



# Help Me Understand Genetics

## Genetic Testing

Reprinted from MedlinePlus Genetics

U.S. National Library of Medicine

National Institutes of Health

Department of Health & Human Services

# CONTENTS

1	What is genetic testing?	1
2	What are the different types of genetic tests?	3
3	What are the uses of genetic testing?	6
4	How is genetic testing done?	8
5	What is informed consent?	9
6	How can I be sure a genetic test is valid and useful?	11
7	What do the results of genetic tests mean?	13
8	What is the cost of genetic testing, and how long does it take to get the results?	15
9	Will health insurance cover the costs of genetic testing?	16
10	What are the benefits of genetic testing?	17
11	What are the risks and limitations of genetic testing?	18
12	What is genetic discrimination?	19
13	Can genes be patented?	20
14	How are genetic screening tests different from genetic diagnostic tests?	21

15	How does genetic testing in a research setting differ from clinical genetic testing?	23
16	What are whole exome sequencing and whole genome sequencing?	24
17	What are secondary findings from genetic testing?	26
18	What is noninvasive prenatal testing (NIPT) and what disorders can it screen for?	29
19	What is circulating tumor DNA and how is it used to diagnose and manage cancer?	32

# Genetic Testing

## 1 What is genetic testing?

Genetic testing is a type of medical test that identifies changes in genes, chromosomes, or proteins. The results of a genetic test can confirm or rule out a suspected genetic condition or help determine a person's chance of developing or passing on a genetic disorder. More than 77,000 genetic tests are currently in use, and others are being developed.

Genetic testing involves looking for changes in:

- **Genes:** Gene tests study DNA sequences to identify variations (mutations) in genes that can cause or increase the risk of a genetic disorder. Gene tests can be narrow or large in scope, analyzing an individual DNA building block (nucleotide), one or more genes, or all of a person's DNA (which is known as their genome).
- **Chromosomes:** Chromosomal genetic tests analyze whole chromosomes or long lengths of DNA to see if there are large genetic changes, such as an extra copy of a chromosome, that cause a genetic condition.
- **Proteins:** Biochemical genetic tests study the amount or activity level of proteins or enzymes; abnormalities in either can indicate changes to the DNA that result in a genetic disorder.

Genetic testing is voluntary. Because testing has benefits as well as limitations and risks, the decision about whether to be tested is a personal and complex one. A geneticist or genetic counselor can help by providing information about the pros and cons of the test and discussing the social and emotional aspects of testing.

### **For general information about genetic testing:**

MedlinePlus offers a list of links to information about genetic testing (<https://medlineplus.gov/genetictesting.html>).

The Genetic Testing Registry (<https://www.ncbi.nlm.nih.gov/gtr/>) is a service from the National Library of Medicine that provides a searchable database of genetic tests that have submitted by providers and laboratories.

The National Human Genome Research Institute provides an overview of this topic in its Frequently Asked Questions About Genetic Testing (<https://www.genome.gov/FAQ/Genetic-Testing>). Additional information about genetic testing legislation, policy, and oversight (<https://www.genome.gov/about-genomics/policy-issues/Regulation-of-Genetic-Tests>) is available from the Institute.

You can also search for clinical trials involving genetic testing. ClinicalTrials.gov (<https://clinicaltrials.gov/>), a service of the National Institutes of Health, provides easy access to information on clinical trials. You can search for specific trials or browse by condition or trial sponsor. You may wish to refer to a list of studies related to genetic testing (<https://c>

linicaltrials.gov/search?term=%22genetic+testing%22) that are accepting (or will accept) participants.

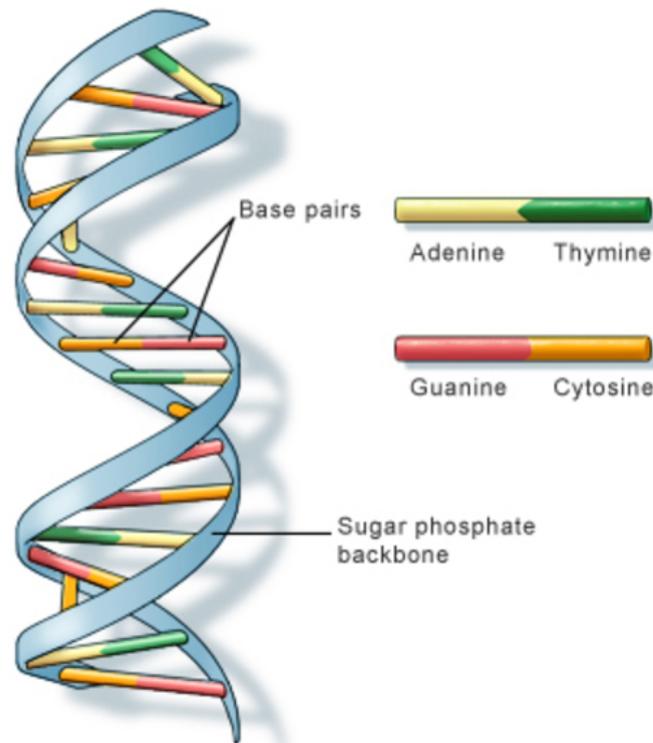
## 2 What are the different types of genetic tests?

Many types of genetic tests are available to analyze changes in genes, chromosomes, or proteins. A health care provider will consider several factors when selecting the appropriate test, including what condition or conditions are suspected and the genetic variations typically associated with those conditions. If a diagnosis is unclear, a test that looks at many genes or chromosomes may be used. However, if a specific condition is suspected, a more focused test may be done.

There are several types of genetic tests:

Molecular tests look for changes in one or more genes. These types of tests determine the order of DNA (Figure 1) building blocks (nucleotides) in an individual's genetic code, a process called DNA sequencing. These tests can vary in scope:

- **Targeted single variant:** Single variant tests look for a specific variant in one gene. The selected variant is known to cause a disorder (for example, the specific variant in the HBB gene that causes sickle cell disease). This type of test is often used to test family members of someone who is known to have a particular variant, to determine whether they have a familial condition. Also, direct-to-consumer genetic testing companies typically analyze a number of specific variants in particular genes (rather than finding all the variants in those genes) when providing health or disease risk information.
- **Single gene:** Single gene tests look for any genetic changes in one gene. These tests are typically used to confirm (or rule out) a specific diagnosis, particularly when there are many variants in the gene that can cause the suspected condition.
- **Gene panel:** Panel tests look for variants in more than one gene. This type of test is often used to pinpoint a diagnosis when a person has symptoms that may fit a wide array of conditions, or when the suspected condition can be caused by variants in many genes. (For example, there are hundreds of genetic causes of epilepsy.)
- **Whole exome sequencing/whole genome sequencing:** These tests analyze the bulk of an individual's DNA to find genetic variations. Whole exome or whole genome sequencing is typically used when single gene or panel testing has not provided a diagnosis, or when the suspected condition or genetic cause is unclear. Whole exome or whole genome sequencing is often more cost- and time-effective than performing multiple single gene or panel tests.



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**FIGURE 1:** DNA is made up of base pairs and a sugar phosphate backbone.

