCATCT TTTAACTCAGGTACTGTGTATATACTTACTTCTCC
TP53_chr17:7572867: region_10:83nt:-59:- 20:f	235	ATGTGACTGGCACGGGAGTTGATCCTGGTTTTACGGCAG GGGAGGGAGAGATGGGGGTGGGAGGCTGTCACTGG
TP53_chr17:7572926: region_10:83nt:1:40:f	236	ATGTGACTGGCACGGGAGTTGATCCTGGTTTTACGTCAG TCTGAGTCAGGCCCTTCTGTCTTGAACATGAGTTT
TP53_chr17:7572966: region_10:83nt:41:80:r	237	ATGTGACTGGCACGGGAGTTGATCCTGGTTTTACCCTGA AGTCCAAAAAGGGTCAGTCTACCTCCCCGCCATAAA
TP53_chr17:7573028: region_10:83nt:+20:+5 9:r	238	ATGTGACTGGCACGGGAGTTGATCCTGGTTTTACGGCAC AGACCCTCTCACTCATGTGATGTCATCTCTCCTCC
ALDH4A1_chr1:1919 9369_rs61757683:G:T :f	239	ATGTGACTGGCACGGGAGTTGATCCTGGTTTTACCAGGG GCTTATGTGTCTCCTTGATGACCTGCGGCGACGTC
ALDH4A1_chr1:1919 9488_rs61757683:G:T :r	240	ATGTGACTGGCACGGGAGTTGATCCTGGTTTTACCCATC ATCTCCTCCCTTCCCCTTCTGCCAGGCTGTTGCA
BRCA1_chr17:412230 15_rs1799966:T:A,C:f	241	ATGTGACTGGCACGGGAGTTGATCCTGGTTTTCACAATTC TGGCTTCTCCCTGCTCACACTTCTTCCATTGCAT

BRCA1_chr17:41223134 rs1799966:T:A,C:r	242	ATGTGACTGGCACGGGAGTTGATCCTGGTTTTTCACGTCAGCTCGTGTTGGCAACATACCATCTTCAACCTCTGCA
BRCA1_chr17:41243921 rs16942:T:C:f	243	ATGTGACTGGCACGGGAGTTGATCCTGGTTTTCTACTAATTCTTTGGCCCCTCTTCGGTAACCCTGAGCCAAATGT
BRCA1_chr17:41244040 rs16942:T:C:r	244	ATGTGACTGGCACGGGAGTTGATCCTGGTTTTTCACGGTGAATAAAGGAAGATACTAGTTTTGCTGAAAATGACA
BRCA2_chr13:32906670 rs144848:A:C:f	245	ATGTGACTGGCACGGGAGTTGATCCTGGTTTTTCACACTCATTTGTATCTGAAGTGGAACCAAATGATACTGATCC
BRCA2_chr13:32906769 rs144848:A:C:r	246	ATGTGACTGGCACGGGAGTTGATCCTGGTTTTTCACAGTTGAGACCATTACAGGCCAAAGACGGTACAACCTCCT
CDKN2A_chr9:21970837 rs3731249:C:T:f	247	ATGTGACTGGCACGGGAGTTGATCCTGGTTTTTCACGAAAA TGAATGCTCTGAGCTTTGGAAGCTCTCAGGGTACA
CDKN2A_chr9:21970956 rs3731249:C:T:r	248	ATGTGACTGGCACGGGAGTTGATCCTGGTTTTTCACGGGCCATCGCGATGTGCGACGGTACCTGCGCGCGGCTGCG
DPYD_chr1:97981316 rs1801159:T:C:f	249	ATGTGACTGGCACGGGAGTTGATCCTGGTTTTTCACCCCCATCCAGCTTCAAAAGCTCTTCGAATCATTGATGTGC
DPYD_chr1:97981435 rs1801159:T:C:r	250	ATGTGACTGGCACGGGAGTTGATCCTGGTTTTTCACCTGCCAAGCCTGAACCTACCCCTCTTTTACACTCCTATTGAT
EPHX1_chr1:226026327 rs2234922:A:G:f	251	ATGTGACTGGCACGGGAGTTGATCCTGGTTTTTCACCCACCCTGACTGTGCTCTGTCCCCCAGGGCTGGACATCC
EPHX1_chr1:226026446 rs2234922:A:G:r	252	ATGTGACTGGCACGGGAGTTGATCCTGGTTTTTCACAGTCA GGAGTGGGATGATCTTATAAACTCGTAGAAAGAG
MYC_chr8:128750752 G123E:f	253	ATGTGACTGGCACGGGAGTTGATCCTGGTTTTTCACCTTCG GGGAGACAACGACGGCGGTGGCGGGAGCTTCTCCA
MYC_chr8:128750871 G123E:r	254	ATGTGACTGGCACGGGAGTTGATCCTGGTTTTTCACCATAC AGTCCTGGATGATGATGTTTTTGATGAAGGTCTCG
RB1_chr13:49039115 rs121913297:G:T:f	255	ATGTGACTGGCACGGGAGTTGATCCTGGTTTTTCACCTTTTAC TGTCTCTCCTCAGACATTCAAACGTGTTTTGATC
RB1_chr13:49039204 rs121913297:G:T:r	256	ATGTGACTGGCACGGGAGTTGATCCTGGTTTTTCACGTGGA AGCATACTGCCAAAATATTGTTTTTCAGTCTCTGCA
TNFRSF14_chr1:2491227 rs2234163:G:A:f	257	ATGTGACTGGCACGGGAGTTGATCCTGGTTTTTCACACGTAC CCCCTCTCAGCCCCCTCCTCTTGACTCCAGCCATG
TNFRSF14_chr1:2491346 rs2234163:G:A:r	258	ATGTGACTGGCACGGGAGTTGATCCTGGTTTTTCACGTGGC GTAAGCGCGGCACGCGGCGCAGTGGTCCCCGTCCT

Genomic samples

Three samples of genomic DNA were analyzed::

- 1) Germline sample NA 06994 - a normal human sample obtained from the Coriell repository;
- 5 2) Cancer cell line NCI-H69 – a cell line known to harbor a mutation in TP53, an amplification of the MYCN locus, and SNVs in ALDH4A1, BRCA1, BRCA2, CDKN2A, DPYD, EPHX1, MYC, RB1 and TNFRSF14 that were included in the target probe set;
- 3) Cancer cell line ZR-75-1, which was reported to harbor an EML4-ALK fusion gene (Lin *et al.*, *Mol. Cancer Res.* 7(9):1466, 2009).
- 10

DNA sequencing libraries are generally constructed from sheared DNA fragments. Acoustic disruption was used to generate DNA fragments that ranged in

size from 200 to >500 bp. Enzymatic fragmentation of the acoustically fragmented DNA was performed in an effort to emulate circulating DNA, which is reputed to be composed of nucleosomal, ~150 bp fragments. Briefly, DNA at 20-40 ng/μl was sonicated on the 200 bp setting, which yields fragments that range in size from 150 bp to 400 bp in a broad smear. The DNA was further fragmented by the addition of 0.01 and 0.02 μl of DNase enzyme (New England Biolabs recombinant bovine DNase) to 50 μl aliquots of DNA in DNase buffer (10 mM Tris pH 8.0, 2.5 mM MnCl₂, 0.5 mM CaCl₂). The DNase reaction was incubated at 37° C for 10 min and stopped with the addition of 0.5 M EDTA to a final concentration of 25 mM. DNA with an average size of 150 bp was purified by “two-sided” bead selection by first adding 0.9 volumes of beads to 1 volume of DNA. The beads bind unwanted larger fragments and are discarded, and an additional 1.6 volumes of beads are added to the supernatant. The bound material is then purified and quantified. An agarose gel of the resulting, highly fragmented, short DNA used for library construction is shown in Figure 6.