Chromosomal tests analyze whole chromosomes or long lengths of DNA to identify large-scale changes. Changes that can be found include an extra or missing copy of a chromosome (trisomy or monosomy, respectively), a large piece of a chromosome that is added (duplicated) or missing (deleted), or rearrangements (translocations) of segments of chromosomes. Certain genetic conditions are associated with specific chromosomal changes, and a chromosomal test can be used when one of these conditions is suspected. (For example, Williams syndrome is caused by a deletion of a section of chromosome 7.)

Gene expression tests look at which genes are turned on or off (expressed) in different types of cells. When a gene is turned on (active), the cell produces a molecule called mRNA from the instructions in the genes, and the mRNA molecule is used as a blueprint to make proteins. Gene expression tests study the mRNA in cells to determine which genes are active. Too much activity (overexpression) or too little activity (underexpression) of certain genes can be suggestive of particular genetic disorders, such as many types of cancer.

Biochemical tests do not directly analyze DNA, but they study the amount or activity level of proteins or enzymes that are produced from genes. Abnormalities in these

substances can indicate that there are changes in the DNA that underlie a genetic disorder. (For example, low levels of biotinidase enzyme activity is suggestive of biotinidase deficiency, which is caused by *BTD* gene variants.)

### **For information about types of genetic testing:**

The Genetic Testing Registry (<https://www.ncbi.nlm.nih.gov/gtr/>) is available from the National Center of Biotechnology and Information at the National Library of Medicine. The Genetic Testing Registry is a database of laboratory-submitted genetic tests.

The Centers of Disease Control and Prevention provides a page discussing genetic testing ([https://www.cdc.gov/genomics/gtesting/genetic\\_testing.htm](https://www.cdc.gov/genomics/gtesting/genetic_testing.htm)).

The Jackson Laboratory compares different types of genetic tests (<https://www.jax.org/education-and-learning/clinical-and-continuing-education/cancer-resources/genetic-testing-technology-comparison>).

GeneReviews compares whole genome sequencing, whole exome sequencing, and the sequencing of a selection of individual genes (<https://www.ncbi.nlm.nih.gov/books/NBK279899/>), particularly their use in the diagnosis of genetic conditions.

### 3 What are the uses of genetic testing?

Genetic testing can provide information about a person's genetic background. The uses of genetic testing include:

#### **Newborn screening**

Newborn screening is used just after birth to identify genetic disorders that can be treated early in life. Millions of babies are tested each year in the United States. The U. S. Health Services and Resource Administration recommends that states screen for a set of 35 conditions, which many states exceed.

#### **Diagnostic testing**

Diagnostic testing is used to identify or rule out a specific genetic or chromosomal condition. In many cases, genetic testing is used to confirm a diagnosis when a particular condition is suspected based on physical signs and symptoms. Diagnostic testing can be performed before birth or at any time during a person's life, but is not available for all genes or all genetic conditions. The results of a diagnostic test can influence a person's choices about health care and the management of the disorder.

#### **Carrier testing**

Carrier testing is used to identify people who carry one copy of a gene mutation that, when present in two copies, causes a genetic disorder. This type of testing is offered to individuals who have a family history of a genetic disorder and to people in certain ethnic groups with an increased risk of specific genetic conditions. If both parents are tested, the test can provide information about a couple's risk of having a child with a genetic condition.

#### **Prenatal testing**

Prenatal testing is used to detect changes in a fetus's genes or chromosomes before birth. This type of testing is offered during pregnancy if there is an increased risk that the baby will have a genetic or chromosomal disorder. In some cases, prenatal testing can lessen a couple's uncertainty or help them make decisions about a pregnancy. It cannot identify all possible inherited disorders and birth defects, however.

#### **Preimplantation testing**

Preimplantation testing, also called preimplantation genetic diagnosis (PGD), is a specialized technique that can reduce the risk of having a child with a particular genetic or chromosomal disorder. It is used to detect genetic changes in embryos that were created using assisted reproductive techniques (ART) such as in-vitro fertilization (IVF). In-vitro fertilization involves removing egg cells from a woman's ovaries and fertilizing them with sperm cells outside the body. To perform preimplantation testing, a small number of cells are taken from these embryos and tested for certain genetic changes. Only embryos without these changes are implanted in the uterus to initiate a pregnancy.

## **Predictive and presymptomatic testing**

Predictive and presymptomatic types of testing are used to detect gene mutations associated with disorders that appear after birth, often later in life. These tests can be helpful to people who have a family member with a genetic disorder, but who have no features of the disorder themselves at the time of testing. Predictive testing can identify mutations that increase a person's risk of developing disorders with a genetic basis, such as certain types of cancer. Presymptomatic testing can determine whether a person will develop a genetic disorder, such as hereditary hemochromatosis (an iron overload disorder), before any signs or symptoms appear. The results of predictive and presymptomatic testing can provide information about a person's risk of developing a specific disorder and help with making decisions about medical care.

## **Forensic testing**

Forensic testing uses DNA sequences to identify an individual for legal purposes. Unlike the tests described above, forensic testing is not used to detect gene mutations associated with disease. This type of testing can identify crime or catastrophe victims, rule out or implicate a crime suspect, or establish biological relationships between people (for example, paternity).

## **For more information about the uses of genetic testing:**

Johns Hopkins Medicine provides additional information about genetic carrier screening ([https://www.hopkinsmedicine.org/gynecology\\_obstetrics/specialty\\_areas/fertility-center/infertility-services/genetic-screening.html](https://www.hopkinsmedicine.org/gynecology_obstetrics/specialty_areas/fertility-center/infertility-services/genetic-screening.html)).

The Centre for Genetics Education offers an overview of prenatal testing (<https://www.genetics.edu.au/SitePages/Prenatal-testing-overview.aspx>), as well as fact sheets about preimplantation genetic diagnosis (<https://www.genetics.edu.au/SitePages/Preimplantation-genetic-diagnosis.aspx>), screening tests during pregnancy, (<https://www.genetics.edu.au/SitePages/Screening-tests-during-pregnancy.aspx>) and diagnostic tests during pregnancy (<https://www.genetics.edu.au/SitePages/Diagnostic-tests-during-pregnancy.aspx>).

The University of Pennsylvania offers an explanation of preimplantation genetic diagnosis (<https://www.pennmedicine.org/for-patients-and-visitors/find-a-program-or-service/penn-fertility-care/embryo-screening>).

Baby's First Test (<https://www.babysfirsttest.org/newborn-screening/screening-101>) offers detailed information about newborn screening.

For information about forensic DNA testing, refer to a page about forensic DNA analysis (<https://learn.genetics.utah.edu/content/science/forensics/>) from the Genetic Science Learning Center at the University of Utah.

## 4 How is genetic testing done?

Once a person decides to proceed with genetic testing, a health care provider can arrange testing. Genetic testing is often done as part of a genetic consultation.

Genetic tests are performed on a sample of blood, hair, skin, amniotic fluid (the fluid that surrounds a fetus during pregnancy), or other tissue. For example, a procedure called a buccal smear uses a small brush or cotton swab to collect a sample of cells from the inside surface of the cheek. The sample is sent to a laboratory where technicians look for specific changes in chromosomes, DNA, or proteins, depending on the suspected disorder. The laboratory reports the test results in writing to a person's doctor or genetic counselor, or directly to the patient if requested.

Newborn screening tests are done on a small blood sample, which is taken by pricking the baby's heel. Unlike other types of genetic testing, a parent will usually only receive the result if it is positive. If the test result is positive, additional testing is needed to determine whether the baby has a genetic disorder.

Before a person has a genetic test, it is important to understand the testing procedure, the benefits and limitations of the test, and the possible consequences of the test results. The process of educating a person about the test and obtaining permission is called informed consent.

Individuals interested in direct-to-consumer genetic testing do not need to go through a health care provider to obtain a test, but they can get it directly from the testing company. After undergoing direct-to-consumer genetic testing, people who test positive for a condition or are found to be at higher risk of developing a disorder are encouraged to follow-up with a genetic counselor or other health care provider.

### **For more information about genetic testing procedures:**

A brief overview of how genetic testing is done (<https://www.cancer.gov/about-cancer/causes-prevention/genetics/genetic-testing-fact-sheet#how-is-genetic-testing-done>) is also available from The National Cancer Institute.

The Genetic Science Learning Center at the University of Utah provides an interactive animation of DNA extraction techniques (<https://learn.genetics.utah.edu/content/labs/extraction/>).

## 5 What is informed consent?

Before a person has a genetic test, it is important to fully understand the testing procedure, the benefits and limitations of the test, and the possible consequences of the test results. The process of educating a person about the test and obtaining permission to carry out testing is called informed consent. "Informed" means that the person has enough information to make an educated decision about testing; "consent" refers to a person's voluntary agreement to have the test done.

In general, informed consent can only be given by adults who are competent to make medical decisions for themselves. For children and others who are unable to make their own medical decisions (such as people with impaired mental status), informed consent can be given by a parent, guardian, or other person legally responsible for making decisions on that person's behalf.

Informed consent for genetic testing is generally obtained by a doctor or genetic counselor during an office visit. The health care provider will discuss the test and answer any questions. If the person wishes to have the test, he or she will then usually read and sign a consent form.

Several factors are commonly included on an informed consent form:

- A general description of the test, including the purpose of the test and the condition for which the testing is being performed.
- How the test will be carried out (for example, a blood sample).
- What the test results mean, including positive and negative results, and the potential for uninformative results or incorrect results such as false positives or false negatives.
- Any physical or emotional risks associated with the test.
- Whether the results can be used for research purposes.
- Whether the results might provide information about other family members' health, including the risk of developing a particular condition or the possibility of having affected children.
- How and to whom test results will be reported and under what circumstances results can be disclosed (for example, to health insurance providers).
- What will happen to the test specimen after the test is complete.
- Acknowledgement that the person undergoing testing has had the opportunity to discuss the test with a health care provider.
- The individual's signature, and possibly that of a witness.

The elements of informed consent may vary, because some states have laws that specify factors that must be included. (For example, some states require disclosure that the test specimen will be destroyed within a certain period of time after the test is complete.)

Informed consent is not a contract, so a person can change their mind at any time after

giving initial consent. A person may choose not to go through with genetic testing even after the test sample has been collected. A person simply needs to notify the health care provider if the decision has been made to not continue with the testing process.

### **For more information about informed consent:**

MedlinePlus offers general information about informed consent by adults (<https://medlineplus.gov/ency/patientinstructions/000445.htm>).

The National Cancer Institute discusses informed consent for genetic testing in the context of inherited cancer syndromes (<https://www.cancer.gov/about-cancer/causes-prevention/genetics/risk-assessment-pdq>).

The National Human Genome Research Institute provides information about informed consent in genomics research (<https://www.genome.gov/about-genomics/policy-issues/Informed-Consent>) and policies and legislation related to informed consent for genetic research studies and testing (<https://www.genome.gov/about-genomics/policy-issues/Informed-Consent/Required-Elements-of-Consent-Form>).

The Centers for Disease Control and Prevention offers several examples of state-required components of informed consent for genetic testing (<https://www.cdc.gov/mmwr/preview/mmwrhtml/rr5806a3.htm>).

## 6 How can I be sure a genetic test is valid and useful?

Before undergoing genetic testing, it is important to be sure that the test is valid and useful. A genetic test is valid if it provides an accurate result. Two main measures of accuracy apply to genetic tests: analytical validity and clinical validity. Another measure of the quality of a genetic test is its usefulness, or clinical utility.

- Analytical validity refers to how well the test predicts the presence or absence of a particular gene or genetic change. In other words, can the test accurately detect whether a specific genetic variant is present or absent?
- Clinical validity refers to how well the genetic variant being analyzed is related to the presence, absence, or risk of a specific disease.
- Clinical utility refers to whether the test can provide helpful information about diagnosis, treatment, management, or prevention of a disease.

All laboratories that perform health-related testing for disease prevention, diagnosis, or treatment, including genetic testing, are subject to federal regulatory standards called the Clinical Laboratory Improvement Amendments (CLIA) or even stricter state requirements. CLIA standards cover how tests are performed, the qualifications of laboratory personnel, and quality control and testing procedures for each laboratory. By controlling the quality of laboratory practices, CLIA standards are designed to ensure the analytical validity of genetic tests.

CLIA standards do not address the clinical validity or clinical utility of genetic tests. The Food and Drug Administration (FDA) requires information about clinical validity for some genetic tests, particularly those tests that can influence a person's medical care. Additionally, states may require additional information on clinical validity for laboratory tests performed for people living in that state. Test takers, health care providers, and health insurance companies are often the ones who determine the clinical utility of a genetic test.

It can be difficult to determine the quality of genetic tests sold directly to the public. Some providers of direct-to-consumer genetic tests are not CLIA-certified, and many direct-to-consumer genetic tests are not regulated by the FDA, so it can be difficult to tell whether the tests are valid. If providers of direct-to-consumer genetic tests offer easy-to-understand information about the scientific basis of their tests, it can help people make more informed decisions. It may also be helpful to discuss any concerns with a health care provider before ordering a direct-to-consumer genetic test and after receiving test results.

### **For more information about determining the quality of genetic tests:**

The Centers for Disease Control and Prevention (CDC) provides an explanation of the factors used to evaluate genetic tests (<https://www.cdc.gov/genomics/gtesting/ACCE/>), including analytical validity, clinical validity, and clinical utility, as part of their ACCE project.

The Genetic Alliance offers information about the quality of genetic tests and current

public policy issues (<http://www.geneticalliance.org/advocacy/policyissues/geneticctesting>) surrounding their regulation.

The U.S. Centers for Medicare and Medicaid Services (CMS) provide an overview of the Clinical Laboratory Improvement Amendments (CLIA) (<https://www.cms.gov/Regulations-and-Guidance/Legislation/CLIA/index>) as well as information on their role in regulating laboratory developed tests ([https://www.cms.gov/Regulations-and-Guidance/Legislation/CLIA/Downloads/LDT-and-CLIA\\_FAQs.pdf](https://www.cms.gov/Regulations-and-Guidance/Legislation/CLIA/Downloads/LDT-and-CLIA_FAQs.pdf)).