Fragmented DNA was end-repaired using the Quick Blunt kit from NEB and blended in the ratios shown in Table 7. Ten nanograms of blended DNA were then ligated to adaptors with the sequences shown in Table 7. For mixes 9 and 15, two ligation reactions with 10 ng each were performed and subsequently pooled. For mix 16, four reactions were done. An estimate of genomic inputs into each library using a qPCR assay is also shown in Table 7.

Table 7. Samples and admixture ratios

Sample	Admix ratio	Code	SEQ ID NO.	Genomic inputs
1)NA06994 = GL	pure	NNNNNAAGATCTTAGTGGCAC	259	202
2)NCI-H69 = N	pure	NNNNNCGACAGAACTATTGCC	260	149
3)ZR-75-1 = Z	pure	NNNNNACTATCTTAGTGGCAC	261	242
4)GL:N	1:1	NNNNNCTCCAGAACTATTGCC	262	200
5)GL:N	2:1	NNNNNAGCATCTTAGTGGCAC	263	83
6)GL:N	4:1	NNNNNCATCAGAACTATTGCC	264	186
7)GL:N	10:1	NNNNNATAATCTTAGTGGCAC	265	264
8)GL:N	20:1	NNNNNAAGAAGGTAGACCCTC	266	203
9)GL:N	100:1	NNNNNTTCTCTACTCGTGAC	267	436
10)GL:Z	1:1	NNNNNACTAAGGTAGACCCTC	268	297
11)GL:Z	2:1	NNNNNGAAGCTACGAGTATCC	269	224
12)GL:Z	4:1	NNNNNAGCAAGGTAGACCCTC	270	73
13)GL:Z	10:1	NNNNNCATTGACGTCTAGAGC	271	181

14)GL:Z	20:1	NNNNNTCACTCTACTCGTGAC	272	224
15)GL:Z	100:1	NNNNNATAAAGGTAGACCCTC	273	580
16)GL:N:Z	500:1:1	NNNNNTACCTCTACTCGTGAC	274	1324

Targeted sequencing

One microgram of each of the sixteen DNA libraries shown in Table 7 were pooled and adjusted to a final volume of 160 μ L. Eight identical 20 μ L aliquots were denatured at 98° C, cooled on ice, and 20 μ L of probes (Table 6) at 1 nM/probe and 50 μ L of CF hyb buffer were added. The samples were annealed for 24 hours from 80° C to 50° C, washed, and amplified. Following amplification of the resulting captured and processed fragments, the final sequencing library was size selected using the Pippin Prep™ instrument with a size selection of 175 – 400 bp. The library was sequenced on an Illumina MiSeq using a 150 read V3 kit.

10 RESULTS

Capture probe performance of high density capture probes that were chosen based on their position with target sequences were monitored. A graphical display of the performance of each capture probe is shown in Figure 7. These data demonstrate that:

- 15 1) all capture probes chosen strictly by positional constraint provided on-target sequence information;
 - 2) most capture probes exhibit very little off-target and unmappable read capture; and
 - 3) the yield of useful, on-target reads was substantially uniform.
- 20 Capture probes that captured a high proportion of off-target and unmappable reads were analyzed further. These capture probes were generally positioned in regions of low sequence complexity/high sequence redundancy. Here, however, such capture probes had no significant detrimental impact on the sequencing depth because the high level of probe redundancy (high density probes) means that all regions are covered by reads
- 25 derived from several probes. The net effect was excellent uniformity of coverage. See, *e.g.*, Figure 8, probe coverage for the TP53 gene using the 40 mer capture probes.

CONCLUSION

Taken together, these data demonstrate that capture probe length can be reduced from 60 nucleotides to 40 nucleotides with little or no discernible loss of probe performance (once capture wash temperatures are adjusted). They also show that probe design can follow positional constraints and can generally ignore sequence context or composition. Even though this methodology produces the occasional poor-performing probe, the high redundancy at close probe spacing more than compensates for individual probe deficiencies.

EXAMPLE 3

10 GENETIC ANALYSIS OF CIRCULATING DNA

PURPOSE

The purpose of this example was to benchmark the genetic analysis of cfDNA using an efficient cloning procedure for cfDNA and target retrieval system.

BACKGROUND

15 While there is tremendous enthusiasm in the scientific and health-care community for “liquid biopsies” – analysis of circulating DNA (cfDNA) for markers associated with potential disease states, there is remarkably little practical information about this potential analyte.

SUMMARY

20 Plasma samples collected from healthy donors and individuals suffering from either ovarian or colon cancers were used to perform the genetic analysis of circulating DNA. The amount and the overall character of circulating cfDNA can vary widely from individual to individual. Surprisingly, the present inventors found that cfDNA is readily clonable with an efficiency indistinguishable from highly purified and
25 fragmented genomic DNA; that the fragment size was remarkably consistent, with an average clone insert size of 170 ± 10 bp (in 7/8 samples); and that the genome representation from such samples was uniform and comparable to experiments

performed using purified gDNA. It was further established that by counting unique reads, the depth of representation in each library provided an estimate of minor allele frequency for tumor markers present in the cfDNA of diseased patients. This study established that construction and target retrieval systems contemplated herein were effectively applied to the quantitative genetic analysis of cfDNA.

METHODS

DNA purification

Eight sets of plasma samples were purchased from Proteogenex, Inc., Culver City, CA (Table 8). Circulating DNA was extracted from the samples (on two separate occasions) using the Circulating Nucleic Acid Purification kit from Qiagen. Samples were passed through DNA mini-columns using centrifugation. The specimen IDs and yield of DNA are shown in Table 8.

Table 8. Plasma samples and cfDNA yields

Sample ID	Patient diagnosis	Specimen type	Volume	DNA yield (ng per mL of input)
D5930P	Healthy donor	plasma	4 mL	11
D5942P	Healthy donor	plasma	4 mL	68
023407P	Colorectal cancer	plasma	4 mL	10
023406P	Colorectal cancer	plasma	4 mL	63
023185P	Colorectal cancer	plasma	4 mL	171
023149P	Colorectal cancer	plasma	4 mL	36
032667P	Ovarian cancer	plasma	4 mL	24
032676P	Ovarian cancer	plasma	4 mL	13

Library construction

Purified DNA from 4 mL of plasma was collected in 100 µl elution buffer. For the four samples collected from colon cancer patients (CRC), the DNA was split in half and one 50 µl aliquot from each patient was sonicated to 200 bp. One 50 µl aliquot of untreated cfDNA and one 50 µl fragmented cfDNA from each patient (the entire sample from each patient) was end repaired by adding (per sample):

- 6 µl of 10X quick blunt buffer (New England Biolabs (NEB))
- 0.6 µl of 10 mM dNTPs
- 2.4 µl of quick blunt enzyme mix

- 1.2 µl of PreCR enzyme mix.