## 7 What do the results of genetic tests mean?

The results of genetic tests are not always straightforward, which often makes them challenging to interpret and explain. Therefore, it is important for patients and their families to ask questions about the potential meaning of genetic test results both before and after the test is performed. When interpreting test results, health care providers consider a person's medical history, family history, and the type of genetic test that was done.

A positive test result means that the laboratory found a change in a particular gene, chromosome, or protein of interest. Depending on the purpose of the test, this result may confirm a diagnosis, indicate that a person is a carrier of a particular genetic variant, identify an increased risk of developing a disease (such as cancer), or suggest a need for further testing. Because family members have some genetic material in common, a positive test result may also have implications for certain blood relatives of the person undergoing testing. It is important to note that a positive result of a predictive or presymptomatic genetic test usually cannot establish the exact risk of developing a disorder. Also, health care providers typically cannot use a positive test result to predict the course or severity of a condition. Rarely, tests results can be false positive, which occur when results indicate an increased risk for a genetic condition when the person is unaffected.

A negative test result means that the laboratory did not find a change that is known to affect health or development in the gene, chromosome, or protein under consideration. This result can indicate that a person is not affected by a particular disorder, is not a carrier of a specific genetic variant, or does not have an increased risk of developing a certain disease. It is possible, however, that the test missed a disease-causing genetic alteration because many tests cannot detect all genetic changes that can cause a particular disorder. Further testing, or re-testing at a later date, may be required to confirm a negative result. Rarely, tests results can be false negative, which occur when the results indicate a decreased risk or a genetic condition when the person is actually affected.

In some cases, a test result might not give any useful information. This type of result is called uninformative, indeterminate, inconclusive, or ambiguous. Uninformative test results sometimes occur because everyone has common, natural variations in their DNA, called polymorphisms, that do not affect health. If a genetic test finds a change in DNA that has not been confirmed to play a role in the development of disease, known as a variant of uncertain significance (VUS or VOUS), it can be difficult to tell whether it is a natural polymorphism or a disease-causing variant. For these variants, there may not be enough scientific research to confirm or refute a disease association or the research may be conflicting. An uninformative result cannot confirm or rule out a specific diagnosis, and it cannot indicate whether a person has an increased risk of developing a disorder. In some cases, testing other affected and unaffected family members can help clarify this type of result.

**For more information about interpreting genetic test results:**

The National Cancer Institute fact sheet Genetic Testing for Hereditary Cancer Syndromes (<https://www.cancer.gov/about-cancer/causes-prevention/genetics/genetic-testing-fact-sheet#q6>) provides an explanation of positive and negative genetic test results.

The Centers for Disease Control and Prevention (CDC) offers a fact sheet about genetic testing ([https://www.cdc.gov/genomics/gtesting/genetic\\_testing.htm](https://www.cdc.gov/genomics/gtesting/genetic_testing.htm)), including an explanation of the types of genetic test results.

## **8 What is the cost of genetic testing, and how long does it take to get the results?**

The cost of genetic testing can range from under \$100 to more than \$2,000, depending on the nature and complexity of the test. The cost increases if more than one test is necessary or if multiple family members must be tested to obtain a meaningful result. For newborn screening, costs vary by state. Some states cover part of the total cost, but most charge a fee of \$30 to \$150 per infant.

From the date that a sample is taken, it may take a few days to weeks to receive the test results. Results for prenatal testing are usually available more quickly because time is an important consideration in making decisions about a pregnancy. The doctor or genetic counselor who orders a particular test can provide specific information about the cost and time frame associated with that test.

### **For more information about the logistics of genetic testing:**

The National Human Genome Research Institute discusses the coverage and reimbursement of genetic tests (<https://www.genome.gov/about-genomics/policy-issues/Coverage-Reimbursement-of-Genetic-Tests>).

## 9 Will health insurance cover the costs of genetic testing?

In many cases, health insurance plans will cover the costs of genetic testing when it is recommended by a person's doctor. Health insurance providers have different policies about which tests are covered, however. A person may wish to contact their insurance company before testing to ask about coverage.

Some people may choose not to use their insurance to pay for testing. Instead, they may opt to pay out-of-pocket for the test or pursue direct-to-consumer genetic testing, if available. People considering genetic testing may want to find out more about their state's privacy protection laws before they ask their insurance company to cover the costs. (Refer to *What is genetic discrimination?* for more information.)

### **For more information about insurance coverage of genetic testing:**

The National Human Genome Research Institute provides information about Coverage and Reimbursement of Genetic Tests (<https://www.genome.gov/about-genomics/policy-issues/Coverage-Reimbursement-of-Genetic-Tests>).

Genes In Life discusses insurance coverage (<http://www.genesinlife.org/after-diagnosis/plan-future/insurance-and-financial-planning>) and reimbursement (<http://www.genesinlife.org/testing-services/testing-genetic-conditions/reimbursement-genetic-testing>) for genetic testing.

## 10 What are the benefits of genetic testing?

Genetic testing has potential benefits whether the results are positive or negative for a gene mutation. Test results can provide a sense of relief from uncertainty and help people make informed decisions about managing their health care. For example, a negative result can eliminate the need for unnecessary checkups and screening tests in some cases. A positive result can direct a person toward available prevention, monitoring, and treatment options. Some test results can also help people make decisions about having children. Newborn screening can identify genetic disorders early in life so treatment can be started as early as possible.

### **For more information about the benefits of genetic testing:**

The Centers for Disease Control and Prevention (CDC) offers a fact sheet about genetic testing ([https://www.cdc.gov/genomics/gtesting/genetic\\_testing.htm](https://www.cdc.gov/genomics/gtesting/genetic_testing.htm)).

## 11 What are the risks and limitations of genetic testing?

The physical risks associated with most genetic tests are very small, particularly for those tests that require only a blood sample or buccal smear (a method that samples cells from the inside surface of the cheek). The procedures used for prenatal diagnostic testing (called amniocentesis and chorionic villus sampling) carry a small but real risk of losing the pregnancy (miscarriage) because they require a sample of amniotic fluid or tissue from around the fetus.

Many of the risks associated with genetic testing involve the emotional, social, or financial consequences of the test results. People may feel angry, depressed, anxious, or guilty about their results. In some cases, genetic testing creates tension within a family because the results can reveal information about other family members in addition to the person who is tested. The possibility of genetic discrimination in employment or insurance is also a concern. (Refer to What is genetic discrimination? for additional information.)

Genetic testing can provide only limited information about an inherited condition. The test often can't determine if a person will show symptoms of a disorder, how severe the symptoms will be, or whether the disorder will progress over time. Another major limitation is the lack of treatment strategies for many genetic disorders once they are diagnosed.

A genetics professional can explain in detail the benefits, risks, and limitations of a particular test. It is important that any person who is considering genetic testing understand and weigh these factors before making a decision.

### **For more information about the risks and limitations of genetic testing:**

The American College of Medical Genetics and Genomics (ACMG) published a policy statement about the risks associated with incorrect genetic test results or interpretation ([https://www.acmg.net/docs/LDT\\_Release.pdf](https://www.acmg.net/docs/LDT_Release.pdf)).

## 12 What is genetic discrimination?

Genetic discrimination occurs when people are treated differently by their employer or insurance company because they have a gene mutation that causes or increases the risk of an inherited disorder. Fear of discrimination is a common concern among people considering genetic testing.

Several laws at the federal and state levels help protect people against genetic discrimination. In particular, a federal law called the Genetic Information Nondiscrimination Act (GINA) is designed to protect people from this form of discrimination.

GINA has two parts: Title I, which prohibits genetic discrimination in health insurance, and Title II, which prohibits genetic discrimination in employment. Title I makes it illegal for health insurance providers to use or require genetic information to make decisions about a person's insurance eligibility or coverage. This part of the law went into effect on May 21, 2009. Title II makes it illegal for employers to use a person's genetic information when making decisions about hiring, promotion, and several other terms of employment. This part of the law went into effect on November 21, 2009.

GINA and other laws do not protect people from genetic discrimination in every circumstance. For example, GINA does not apply when an employer has fewer than 15 employees. GINA also does not protect against genetic discrimination in forms of insurance other than health insurance, such as life, disability, or long-term care insurance.

### **For more information about genetic discrimination and GINA:**

The National Human Genome Research Institute provides detailed discussions of genetic discrimination and current laws that address this issue:

- Genetic Discrimination (<https://www.genome.gov/about-genomics/policy-issues/Genetic-Discrimination>)
- NHGRI Genome Statute and Legislation Database (<https://www.genome.gov/about-genomics/policy-issues/Genome-Statute-Legislation-Database>)
- Genetic Information Nondiscrimination Act (GINA) of 2008 (<https://www.genome.gov/24519851/genetic-information-nondiscrimination-act-of-2008>)

The Genetic Alliance offers links to resources and policy statements on genetic discrimination (<http://www.geneticalliance.org/advocacy/policyissues/geneticdiscrimination>).

More detailed information about GINA is available from these resources

- Coalition for Genetic Fairness (<http://www.geneticfairness.org/ginaresource.html>)
- GINAHelp.org (<http://www.ginahelp.org/>)

## 13 Can genes be patented?

A gene patent is the exclusive rights to a specific sequence of DNA (a gene) given by a government to the individual, organization, or corporation who claims to have first identified the gene. Once granted a gene patent, the holder of the patent dictates how the gene can be used, in both commercial settings, such as clinical genetic testing, and in noncommercial settings, including research, for 20 years from the date of the patent. Gene patents have often resulted in companies having sole ownership of genetic testing for patented genes.

On June 13, 2013, in the case of the Association for Molecular Pathology v. Myriad Genetics, Inc., the Supreme Court of the United States ruled that human genes cannot be patented in the U.S. because DNA is a "product of nature." The Court decided that because nothing new is created when discovering a gene, there is no intellectual property to protect, so patents cannot be granted. Prior to this ruling, more than 4,300 human genes were patented. The Supreme Court's decision invalidated those gene patents, making the genes accessible for research and for commercial genetic testing.

The Supreme Court's ruling did allow that DNA manipulated in a lab is eligible to be patented because DNA sequences altered by humans are not found in nature. The Court specifically mentioned the ability to patent a type of DNA known as complementary DNA (cDNA). This synthetic DNA is produced from the molecule that serves as the instructions for making proteins (called messenger RNA).

### **For more information about gene patenting and the Supreme Court ruling:**

Read about the Supreme Court case (<https://www.scotusblog.com/case-files/cases/association-for-molecular-pathology-v-myriad-genetics-inc/>) and ruling against gene patenting.

The National Institutes of Health (<https://www.nih.gov/about-nih/who-we-are/nih-director/statements/statement-nih-director-francis-collins-us-supreme-court-ruling-gene-patenting>), the American College of Medical Genetics and Genomics (<https://www.acmg.net/docs/GenePatientsDecision.pdf>), and the American Medical Association (<https://www.ama-assn.org/delivering-care/precision-medicine/gene-patenting>) voice their support for the Supreme Court's ruling on gene patents.

The National Human Genome Research Institute discusses the relationship between Intellectual Property and Genomics. (<https://www.genome.gov/about-genomics/policy-issues/Intellectual-Property>)

## 14 How are genetic screening tests different from genetic diagnostic tests?

Screening tests evaluate an individual's risk of developing a genetic condition, while diagnostic tests identify genetic conditions. All genetic tests have both benefits and limitations.

Genetic screening tests are generally used in people who do not have signs or symptoms of a disorder. These tests estimate whether an individual's risk of having a certain condition is increased or decreased compared with the risk in other people in a similar population. A positive result means that a person's risk of developing the condition is higher than average. A negative screening test means that a person's risk is lower than average. However, having a positive screening result does not mean the individual has the condition. Because screening tests are only estimates, in some cases the results indicate an increased risk for a genetic abnormality when the person is actually unaffected (false positive), or the results indicate a decreased risk for a genetic abnormality when the person is really affected (false negative). While genetic screening tests do not provide a conclusive answer, they can help guide next steps, such as whether additional, diagnostic testing is needed.

Genetic diagnostic tests are often used in people who have signs and symptoms. These tests are used to confirm or rule out suspected genetic conditions. Diagnostic tests can also help inform a person's chance of developing a genetic condition or of passing on a genetic condition to their children. Diagnostic testing can be performed before birth or at any time during a person's life, but it is not available for all genes or all genetic conditions. The results of a diagnostic test can be used to guide a person's choices about health care and the management of the disorder.

Examples of genetic screening tests include:

**Noninvasive prenatal testing/screening (NIPT/NIPS):** This screening test is performed before birth to help determine the risk that a fetus will be born with certain genetic abnormalities, such as Down syndrome and other chromosomal disorders.

**Newborn screening:** In the United States, a screening test is performed on all newborns shortly after birth. This test can assess the risk for developing more than 35 genetic conditions. For many of these conditions, the test analyzes various protein and enzyme levels, which would be abnormal in affected individuals.

Examples of genetic diagnostic tests include:

**Molecular gene tests:** These tests determine the order of DNA building blocks (nucleotides) in an individual's genetic code, a process called DNA sequencing. The purpose of these tests is to identify genetic changes that can cause disease.

**Chromosomal tests:** These tests analyze whole chromosomes or long lengths of DNA to identify large-scale changes, such as an extra or missing copy of a chromosome (trisomy or monosomy, respectively) or abnormalities of large segments of

chromosomes, that underlie certain genetic conditions.

**For more information about the difference between screening and diagnostic genetic tests:**

The Centers for Disease Control and Prevention (CDC) provides information about genetic testing ([https://www.cdc.gov/genomics/gtesting/genetic\\_testing.htm](https://www.cdc.gov/genomics/gtesting/genetic_testing.htm)).