Samples were incubated at 20° C for 30 min and at 70° C for 10 min. Ligations with adaptors (Table 2) were performed by combining:

- 60 µl end-repaired cfDNA
- 12 µl adaptor duplex (10 µM)
- 10 µl 10X ligase buffer (NEB)
- 15 µl 50% PEG₈₀₀₀
- 3 µl HC T4 DNA ligase

Table 9. Samples and codes used for four CRC plasma samples

Progenex ID	Sample #	Pretreatment	Adapter
23149	1	none	NNNNNTTTTGTGTGTGTGTG (SEQ ID NO:275)
23407	2	none	NNNNNACTACACACACACAC (SEQ ID NO:276)
23406	3	none	NNNNNCTCGTGTGTGTGTGT (SEQ ID NO:277)
23185	4	none	NNNNNGAACACACACACACA (SEQ ID NO:278)
23149	5	frag	NNNNNCATGTGTGTGTGTGT (SEQ ID NO:279)
23407	6	frag	NNNNNGTGCACACACACACA (SEQ ID NO:280)
23406	7	frag	NNNNNATAACACACACACAC (SEQ ID NO:281)
23185	8	frag	NNNNNTACTGTGTGTGTGTG (SEQ ID NO:282)

- 10 Reactions were incubated at 22° C for one hour and 65° C for 10 min. Ligation products were purified by the addition of 100 µl beads, washing, and elution in 40 µl TEzero. All 40 µl of ligation product was amplified by PCR with primer ACA2 (SEQ ID NO:283) and the samples were combined in equal mass for targeted capture.

Targeted sequence capture and sequencing

- 15 The four unfragmented and four fragmented colon plasma samples (Figure 9C) were hybridized with our high-density, 40 nucleotide probe set that targets TP53, ALK, among others. The capture complexes were processed as described above in Example 2.

RESULTS

- 20 *Library appearance*

A false-color picture of a 2% agarose gel loaded with 50 ng of each library is shown in Figure 9A. The average fragment size was in a tight range of 260 ± 20 bp. These data indicated that the clonable fraction of cfDNA is present predominantly as

nucleosomal fragments. In addition, the size of the cfDNA libraries had the same basic superficial appearance as cfDNA in kidney dialysis patients (Atamaniuk *et al.*, *Clinical Chemistry* 52(3):pp. 523-26 (2006)) except that the cfDNA libraries were shifted to higher mass by the addition of adaptor sequences (Figure 9B). In contrast, the cfDNA libraries differed dramatically from sonicated gDNA libraries, which appear as broad smears.

Four additional sets of cfDNA libraries were constructed from the two ovarian cancer patient plasma samples and two plasma samples from healthy volunteers. 38 µl aliquots of cfDNA were end-repaired in 50 µl total volume.. Ligations included 40 µl of end-repaired fragment, 16 µl of adaptor (10 µM), 8 ul of 10X ligase buffer, 16 µl of 50% PEG and 4 µl of HC T4 DNA ligase in a total volume of 80 µl . The ligation reaction was incubated at 20° C for 1 hour and 65° C for 10 min. For purification, 20 µl of TEzero and 150 µl of beads were added. The purified ligation products were resuspended in 40 µl , all of which was used in a subsequent 200 µl library amplification by PCR. The resulting amplified libraries are shown in Figure 9C.

Sequencing data analysis

The average unique read count observed in each of the eight libraries ranges from ~700 unique reads to >3000 unique reads, defining a range of sensitivities from ~0.15% to ~0.03%. Figure 10. A rare mutant read will likely be observed more than once, meaning minimum sensitivities are less than those calculated above. In preferred embodiments, unique reads provide the lower bound on statistically defensible observation frequencies.

cfDNA cloning efficiency

Sample 23407 was used as a benchmark. 10 ng/mL of cfDNA was recovered from the plasma sample and 20 ng of the isolated cfDNA was used in each of two library construction efforts. The unique read counts indicated that we recovered an average of 700 unique reads (genome equivalents) from unfragmented DNA (“23407” in Figure 10). Given that each genome contains 0.003 ng of gDNA, 2.1 ng of input DNA in this library (10% cloning efficiency) was recovered.

Fragmentation prior to library construction with this sample increased the library yield by more than two-fold (“23407 frag” in Figure 10). This indicates that

much of the DNA present in the 23407 sample was high molecular weight DNA that required fragmentation in order to be clonable. Thus, the library cloning efficiency was likely far greater than 10% and was likely in the range of 20% for input cfDNA. This cloning efficiency is comparable to highly purified genomic DNA and indicates that
5 cfDNA was not likely modified in any way that is deleterious to downstream cloning efforts.

Library coverage

The cfDNA libraries resembled a set of discrete bands with random coverage of target regions. Figure 11 shows a random sampling of sequence data. A random set of
10 reads from sample 23407 that was not fragmented prior to cloning (see Figure 10), and that were captured by the TP53 probe “chr17:7579351:region_3:280nt:41:80:r” (SEQ ID NO:201) were aligned using BLAT. Given the way that the sample was prepared, these are likely a reflection of cfDNA fragments in general because the left hand portion of these reads (the read start sites) are randomly distributed across the target
15 region. This random distribution indicates the random breakage of genomic DNA, and it demonstrates that despite the band-like appearance of cfDNA libraries, the sequencing output was a random coverage of the target region. The random distribution is important for effective genetic analysis using technology contemplated herein.

Figure 12 provides a more high resolution overview of TP53 coding region
20 sequencing for a typical cfDNA library. The elements of targeted sequencing – coverage across all target regions and uniform depth at each sequenced base – are readily apparent. At this depth of >4000 unique reads per base, and with a requirement that legitimate candidate base changes must be encountered at least twice, it is possible to estimate that the mutation detection sensitivity for this particular library was about 1
25 mutation in 2000 sequences, or 0.05%. This level of sensitivity represents a surprising and unexpected outstanding technical achievement.

CONCLUSION

cfDNA was isolated and cloned from plasma clones with an efficiency comparable to highly purified gDNA isolated from cell lines (the gold standard). The
30 cfDNA libraries resembled circulating nucleosomal-sized DNA fragments + adaptors

and the ends possessed sufficiently random character, which enabled efficient genetic analysis. In addition, the highly uniform size characteristic of plasma cfDNA libraries allows designing capture strategies and underlying probe sequences to maximize reliable coverage of targets as far as 120 bp (= 160 – 40) from the ends of probes.

5

EXAMPLE 4

MEASUREMENT OF GENOME EQUIVALENTS IN CIRCULATING DNA LIBRARIES

PURPOSE AND BACKGROUND

One of the major challenges in the analysis of circulating, cell-free DNA is achieving sufficient assay sensitivity. If sufficient sensitivity is not achieved then analysis of the cfDNA libraries is confounded: if a sample is sequenced and no mutational events are detected, that result could be interpreted to mean that no mutations are present, or that significant events were missed because the sampling depth was too small. The sensitivity of an assay is defined in statistical terms as the false negative rate. In the context of sequencing circulating, cell-free DNA, a significant obstacle is the detection of a rare sequence that is blended in a large excess of reference sequence.

One method for determining assay sensitivity is to measure the occurrences of mutant sequence in a set of samples where mutant sequence is progressively diluted into non-mutant, reference sequence. The dilution at which mutant sequences are no longer detected defines assay sensitivity. This method is adequate if both the identity of the mutant sequence and the extent of dilution are known. Unfortunately, clinical samples do not generally provide either parameter. Often the identity of the mutant sequence is not known, and the extent of dilution varies from sample to sample. In this context, assay sensitivity is established on a sample-by-sample basis.