The American Medical Association provides details on genetic testing (<https://www.ama-assn.org/delivering-care/precision-medicine/genetic-testing>).

Genes In Life discusses diagnostic genetic testing (<http://www.genesinlife.org/testing-services/testing-genetic-conditions/diagnostic-testing>).

MedlinePlus has additional information on newborn screening (<https://medlineplus.gov/newbornscreening.html>).

## 15 How does genetic testing in a research setting differ from clinical genetic testing?

The main differences between clinical genetic testing and research testing are the purpose of the test and who receives the results. The goals of research testing include finding unknown genes, learning how genes work, developing tests for future clinical use, and advancing our understanding of genetic conditions. The results of testing done as part of a research study are usually not available to patients or their healthcare providers. Clinical testing, on the other hand, is done to find out about an inherited disorder in an individual patient or family. People receive the results of a clinical test and can use them to help them make decisions about medical care or reproductive issues.

It is important for people considering genetic testing to know whether the test is available on a clinical or research basis. Clinical and research testing both involve a process of informed consent in which patients learn about the testing procedure, the risks and benefits of the test, and the potential consequences of testing.

### **For more information about the differences between clinical and research testing:**

The Ohio State University's Wexner Medical Center describes the difference between clinical and research genetic testing (<https://wexnermedical.osu.edu/genetics/facts-about-testing>).

Additional information about clinical and research tests (<https://www.ncbi.nlm.nih.gov/gtr/docs/about/#tests>) is available from the Genetic Testing Registry.

## 16 What are whole exome sequencing and whole genome sequencing?

Determining the order of DNA building blocks (nucleotides) in an individual's genetic code, called DNA sequencing, has advanced the study of genetics and is one technique used to test for genetic disorders. Two methods, whole exome sequencing and whole genome sequencing, are increasingly used in healthcare and research to identify genetic variations; both methods rely on new technologies that allow rapid sequencing of large amounts of DNA. These approaches are known as next-generation sequencing (or next-gen sequencing).

The original sequencing technology, called Sanger sequencing (named after the scientist who developed it, Frederick Sanger), was a breakthrough that helped scientists determine the human genetic code, but it is time-consuming and expensive. The Sanger method has been automated to make it faster and is still used in laboratories today to sequence short pieces of DNA, but it would take years to sequence all of a person's DNA (known as the person's genome). Next-generation sequencing has sped up the process (taking only days to weeks to sequence a human genome) while reducing the cost.

With next-generation sequencing, it is now feasible to sequence large amounts of DNA, for instance all the pieces of an individual's DNA that provide instructions for making proteins. These pieces, called exons, are thought to make up 1 percent of a person's genome. Together, all the exons in a genome are known as the exome, and the method of sequencing them is known as whole exome sequencing. This method allows variations in the protein-coding region of any gene to be identified, rather than in only a select few genes. Because most known mutations that cause disease occur in exons, whole exome sequencing is thought to be an efficient method to identify possible disease-causing mutations.

However, researchers have found that DNA variations outside the exons can affect gene activity and protein production and lead to genetic disorders--variations that whole exome sequencing would miss. Another method, called whole genome sequencing, determines the order of all the nucleotides in an individual's DNA and can determine variations in any part of the genome.

While many more genetic changes can be identified with whole exome and whole genome sequencing than with select gene sequencing, the significance of much of this information is unknown. Because not all genetic changes affect health, it is difficult to know whether identified variants are involved in the condition of interest. Sometimes, an identified variant is associated with a different genetic disorder that has not yet been diagnosed (these are called incidental or secondary findings).

In addition to being used in the clinic, whole exome and whole genome sequencing are valuable methods for researchers. Continued study of exome and genome sequences can help determine whether new genetic variations are associated with health conditions, which will aid disease diagnosis in the future.

## **For more information about DNA sequencing technologies and their use:**

An illustration of the decline in the cost of DNA sequencing (<https://www.genome.gov/about-genomics/fact-sheets/Sequencing-Human-Genome-cost>), including that caused by the introduction of new technologies, is provided by the National Human Genome Research Institute.

The American College of Medical Genetics and Genomics has laid out their policies regarding whole exome and whole genome sequencing (<https://www.acmg.net/PDFLibrary/Genomic-Sequencing-Clinical-Application.pdf>), including when these methods should be used, what results may arise, and what the results might indicate.

GeneReviews compares whole genome sequencing, whole exome sequencing, and the sequencing of a selection of individual genes (<https://www.ncbi.nlm.nih.gov/books/NBK279899/>), particularly their use in the diagnosis of genetic conditions.

The Mount Sinai School of Medicine Genomics Core Facility describes the techniques used in whole exome sequencing (<https://icahn.mssm.edu/research/genomics/core-facility/whole-exome>).

## 17 What are secondary findings from genetic testing?

Secondary findings are genetic test results that provide information about changes (variants) in a gene unrelated to the primary purpose for the testing.

When a clinician orders a genetic test to discover the genetic cause of a particular condition, the test will often sequence one or a few genes that seem most likely to be associated with that individual's set of signs and symptoms. However, if the individual's signs and symptoms do not have an obvious genetic cause, a clinician might order a test that sequences all of the pieces of an individual's DNA that provide instructions for making proteins (called an exome) or a test that sequences all of an individual's DNA building blocks (nucleotides), called a genome. These tests are called whole exome sequencing and whole genome sequencing, respectively.

Many more genetic changes can be identified with whole exome and whole genome sequencing than by sequencing just one or a few genes. Sometimes, testing finds a variant that is associated with a condition other than the one for which testing was originally indicated. This is called a secondary finding. Some individuals with a secondary finding may not yet have any of the symptoms associated with the condition, but may be at risk of developing it later in life. For example, a person with a variant in the *BRCA1* gene, which is associated with an increased risk of breast cancer and ovarian cancer, may not have developed cancer. Other individuals with secondary findings may have a known medical condition, such as extremely high cholesterol, but receive results that indicate a genetic cause for that condition, such as a variant in the *LDLR* gene.

In 2013, then again in 2017 and 2021, the American College of Medical Genetics and Genomics (ACMG) recommended that all labs performing whole exome and whole genome sequencing tests report particular secondary findings, in addition to any variants that are found related to the primary purpose of the testing. In the 2021 updated recommendations, ACMG proposed a list of 73 genes that are associated with a variety of conditions, from cancer to heart disease. The 73 genes for which secondary findings are reported were chosen because they are associated with conditions that have a definable set of clinical features, the possibility of early diagnosis, a reliable clinical genetic test, and effective intervention or treatment. The goal of reporting these secondary findings to an individual is to provide medical benefit by preventing or better managing health conditions. The variants that are reported are known to cause disease. Variants of unknown significance, whose involvement in disease at the current time is unclear, are not reported.

The information provided by secondary findings can be very important because it may help prevent a disease from occurring or guide the management of signs and symptoms if the disease develops or is already present. However, as with any type of medical diagnosis, the news of an unexpected potential health problem may lead to additional health costs and stress for individuals and their families. On the basis of secondary findings, additional testing to confirm results, ongoing screening tests, or preventive care may be advised. Individuals receiving whole exome or whole genome sequencing can choose to "opt out" of analysis of the 73 secondary finding genes and not receive

variant results. As whole exome and whole genome sequencing become more common, it is important for individuals to understand what type of information they may learn and how it can impact their medical care.

### **Scientific journal articles for further reading**

Robert C. Green MD, MPH, Jonathan S. Berg MD, PhD, Wayne W. Grody MD, PhD, Sarah S. Kalia ScM, CGC, Bruce R. Korf MD, PhD, Christa L. Martin PhD, FACMG, Amy L. McGuire JD, PhD, Robert L. Nussbaum MD, Julianne M. O'Daniel MS, CGC, Kelly E. Ormond MS, CGC, Heidi L. Rehm PhD, FACMG, Michael S. Watson PhD, FACMG, Marc S. Williams MD, FACMG & Leslie G. Biesecker MD. ACMG recommendations for reporting of incidental findings in clinical exome and genome sequencing. *Genet Med.* 2013 Jul;15(7):565-74. doi: 10.1038/gim.2013.73. Epub 2013 Jun 20. PubMed: 23788249. Free full-text article from PubMed Central: 3727274.

Sarah S. Kalia ScM, Kathy Adelman, Sherri J. Bale PhD, Wendy K. Chung MD, PhD, Christine Eng MD, James P. Evans MD, PhD, Gail E. Herman MD, PhD, Sophia B. Hufnagel MD, Teri E. Klein PhD, Bruce R. Korf MD, PhD, Kent D. McKelvey MD, Kelly E. Ormond MS, C. Sue Richards PhD, Christopher N. Vlangos PhD, Michael Watson PhD, Christa L. Martin PhD & David T. Miller MD, PhD ; on behalf of the ACMG Secondary Findings Maintenance Working Group. Recommendations for reporting of secondary findings in clinical exome and genome sequencing, 2016 update (ACMG SF v2.0): a policy statement of the American College of Medical Genetics and Genomics. *Genet Med.* 2017 Feb;19(2):249-255. doi: 10.1038/gim.2016.190. Epub 2016 Nov 17. PubMed: 27854360.

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### **Learn more about secondary genetic findings:**

The Columbia University Medical Center has videos giving an Introduction to Secondary Findings (<http://www.learninggenetics.org/secondary-findings.html>) as well as discussing the Pros and Cons of Secondary Findings (<http://www.learninggenetics.org/ros-cons.html>) and Decisions about Secondary Findings (<http://www.learninggenetics.org/decisions.html>).

The American College of Medical Genetics and Genomics provides ACT Sheets (<https://www.ncbi.nlm.nih.gov/books/NBK553548/>) on secondary findings for multiple genes, which is available through the NCBI Bookshelf.

MedlinePlus Genetics has information on many of the genetic conditions (<https://vsearch.nlm.nih.gov/vivisimo/cgi-bin/query-meta?&v:project=medlineplus&v:sources=medlineplus-bundle&query=secondary%20findings&binning-state=group%3d%3dGenetics%0aalpha%3d%3dGenetic%20Conditions&>) and genes (<https://vsearch.nlm.nih.gov/vivisimo/cgi-bin/query-meta?&v:project=medlineplus&v:sources=medlineplus-bundle&query=secondary%20findings&binning-state=group%3d%3dGenetics%0aalpha%3d%3dGenes&>) that are associated with the 73 ACMG-recommended secondary finding genes.

The U.S. National Library of Medicine provides a list of the ACMG-recommended secondary finding genes and their associated conditions (<https://www.ncbi.nlm.nih.gov/clinvar/docs/acmg/>).

## 18 What is noninvasive prenatal testing (NIPT) and what disorders can it screen for?

Noninvasive prenatal testing (NIPT), sometimes called noninvasive prenatal screening (NIPS), is a method of determining the risk that the fetus will be born with certain genetic abnormalities. This testing analyzes small fragments of DNA that are circulating in a pregnant woman's blood. Unlike most DNA, which is found inside a cell's nucleus, these fragments are free-floating and not within cells, and so are called cell-free DNA (cfDNA). These small fragments usually contain fewer than 200 DNA building blocks (base pairs) and arise when cells die off and get broken down and their contents, including DNA, are released into the bloodstream.

During pregnancy, the mother's bloodstream contains a mix of cfDNA that comes from her cells and cells from the placenta. The placenta is tissue in the uterus that links the fetus and the mother's blood supply. These cells are shed into the mother's bloodstream throughout pregnancy. The DNA in placental cells is usually identical to the DNA of the fetus. Analyzing cfDNA from the placenta provides an opportunity for early detection of certain genetic abnormalities without harming the fetus.

NIPT is most often used to look for chromosomal disorders that are caused by the presence of an extra or missing copy (aneuploidy) of a chromosome. NIPT primarily looks for Down syndrome (trisomy 21, caused by an extra chromosome 21), trisomy 18 (caused by an extra chromosome 18), trisomy 13 (caused by an extra chromosome 13), and extra or missing copies of the X chromosome and Y chromosome (the sex chromosomes). The accuracy of the test varies by disorder.

NIPT may include screening for additional chromosomal disorders that are caused by missing (deleted) or copied (duplicated) sections of a chromosome. NIPT is beginning to be used to test for genetic disorders that are caused by changes (variants) in single genes. As technology improves and the cost of genetic testing decreases, researchers expect that NIPT will become available for many more genetic conditions.

NIPT is considered noninvasive because it requires drawing blood only from the pregnant woman and does not pose any risk to the fetus. NIPT is a screening test, which means that it will not give a definitive answer about whether or not a fetus has a genetic condition. The test can only estimate whether the risk of having certain conditions is increased or decreased. In some cases, NIPT results indicate an increased risk for a genetic abnormality when the fetus is actually unaffected (false positive), or the results indicate a decreased risk for a genetic abnormality when the fetus is actually affected (false negative). Because NIPT analyzes both fetal and maternal cfDNA, the test may detect a genetic condition in the mother.

There must be enough fetal cfDNA in the mother's bloodstream to be able to identify fetal chromosome abnormalities. The proportion of cfDNA in maternal blood that comes from the placenta is known as the fetal fraction. Generally, the fetal fraction must be above 4 percent, which typically occurs around the tenth week of pregnancy. Low fetal fractions can lead to an inability to perform the test or a false negative result. Reasons for low fetal fractions include testing too early in the pregnancy, sampling errors,

maternal obesity, and fetal abnormality.

There are multiple NIPT methods to analyze fetal cfDNA. To determine chromosomal aneuploidy, the most common method is to count all cfDNA fragments (both fetal and maternal). If the percentage of cfDNA fragments from each chromosome is as expected, then the fetus has a decreased risk of having a chromosomal condition (negative test result). If the percentage of cfDNA fragments from a particular chromosome is more than expected, then the fetus has an increased likelihood of having a trisomy condition (positive test result). A positive screening result indicates that further testing (called diagnostic testing, because it is used to diagnose a disease) should be performed to confirm the result.