To assign a sensitivity value on a sample-by-sample basis, the numbers of different and distinct sequences that are present in each sample are measured, by measuring the number of genome equivalents that are present in a sequencing library. By way of a non-limiting example, if a DNA sequencing library is known to contain 3 ng (3000 pg) of human genomic DNA and each human genome has a mass of 3 pg, then

the library possesses $3000 \div 3 = 1000$ genome equivalents of DNA. If a mutant DNA sequence must be detected twice to be statistically significant, then an estimate of the best possible sensitivity of detection for this particular library is $2 \text{ mutant sequences} \div 1000 \text{ total sequences} = 0.002 = 0.2\%$. To establish sensitivity, the number of genome
5 equivalents must be measured for each sample library.

SUMMARY

Two methods were used to measure genome equivalents. The first method is based on quantitative PCR (qPCR). A genomic library was constructed using ligation of adaptors to genomic fragments and a pair of PCR primers, one that is specific to a
10 common genomic sequence (*e.g.*, Alu I repeat) and one that is specific to the adaptor. The abundance of ligated adaptor:fragment sequences of these cfDNA libraries was measured. A standard library of known concentration was used to construct a standard curve and the measurements were fit to the resulting standard curve and a value for genome equivalents was derived from the fit.

15 The second method to measure genome equivalents used bioinformatics counting after sequencing was performed. Each unique sequence in a library was identified by its random sequence label and the starting nucleotide of the genomic sequence. Moreover, each unique sequence must be derived from an independent genome. Therefore, the sum of unique sequences present in sequence data established a
20 precise quantitative measurement of the number of genome equivalents present in a sample.

METHODS AND RESULTS

qPCR assay development

The first version of a qPCR-based genome equivalence assay used the ACA2
25 primer (Table 10), but this assay chronically under-reports the number of genome equivalents that are present in a cfDNA library (Figure 13).

Table 10. PCR primers used in the development of the genome equivalent qPCR assay

Name	SEQ ID NO:	Sequence
ACA2	283	TGCAGGACCAGAGAATTCGAATACA
ACA2_FL FP	284	AATGATACGGCGACCACCGAGATCTACACGTCATGCAGGACCAG AGAATTCGAATACA
Alu_F1	285	CGGTGGCTCACGCCTGTA
Alu_R1	286	GCCTCGGCCTCCCAAAGT
Alu_F2	287	GAGGCTGAGGCAGGAGAATCG
Alu_R2	288	GTCGCCAGGCTGGAGTG

The improved version of the assay was based on endogenous repeats (*e.g.*, Alu repeats) that are found at very high frequency throughout the human genome. By coupling an Alu-specific primer with an adaptor-specific primer, the frequency with which adaptors are joined to genomic fragments was reliably measured. Standard curves using libraries of known genome equivalents were generated, and the number of genome equivalents in cloned libraries was measure by fitting to the curve.

The PCR primers used to develop an Alu + adaptor-based qPCR assay are shown in Table 10. The PCR primers for Alu amplification were designed from consensus a consensus human Alu sequence (Batzer & Deininger, *Nat Rev Genet.* 3(5):370-9 (2002)) using PRIMER3 (Alu_F1 & Alu_R1, SEQ ID NOs:285 and 286, respectively). The remaining two Alu primers (Alu_F2 and Alu_R2, SEQ ID NOs:287 and 288, respectively) were reported in the literature (Marullo *et al.*, *Genome Biology* 11:R9 (2010)).

A schematic of the assay design is provided in Figure 14. Because a single PCR primer can used to amplify the genomic DNA libraries (Figure 14A), a primer that recognizes the adaptor sequence but that cannot amplify genomic clones was used. The 58 nucleotide ACA2-FLFP primer (henceforth abbreviated AF, SEQ ID NO:284) fills these criteria because its length induces strong stem-loop PCR suppression (Figure 14B). Additionally, a functional pair of Alu primers were used (Figure 14C). Moreover, a primer pair consisting of one Alu primer and the long ACA2 primer that did not amplify genomic DNA used (Figure 14D). These same primers also amplified genomic library clones (Figure 14E).

All of the required elements for a functional Alu-based assay were validated. Figure 15. Specifically, the long primer alone was inert, both sets of Alu primer pairs

recognized human genomic DNA, and any combination of one Alu primer and the long ACA2 primer amplified genomic library clones (Figure 15A). Finally, the ability of Alu primer plus long ACA2 primer pair to discriminate between genomic DNA and genomic library clones is shown in Figure 15B. The combination of Alu_R1 and AF
 5 primers were used for measuring genome equivalents in the newly constructed libraries.

A direct comparison between the ACA2-based and the Alu-based qPCR assays is shown in Figure 16. An 8-fold difference in genome equivalents was found. In addition the Alu-based assays provided a more consistent performance library-to-library and a better alignment between qPCR derived equivalents and bioinformatically
 10 counted tag equivalents in sequencing runs (Table 11).

Table 11. qPCR vs counted sequencing tags

Sample	Alu-based qPCR	counted tags
Run_68 50to1	6962	3459
Run_68 1000to1	10937	4641

High-sensitivity library adaptors for sequence-based counting of genome equivalents

As discussed above, the reality of disease surveillance using cfDNA is that
 15 mutant sequences may be rare constituents in an otherwise vast excess of “normal” (meaning germline) DNA sequences. Thus, highly sensitive and quantifiable sequencing assays are needed. Assay sensitivity could be made by counting the number of unique sequences present in a sequencing library. However, such counting would lead to a *false underestimate* of sensitivity because cfDNA fragments are rather short
 20 (~165 bp) and may lead to identical reads that were actually derived from independent cloning events. One solution to this problem is to mark each independent sequencing clone during library construction by including, for example, a set of DNA tags in the adaptors used to construct libraries.

A set of such library construction adaptors was specifically designed to measure
 25 the number of genome equivalents present in cfDNA libraries, and, by extension, the sensitivity of sequencing assays used to monitor mutant sequences.

The architecture of high-sensitivity library adaptors that were configured to accommodate large numbers of genome equivalents in cfDNA libraries is shown in Figure 17. There is a substantial amount of molecular engineering within the 45

nucleotide ligation strand, which is the strand that becomes attached to end repaired cfDNA fragments. The adaptors comprise at least five elements.

Element 1 is a PCR primer binding site for the single-primer library amplification primer ACA2 (Table 12).

5 Table 12

Element	Function	Number of sequences	Sequences (5' → 3')	SEQ ID NO:
Element 1	PCR primer binding site	1	TGCAGGACCAGAGAATTCTGAATACA	289

Element 2 is a 5 nucleotide read code. The combination of this code with the genomic DNA sequence constitutes the DNA tag that was used to uniquely identify each read. The 5 nucleotide codes consist of 256 possible unique sequences that were chosen to be 2 base changes different from every other code in the set. This feature
 10 enabled unique and distinct reads to be differentiated from reads that appeared to be unique owing to a sequencing error in the code region. Seven codes in which G residues are over-represented and that were shown empirically to interfere with adaptor function were removed, leaving 249 random codes. Table 13.

Table 13

Element		Function		Number of sequences			
Element 2		Distinct sequence labels		249			
Sequences (5' → 3')	SEQ ID NO:	Sequences (5' → 3')	SEQ ID NO:	Sequences (5' → 3')	SEQ ID NO:	Sequences (5' → 3')	SEQ ID NO:
CGGGT	290	GGGTC	354	AGAGA	418	CCGGA	482
CGGTG	291	GGTCG	355	AGCCG	419	CGACG	483
CGTGG	292	GGTGC	356	AGCGC	420	CGAGC	484
GCGGT	293	GTCGG	357	AGGAA	421	CGCAG	485
GCGTG	294	GTGCG	358	AGGCC	422	CGCGA	486
GCTGG	295	GTGGC	359	AGGTT	423	CGGAC	487
GGCGT	296	TGCGG	360	AGTGT	424	CGGCA	488
GGCTG	297	TGGCG	361	AGTTG	425	GAAAG	489
GGGCT	298	TGGGC	362	ATGGT	426	GAAGA	490
TTAAA	299	AAAGG	363	ATGTG	427	GACCG	491
TTACC	300	AAGAG	364	ATTGG	428	GACGC	492
TTATT	301	AAGGA	365	CACGG	429	GAGAA	493
TTCAC	302	ACCGG	366	CAGCG	430	GAGCC	494
TTCCA	303	ACGCG	367	CAGGC	431	GAGTT	495
TTTAT	304	ACGGC	368	CCAGG	432	GATGT	496
TTTTA	305	AGAAG	369	CCGAG	433	GATTG	497

GCACG	306	GTGTA	370	AACTG	434	AGTCA	498
GCAGC	307	GTTAG	371	AAGCT	435	ATACG	499
GCCAG	308	GTTGA	372	AAGTC	436	ATAGC	500
GCCGA	309	TAGGT	373	AATCG	437	ATCAG	501
GCGAC	310	TAGTG	374	AATGC	438	ATCGA	502
GCGCA	311	TATGG	375	ACAGT	439	ATGAC	503
GGAAA	312	TGAGT	376	ACATG	440	ATGCA	504
GGACC	313	TGATG	377	ACGAT	441	CAAGT	505
GGATT	314	TGGAT	378	ACGTA	442	CAATG	506
GGCAC	315	TGGTA	379	ACTAG	443	CAGAT	507
GGCCA	316	TGTAG	380	ACTGA	444	CAGTA	508
GGTAT	317	TGTGA	381	AGACT	445	CATAG	509
GGTTA	318	TTAGG	382	AGATC	446	CATGA	510
GTAGT	319	TTGAG	383	AGCAT	447	CCCGT	511
GTATG	320	TTGGA	384	AGCTA	448	CCCTG	512
GTGAT	321	AACGT	385	AGTAC	449	CCGCT	513
CCGTC	322	CTGTT	386	GTAAC	450	TCCGC	514
CCTCG	323	CTTGT	387	GTACA	451	TCGAA	515
CCTGC	324	CTTTG	388	GTCAA	452	TCGCC	516
CGAAT	325	GAACT	389	GTCCC	453	TCGTT	517
CGATA	326	GAATC	390	GTCTT	454	TCTGT	518
CGCCT	327	GACAT	391	GTTCT	455	TCTTG	519
CGCTC	328	GACTA	392	GTTTC	456	TGAAC	520
CGTAA	329	GATAC	393	TAACG	457	TGACA	521
CGTCC	330	GATCA	394	TAAGC	458	TGCAA	522
CGTTT	331	GCAAT	395	TACAG	459	TGCCC	523
CTAAG	332	GCATA	396	TACGA	460	TGCTT	524
CTAGA	333	GCCCT	397	TAGAC	461	TGTCT	525
CTCCG	334	GCCTC	398	TAGCA	462	TGTTC	526
CTCGC	335	GCTAA	399	TCAAG	463	TTCGT	527
CTGAA	336	GCTCC	400	TCAGA	464	TTCTG	528
CTGCC	337	GCTTT	401	TCCCG	465	TTGCT	529
TTGTC	338	ACTTC	402	CCACC	466	TATAA	530
TTTCG	339	ATAAT	403	CCATT	467	TATCC	531
TTTGC	340	ATATA	404	CCCAC	468	TATTT	532
AAAAA	341	ATCCT	405	CCCCA	469	TCACT	533
AAACC	342	ATCTC	406	CCTAT	470	TCATC	534
AAATT	343	ATTAA	407	CCTTA	471	TCCAT	535
AACAC	344	ATTCC	408	CTACT	472	TCCTA	536
AACCA	345	ATTTT	409	CTATC	473	TCTAC	537
AATAT	346	CAAAC	410	CTCAT	474	TCTCA	538
AATTA	347	CAACA	411	CTCTA	475		
ACAAC	348	CACAA	412	CTTAC	476		

ACACA	349	CACCC	413	CTTCA	477
ACCAA	350	CACTT	414	TAAAT	478
ACCCC	351	CATCT	415	TAATA	479
ACCTT	352	CATTC	416	TACCT	480
ACTCT	353	CCAAA	417	TACTC	481

Element 3 is a 3 nucleotide sample code that differ by at least two base changes. This element was used to identify different samples and enabled sample multiplexing within a sequencing run. Table 14.

Table 14

Element	Function	Number of sequences	Sequences (5' -> 3')	SEQ ID NO:
Element 3	Distinct sample labels; sample multiplexing	16	AAG	539
			CTC	540
			GGT	541
			TCA	542
			ACT	543
			CGA	544
			GTG	545
			TAC	546
			AGC	547
			CCG	548
			GAA	549
			TTT	550
			ATA	551
			CAT	552
			GCC	553
			TGG	554

- 5 Element 4 is a 12 nucleotide anchor sequence with three important characteristics with respect to library construction and downstream sequencing. Table 15. These are A) each 12 base extension is part of a family of four 12 base extensions that collectively represent each of the four possible DNA bases at each site within extension. This feature, balanced base representation, is required by the Illumina

- sequencing instrument in order to calibrate proper base calling in sequencing reads. B) Each extension is composed of only two of four possible bases, and these are specifically chosen to be either 6 A's + 6 C's or 6 G's + 6 T's. This extension formed from only two bases greatly reduces the possibility that the extension sequence will
- 5 participate in secondary structure formation that would preclude proper adaptor function. C) Because each extension is composed of equal numbers of A+C or G+T, each extension shares roughly the same melting temperature and duplex stability as every other extension in a set of four.

Table 15.

Element	Function	Number of sequences	Sequences (5' → 3')	SEQ ID NO:
Element 4	12 nucleotide extension that provides a duplexing site for the partner oligonucleotide	4	ACCCACACCAAA	555
			CAAACACAACCC	556
			GTGTGGGTTGTT	557
			TGTGTTTGGTGG	558

- 10 Element 5 is the two base sequence found at the 3' end of Element 4. The particular two base extensions were chosen based on empirical data that shows that these two base sequences are efficient substrates for ligation. Table 15.

4.

- The adaptor module is hybridized to a partner oligonucleotide. Table 16. The
- 15 hybridization takes place between the sequence within Element 4 and the partner oligonucleotide. The double-stranded adaptor was ligated to end-repaired cfDNA.

Table 16.