### **Scientific journal articles for further reading**

Committee Opinion No. 640: Cell-Free DNA Screening For Fetal Aneuploidy. *Obstet Gynecol.* 2015 Sep;126(3):e31-7. doi: 10.1097/AOG.0000000000001051. PubMed: 26287791.

Dondorp W, de Wert G, Bombard Y, Bianchi DW, Bergmann C, Borry P, Chitty LS, Fellmann F, Forzano F, Hall A, Henneman L, Howard HC, Lucassen A, Ormond K, Peterlin B, Radojkovic D, Rogowski W, Soller M, Tibben A, Tranebjærg L, van El CG, Cornel MC. Non-invasive prenatal testing for aneuploidy and beyond: challenges of responsible innovation in prenatal screening. Summary and recommendations. *Eur J Hum Genet.* 2015 Apr 1. doi: 10.1038/ejhg.2015.56. [Epub ahead of print] PubMed: 25828867.

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### **For more information about NIPT:**

MedlinePlus Medical Test: Prenatal Cell-Free DNA Screening (<https://medlineplus.gov/ab-tests/prenatal-cell-free-dna-screening/>)

Genomics Education Programme (UK): What is NIPT? (<https://www.genomicseducation.hee.nhs.uk/blog/what-is-nipt/>)

National Human Genome Research Institute: Noninvasive Prenatal Genetic Testing (<https://www.genome.gov/dna-day/15-ways/noninvasive-prenatal-genetic-testing>)

Centre for Genetics Education (Australia): Fact Sheet: Non-Invasive Prenatal Testing (NIPT) (<https://www.genetics.edu.au/SitePages/Non-invasive-prenatal-testing.aspx>)

National Society of Genetic Counselors: Questions Expectant Mothers Should Ask Before Prenatal Screening (<https://www.aboutgeneticcounselors.org/Resources-to-Help-You/Post/questions-expectant-mothers-should-ask-before-prenatal-screening>)

Eunice Kennedy Shriver National Institute of Child Health and Human Development: How do Health Care Providers Diagnose Birth Defects? (<https://www.nichd.nih.gov/health/topics/birthdefects/conditioninfo/diagnosed>)

Genetic Support Foundation: Prenatal Cell-free DNA (cfDNA) Screening (<https://www.geneticsupport.org/genetics-pregnancy/prenatal-screening-tests/cell-free-dna-screening/>)

## 19 What is circulating tumor DNA and how is it used to diagnose and manage cancer?

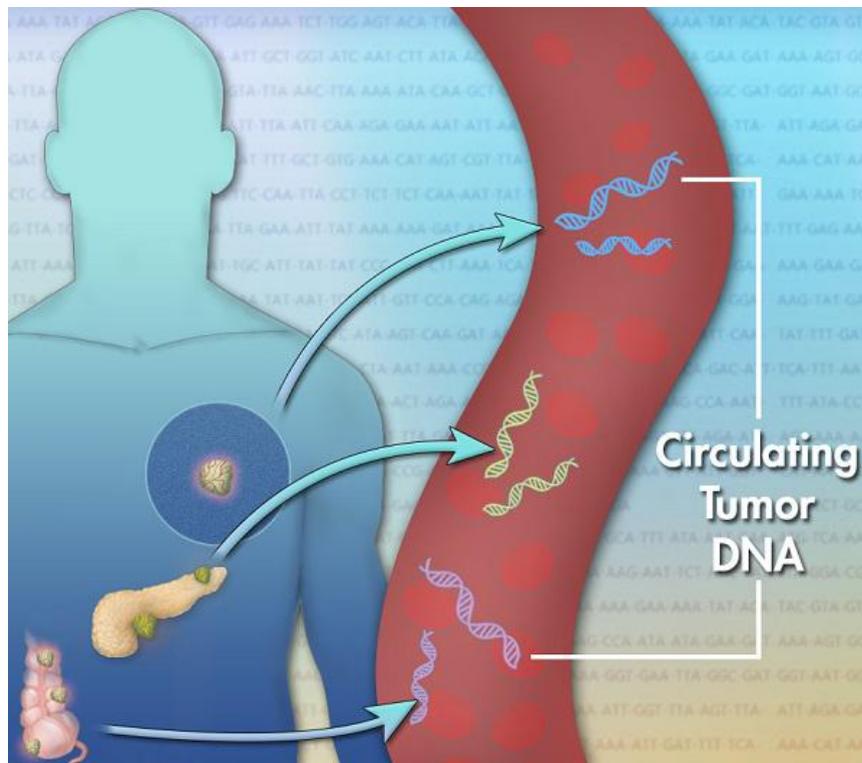
Circulating tumor DNA (ctDNA) is found in the bloodstream and refers to DNA that comes from cancerous cells and tumors. Most DNA is inside a cell's nucleus. As a tumor grows, cells die and are replaced by new ones. The dead cells get broken down and their contents, including DNA, are released into the bloodstream. ctDNA are small pieces of DNA, usually comprising fewer than 200 building blocks (nucleotides) in length.

The quantity of ctDNA varies among individuals and depends on the type of tumor, its location, and for cancerous tumors, the cancer stage.

Detection of ctDNA can be helpful in the following cases:

- Detecting and diagnosing a tumor. Because tumor DNA has acquired multiple genetic changes (variants), leading to tumor development, ctDNA is not an exact match to the individual's DNA. Finding DNA with genetic differences aids in tumor detection. Diagnosing the type of tumor using ctDNA can reduce the need for getting a sample of the tumor tissue (tumor biopsy), which can be challenging when a tumor is difficult to access, such as a tumor in the brain or lung.
- Guiding tumor-specific treatment. Analyzing the genome of tumor cells using ctDNA can help doctors determine which treatment will be most effective. Currently, however, approval from the U.S. Food and Drug Administration for ctDNA testing to personalize cancer treatment is limited.
- Monitoring treatment. A decrease in the quantity of ctDNA suggests the tumor is shrinking and treatment is successful.
- Monitoring periods with no symptoms (remission of cancer). A lack of ctDNA in the bloodstream indicates that the cancer has not returned.

Scientists have discovered that dying tumor cells release small pieces of their DNA into the bloodstream. These pieces are called cell-free circulating tumor DNA (ctDNA). (Figure 2)



**FIGURE 2:** Illustration of DNA fragments in a blood vessel with arrows indicating the fragments originated from tumors in body organs.

### Scientific journal articles for further reading

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Stewart CM, Kothari PD, Mouliere F, Mair R, Somnay S, Benayed R, Zehir A, Weigelt B, Dawson SJ, Arcila ME, Berger MF, Tsui DW. The value of cell-free DNA for molecular pathology. *J Pathol.* 2018 Apr;244(5):616-627. doi: 10.1002/path.5048. Epub 2018 Mar 12. PubMed: 29380875.

### For more information about ctDNA:

National Human Genome Research Institute: Cancer Genomics (<https://www.genome.gov/dna-day/15-ways/cancer-genomics>)

PHG Foundation (UK): Circulating Tumour DNA Technology: The Future of Cancer

Management? (<https://www.phgfoundation.org/briefing/ctDNA-the-future-of-cancer-management>)