Element	Function	Number of sequences	Sequences (5' → 3')	SEQ ID NO:
Element 4	12 nucleotide extension that provides a duplexing site for the partner oligonucleotide	4	TTTGGTGTGGGT	559
			GGGTTGTGTTTG	560
			AACAACCCACAC	561
			CCACCAAACACA	562

- To convert a set of 256 independently synthesized and pooled ligation strands (each of which shares a common sample code and therefore constitutes a single sample
- 20 adaptor set) to duplexes suitable for ligation, the 45 nucleotide ligation strand was

combined with the appropriate complementary 12 nucleotide partner strand, heated to 95° C, cooled to 65° C for 5 min, then cooled to room temperature. This duplex formed a blunt end ligation substrate as shown in Figure 17B. Following ligation and DNA purification, a DNA polymerase-mediated step that occurs prior to PCR amplification
5 displaced the partner strand and copied the ligation strand to form a double-strand adaptor that was suitable for exponential amplification by single-primer PCR.

The quantitative analysis of genome equivalents derived from targeted sequencing data was then performed. Each unique read was considered a unique ligation event and the sum of unique reads was considered equivalent to the number of
10 genome equivalents analyzed.

A rough, “back-of-the-envelope”, “rule-of-thumb” calculation was performed to determine the number of genome equivalents that could be analyzed. Each cfDNA clone was approximately 150 base pairs, 50 base pairs of which were required for binding to capture probes. This left roughly 100 possible sequence start sites within
15 any captured cfDNA clone. The attachment of 249 random codes to each of the 100 possible start sites created a total repertoire of ~249,000 possible unique clones. As the number of unique clones approaches the total number of possible sequence combinations, probability dictates that the same code and start site combinations will be created by independent events and that these independent events will be inappropriately
20 grouped within single families. The net result will be an underestimate of genome equivalents analyzed, and rare mutant reads may be discarded as sequencing errors because they overlap with wild-type reads bearing the same identifiers. To avoid this, efforts were made using the qPCR assay to constrain genomic inputs to one tenth or less the number of possible unique clones. For example, a single adaptor has 24,900
25 possible clones and thus, has a reliable capacity to provide accurate analysis for libraries consisting of 2500 or fewer genome equivalents.

The procedure that is outlined is provided as an example and the methods contemplated herein are not meant to be bound by this example. In some cases, the number of genome equivalents to be analyzed may well exceed the 2500 limit
30 illustrated in the preceding paragraph. To expand the depth of genome equivalents, two solutions to this problem are readily available. The first solution is to use more than

one adaptor set per sample. By combining adaptors, it is possible to expand the total number of possible clones and therefore, expand the comfortable limits of genomic input. As a non-limiting example, the combination of four adaptor sets used for one sample would expand the analysis to $24,900 \times 4 = 99,600$ possible sequences and
5 ~10,000 reasonably analyzed genome equivalents. The second solution is to expand the code in Element 2 of Figure 17A to 6, 7, or more bases. The number of possible codes that differ by at least 2 bases from every other code scales as $4^{(n-1)}$ where n is the number of bases within Element 2. Thus, in the non-limiting example presented here, n = 5 and $4^{(5-1)} = 256$; therefore, the inclusion of additional bases expands the available
10 repertoire by a factor of four for each additional base.

CONCLUSION

The results from this example showed that two independent methods for the determination of genome equivalents have utility in sample processing workflow. The first method, qPCR, was implemented during the library construction phase of cfDNA
15 analysis and it was used as a quality control step to ensure that adequate numbers of genome equivalents are moved through library amplification, targeted sequence capture, and DNA sequencing. The other method use explicit counting of unique reads as a more direct measure of the actual number of genome equivalents that fell under informatics consideration.

20

EXAMPLE 5

QUANTITATIVE GENETIC ANALYSIS

PURPOSE

The purpose of this example was to apply quantitative genetic analysis to normal DNA admixed cancer genomes and to uncharacterized cfDNA isolated from the
25 plasma of cancer patients.

BACKGROUND

Three types of genomic events are prevalent in human cancers. These are somatic mutations that alter the function of the affected gene and its expressed protein product(s); genomic rearrangements that create chimeric gene fusions and therefore
5 expressed fusion proteins with novel biological properties; and changes in gene copy number that lead to gene loss and under expression of gene product(s), or, conversely, amplification of genes and over-representation of the corresponding gene product(s). In the circulating DNA of a cancer patient, these aberrant loci, many of which have critical significance in guiding patient care, are admixed (blended) with the patient's normal,
10 germline DNA.

SUMMARY

In the previous examples, technology has been described that was configured for the analysis of circulating, cell-free DNA (cfDNA), with an aim toward cancer surveillance. However, the technology is widely applicable to any analytical,
15 diagnostic and monitoring paradigm including, but not limited to r genetic diseases; fetal testing; mendelian disorders; pathogen screening; and organ transplant monitoring in which circulating DNA is a potential analyte. In this example, the technical features highlighted in previous examples are applied to the analysis of admixed cancer samples. In the first phase of this validation, cancer-derived cell lines were admixed with normal
20 human DNA at defined dilutions, and quantitative genetic analysis was performed. In the second phase of this study, uncharacterized cfDNA was isolated from the plasma of cancer patients and subsequently examined using quantitative genetic analysis.

*METHODS**Admixtures of cell line genomic DNA with normal human DNA*

25 The following DNA samples were used:

- NA06994 - normal human genomic DNA (Coriell repository);
- NCI-H2228 - non-small cell lung cancer cell line (ATCC), harbors mutation in TP53 (Q331*) and EML4-ALK gene fusion (breakpoint unknown); and

- NCI-H69 – small cell lung cancer cell line (ATCC), harbors amplification of the MYCN gene (~100 copies).

Library preparation: Genomic DNA isolated from cell lines (all three above) is high molecular weight material that is dissimilar to the small size of cfDNA. To mimic
 5 cfDNA in these validation experiments, genomic DNAs were first fragmented on the “150 bp” setting using a Covaris Acoustic Sonicator. The sonication generally produces a broad smear, and the DNA was further processed using “two sided” bead selection. A dilute solution of DNA purification beads were added to the sample and the higher molecular mass fragments that adhere to the beads were discarded (the size
 10 of purified DNA is proportional to the amount of beads added). An additional aliquot of beads are added to the remaining supernatant and in this second round, DNA that adheres to the beads that (in a higher overall concentration of binding buffer) are purified. This “two-sided” purification produces a narrow size distribution that is a reasonable proxy for cfDNA (Figure 18).

15 Fragmented genomic DNA was end repaired, quantified, and mixed in the various ratios shown in Table 17 and described in the results section below.

Table 17. Samples and admixtures used for validation studies

Sample, Admixture	genome equivalents (qPCR)
Pure H2228	2248
NA06994:H2228 4:1	2616
NA06994:H2228 10:1	2600
NA06994:H2228 20:1	2968
NA06994:H2228 50:1	5000
NA06994:H2228 1000:1	10000
Sample, Admixture	genome equivalents (qPCR)
Pure H69	2472
NA06994:H69 4:1	2768
NA06994:H69 10:1	3088
NA06994:H69 20:1	2944
NA06994:H69 40:1	1616
NA06994:H69 100:1	1920
NA06994:H69 200:1	2920
NA06994:H69 500:1	17520

cfDNA libraries may have limited DNA inputs. The amount of cfDNA obtained per mL of patient plasma is widely variable, but the lower limits (e.g., Example 3) are

generally ~10 ng/mL, which is equivalent to 3300 human genomes. To guard against limited cfDNA quantities, the admixture experiments were modeled to reflect the lower limits of cfDNA that were routinely collected from patients. This constraint was applied to all but the most extreme admixtures. In these latter admixtures, libraries were made to mimic inputs from 4 mLs (NA06994:H2228 1000:1) or 8 mLs (NA06994:H69 500:1) of low yield patient cfDNA. Admixed samples were then ligated to the adaptor sets described in Example 4. Measurement of the genome equivalents in each purified library using qPCR (Example 4) is also shown in Table 17. Libraries were amplified, quantified, and equivalent masses of each library were pooled (500 ng of each). The pooled sample was hybridized with the proof-of-concept, high-density 40 mer capture probes listed in Table 6 of Example 2. The resulting complexes were captured on streptavidin-coated beads, washed, processed, amplified, purified and size-selected as described in previous examples. The resulting library was analyzed using an Illumina 150bp-V3 Miseq sequencing kit on the Illumina MiSeq instrument.

For bioinformatics analysis, a rare somatic variant caller was used to detect mutations, a split read aligner was used to detect fusion genes, and in-house analysis that quantifies and statistically fits tags was used to call copy number variation (CNV).

The detection of an admixed point mutation in the TP53 gene is shown in Figure 19. The “expected” frequency deviates from the admix ratio because it is known that TP53 is hemizygous in the NCI-H2228 cell line. Automated software was able to call the mutant allele in the 50:1 admixture. Manual curation was required to call the mutant event at 1000:1. With respect to specificity, the tag filtering described in Example 1 was applied to the analysis, and no other mutation calls in TP53 were detected after applying this tag filter.

Cell line NCI-H2228 is known to harbor a fusion gene between EML4 and ALK; the cell line serves as a positive control in both fluorescence *in situ* hybridization assays and in detection of fusion gene transcripts using RT-PCR. There are no published reports of the exact location of the gene fusion junction. Using dense probe coverage of the intron 19 region of ALK, sequence analysis revealed precise location and sequence of the junction formed when the two genes fused (Figure 20). The frequency of normal reads versus junction reads in the NCI-H2228 cell line (378 vs

249, respectively) suggests that the fusion gene is heterozygous with a normal copy of ALK.

Detection of junction reads as a function of admixture is shown in Figure 21. As with point mutation detection, the expected values were adjusted to reflect the fact
5 that the mutant allele is found in one copy per diploid genome. No fusion reads were detected in the 1000:1 admixed sample.

Figure 22 shows the results of CNV determination for the MYCN gene as a function of admixture. The NCI-H69 cell line harbors a highly amplified MYCN gene. MYCN is normally found as a single copy gene, two per diploid genome, and thus the
10 expected result for progressively more dilute admixtures is that the tag-calculated CNV should asymptotically approach 2 copies (the asymptote is highlighted in the figure). The validation experiment shown here indicated that the assay system described in this invention is robustly sensitive to highly amplified genes.

Variant discovery in cfDNA from cancer patients

15 The most rigorous validation of the technology contemplated herein is to apply it to cfDNA samples in which the spectrum of mutations is unknown. An analysis was performed by sequencing matched cfDNA, tumor and normal adjacent tissue (NAT) samples from two ovarian cancer patients. In addition, two cfDNA samples from colorectal cancer (CRC) patients and two cfDNA samples from healthy volunteers were
20 analyzed. In no case, were mutations, fusions or abnormal CNV detected in the healthy volunteer samples.

Libraries of cfDNA from the four cancer patients were initially screened using the targeted probes described in Table 6 of Example 2. These probes were primarily configured to detect point mutations in the TP53 gene, gene fusions with ALK and
25 amplifications of the MYCN. The results of this initial sequencing screen are shown in Figure 23. A point mutation occurring at the same base position was found in the cfDNA, tumor, and NAT of one ovarian patient. No TP53 mutations were found in the other set of ovarian cancer patient matched samples. Point mutations were also detected in the two CRC cfDNA libraries for which matching tissues were unavailable.
30 All of these point mutations have been previously identified in tumors and all are known to be causal drivers of tumorigenesis. The mutant sequence detection in cfDNA

library CRC406 of 0.9% was well within the scope of assay sensitivity. Sensitivity is defined by the presence of multiple families of tagged reads, all of which possess the mutant sequence. These data highlight the clinical utility of the system contemplated herein.

- 5 To further explore the detection of cancer-related changes in cfDNA libraries and associated tissues, the same libraries were hybridized to a set of 679 probes that are directed to a total of 20 different cancer-related genes (Table 18). In this probe set, all of the coding regions of 14 genes were targeted while select loci were targeted in the remaining 6 genes.

10 Table 18. Cancer genes targeted

Genes: coding region targeted	Genes: select regions targeted
BRCA1	ALK
BRCA2	DPYD
BRAF	EPHX1
CDH1	MYC
ERBB2	TNFRSF14
JAK2	ALDH4A1
NF2	
PIK3CA	
RB1	
CDKN2A	
KRAS	
MYCN	
PTEN	
TP53	

- As shown in Figure 24, the OVA1 sample, which lacked any detectable changes in TP53, carried a mutation in KRAS that was found in both cfDNA and in the corresponding tumor. This observation highlights a significant feature of the assay system described here. Libraries created from cfDNA can be interrogated with
- 15 hundreds (as in this example), and even thousands, of targeting probes. The sequencing of the resulting targeted libraries revealed somatic mutations that reside within the tumor and not within the germline of the affected individual. These tumor-associated somatic markers can also be used to quantify the amount of circulating DNA that is shed from the tumor (as opposed to cfDNA that has germline sequence). Thus, the
- 20 discovery of mutations, regardless of their biological significance, also provides an estimate of tumor content in admixed cfDNA.

Many targeted therapies are most successful in the presence of normal genes (*e.g.*, EGFR inhibitors work only in the presence of wild-type KRAS). A quantitative

assessment of circulating tumor DNA levels becomes especially significant in these cases where mutations in genes are not found. In other words, the demonstrable presence of circulating tumor DNA coupled with a wild-type sequencing result at a particular target gene suggests that the target gene is normal within the tumor, and such results can have a significant influence in guiding the choice of therapies. Such is the case with the OVA1 sample highlighted in Figure 24. The presence of the KRAS mutation in the cfDNA library suggested that this patient's tumor harbors a wild-type TP53 gene(s).

Another example of aberrant gene discovery is shown in Figure 25. The targeted quantitative genetic analysis system revealed the presence of a significant amplification in the ERBB2 gene, otherwise referred to as HER-2/neu. While this type of amplification has been much publicized in breast cancer, it is occasionally identified in colorectal carcinomas as well.

CONCLUSION

Validation experiments with cell line DNA revealed the thresholds of detection of three types of genetic variation that are central to driving neoplastic growth in cancers. Characterization of cfDNA derived from cancer patients revealed tumor-associated genetic changes that were well above the thresholds set by reconstruction experiments in all four samples analyzed. These data indicated that the quantitative analysis system contemplated herein may have significant clinical utility, especially in settings where liquid biopsies are most appropriate.

In general, in the following claims, the terms used should not be construed to limit the claims to the specific embodiments disclosed in the specification and the claims, but should be construed to include all possible embodiments along with the full scope of equivalents to which such claims are entitled. Accordingly, the claims are not limited by the disclosure.

CLAIMS

1. A method for genetic analysis of cell-free DNA (cfDNA) comprising:
 - (a) treating cfDNA with one or more end-repair enzymes to generate end-repaired cfDNA;
 - (b) ligating one or more adaptors to each end of the end-repaired cfDNA to generate a cfDNA library;
 - (c) amplifying the cfDNA library to generate cfDNA library clones;
 - (d) determining the number of genome equivalents in the cfDNA clone library; and
 - (e) performing a quantitative genetic analysis of one or more target genetic loci in the cfDNA library clones.
2. The method of claim 1, further comprising isolating cfDNA from a biological sample of a subject.
3. The method of claim 1 or claim 2, wherein the cfDNA is isolated from a biological sample selected from the group consisting of: amniotic fluid, blood, plasma, serum, semen, lymphatic fluid, cerebral spinal fluid, ocular fluid, urine, saliva, stool, mucous, and sweat.
4. The method of any one of claims 1-3, wherein the one or more adaptors comprise a plurality of adaptor species.
5. The method of any one of claims 1-4, wherein the one or more adaptors each comprise a primer binding site for amplification of the cfDNA library.
6. The method of any one of claims 1-5, wherein the one or more adaptors each comprise one or more unique read codes.

7. The method of any one of claims 1-6, wherein the one or more adaptors each comprise one or more sample codes for sample multiplexing.

8. The method of any one of claims 1-6, wherein the one or more adaptors each comprise one or more sequences for DNA sequencing.

9. The method of any one of claims 1-8, wherein qPCR is performed on the cfDNA clone library and a qPCR measurement is compared to standards of known genome equivalents to determine the genome equivalents of the cfDNA clone library.

10. The method of claim 9, wherein the qPCR is performed with a primer that binds to an Alu sequence and a primer that binds to a sequence in an adaptor.

11. The method of any one of claims 1-10, wherein the quantitative genetic analysis is performed on a plurality of genetic loci in the cfDNA library clones.

12. The method of any one of claims 1-11, wherein the quantitative genetic analysis is performed on a plurality of genetic loci in a plurality of cfDNA clone libraries.

13. The method of any one of claims 1-12, wherein the quantitative genetic analysis comprises hybridizing one or more capture probes to a target genetic locus to form capture probe-cfDNA clone complexes.

14. The method of claim 13, wherein the quantitative genetic analysis comprises isolating the capture probe-cfDNA clone complexes.

15. The method of claim 14, wherein the quantitative genetic analysis comprises amplification of the cfDNA clone sequence in the isolated hybridized capture probe-cfDNA clone complexes.

16. The method of any one of claims 1-15, wherein the quantitative genetic analysis comprises DNA sequencing to generate a plurality of sequencing reads.
17. The method of 16, further comprising bioinformatic analysis of the plurality of sequencing reads.
18. The method of any one of claims 1-17, wherein bioinformatics analysis is used:
- (a) to quantify the number of genome equivalents analyzed in the cfDNA clone library;
 - (b) to detect genetic variants in a target genetic locus;
 - (c) to detect mutations within a target genetic locus;
 - (d) to detect genetic fusions within a target genetic locus; and
 - (e) to measure copy number fluctuations within a target genetic locus.
19. The method of any one of claims 2-18, wherein the subject does not have a genetic disease.
20. The method of any one of claims 2-18, wherein the subject has not been diagnosed with a genetic disease.
21. The method of any one of claims 2-18, wherein the subject has been diagnosed with a genetic disease.
22. The method of claim 21, wherein the quantitative genetic analysis is used to identify or detect one or more genetic lesions that cause or associated with the genetic disease.
23. The method of claim 22, wherein the genetic lesion comprises a nucleotide transition or transversion, a nucleotide insertion or deletion, a genomic rearrangement, a change in copy number, or a gene fusion.

24. The method of claim 22, wherein the genetic lesion comprises a genomic rearrangement that fuses the 3' coding region of the ALK gene to another gene.
25. The method of claim 24, wherein the 3' coding region of the ALK gene is fused to the EML4 gene.
26. The method of any one of claims 22-25, wherein the genetic disease is cancer.
27. The method of any one of claims 2-18, wherein the subject is pregnant.
28. The method of claim 27, wherein the quantitative genetic analysis is used to identify or detect one or more genetic variants or genetic lesions of one or more target genetic loci in fetal cfDNA.
29. The method of any one of claims 2-18, wherein the subject is a transplant recipient.
30. The method of claim 27, wherein the quantitative genetic analysis is used to identify or detect donor cfDNA in the subject.
31. A method of predicting, diagnosing, or monitoring a genetic disease in a subject comprising:
- (a) isolating or obtaining cfDNA from a biological sample of a subject;
 - (b) treating the cfDNA with one or more end-repair enzymes to generate end-repaired cfDNA;
 - (c) ligating one or more adaptors to each end of the end-repaired cfDNA to generate a cfDNA library;
 - (d) amplifying the cfDNA library to generate a cfDNA clone library;
 - (e) determining the number of genome equivalents in the cfDNA clone library; and

(f) performing a quantitative genetic analysis of one or more target genetic loci associated with the genetic disease in the cfDNA clone library, wherein the identification or detection of one or more genetic lesions in the one or more target genetic loci is prognostic for, diagnostic of, or monitors the progression of the genetic disease.

32. The method of claim 29, wherein the cfDNA is isolated from a biological sample selected from the group consisting of: amniotic fluid, blood, plasma, serum, semen, lymphatic fluid, cerebral spinal fluid, ocular fluid, urine, saliva, stool, mucous, and sweat.

33. The method of claim 29, wherein the genetic lesion comprises a nucleotide transition or transversion, a nucleotide insertion or deletion, a genomic rearrangement, a change in copy number, or a gene fusion.

34. The method of claim 31, wherein the genetic lesion comprises a genomic rearrangement that fuses the 3' coding region of the ALK gene to another gene.

35. The method of claim 32, wherein the 3' coding region of the ALK gene is fused to the EML4 gene.

36. The method of any one of claims 29-32, wherein the genetic disease is cancer.

37. A companion diagnostic for a genetic disease comprising:

- (a) isolating or obtaining cfDNA from a biological sample of a subject;
- (b) treating the cfDNA with one or more end-repair enzymes to generate end-repaired cfDNA;
- (c) ligating one or more adaptors to each end of the end-repaired cfDNA to generate a cfDNA library;
- (d) amplifying the cfDNA library to generate a cfDNA clone library;
- (e) determining the number of genome equivalents in the cfDNA clone library; and

(f) performing a quantitative genetic analysis of one or more biomarkers associated with the genetic disease in the cfDNA clone library, wherein detection of, or failure to detect, at least one of the one or more biomarkers indicates whether the subject should be treated for the genetic disease.

38. The method of claim 35, wherein the cfDNA is isolated from a biological sample selected from the group consisting of: amniotic fluid, blood, plasma, serum, semen, lymphatic fluid, cerebral spinal fluid, ocular fluid, urine, saliva, stool, mucous, and sweat.

39. The method of claim 35, wherein the biomarker is a genetic lesion.

40. The method of claim 37, wherein the genetic lesion comprises a nucleotide transition or transversion, a nucleotide insertion or deletion, a genomic rearrangement, a change in copy number, or a gene fusion.

41. The method of claim 37, wherein the genetic lesion comprises a genomic rearrangement that fuses the 3' coding region of the ALK gene to another gene.

42. The method of claim 39, wherein the 3' coding region of the ALK gene is fused to the EML4 gene.

43. The method of any one of claims 35-40, wherein the genetic disease is cancer.