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Human disease biomarkers: challenges, advances, and trends in their validation

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ABSTRACT

Biomarkers are important tools in the medical field, once they allow better prediction, characterization, and treatment of diseases. In this scenario, it is essential that biomarkers are highly accurate. Thus, biomarker validation is an essential part of ensuring the effectiveness of a biomarker. Validation of biomarkers is the process by which biomarkers are evaluated for accuracy and consistency, as well as their ability to inform the condition of health or disease. Although, there is no unique measure that can be used to determine the validity for all biomarkers, there are general criteria that all biomarkers must meet to be useful. In this work, we review the definition of biomarkers and discuss the validity components. We then critically discuss the main methods used to validate biomarkers and consider some examples of biomarkers of the diseases which most killer in the world (cardiovascular diseases, cancer, and viral infections), highlighting the potential biochemical pathways of these biomarkers in the biological system. In addition, we also comment on the omic strategies used in the biomarker discovery process and conclude with information about perspectives in biomarker validation through imaging techniques.

Keywords: *Biomarker, cancer, cardiovascular diseases, viral infection, validation, analytical instrumentation.*

1. Introduction

The development of disease is related to a set of extrinsic factors that involve environmental aspects and lifestyle habits, as well as it may be related to intrinsic factors regulated mainly by genes [1]. It is known that depending on these factors, a great diversity in the clinical expression of the same disease may exist [2]. Obviously, other factors, mainly related to new forms of treatment, can influence the course of the disease, as well as its clinical expression in the biological system. In this sense, biomarkers emerge as dynamic and important tools to understand the cause, type, severity, and treatment monitoring of human diseases [3].

Biomarkers are entities that can be measured experimentally, indicating the normal or pathological condition of an organism, as well as indicating the organism's response to a pharmacological treatment [4]. The identification and validation of different biomarkers of human disease, whether genetic or biochemical, have contributed not only to the diagnosis of diseases related to humans, but also to the understanding of their causes and the response mechanisms to the therapeutic procedure [5]. Biochemical markers (proteins, lipids, metabolites and others) have shown a strong association with different types of diseases, such as: cancer [6–8] , cardiovascular diseases [9,10] and even psychiatric diseases [11–14] and have been widely used as an auxiliary method in the diagnosis of chronic autoimmune and inflammatory diseases, as for example, diabetes [15,16] and degenerative arthritis [17]. In view of technological advances and the application of multidisciplinary research strategies that make it possible to study diseases and their relationship to human health,

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genetic markers have been associated with numerous diseases, which confirms the influence of genes on the development of inflammatory and infectious diseases, neoplastic (tumoral) and cardiac [4–6,10].

The development of a biomarker for clinical purposes requires different step of discovery and validation [18,19]. In general, the discovery stage is related to the application of omic strategies, such as: genomics [20], transcriptomics [21], proteomics [22], metabolomics [23] and others that aim to extract and identify possible biomarkers in biological samples (tissue, cell, fluid). The validation step is essential for recognizing a biomolecule as a biological marker. Validation is essentially based on quantitative and qualitative measures to confirm whether the concentration or status of a probable biomarker is significantly different between disease and control, or whether there is a significant response from a therapeutic intervention [5,18]. For a biomolecule to be confirmed as a biological marker it is necessary that it also has important characteristics, such as, reflecting the interaction of the biological system in a qualitative and/or quantitative way with the disease or with a pharmacological agent; be sensitive and specific to the disease or treatment; be qualitatively and quantitatively reproducible, as well as in its analytical measure, present adequate accuracy and precision [19]. Although, in recent times, the biomarker discovery process has gained great emphasis in the scientific field through omic strategies, the validation of such biomolecules has not been seen with the same enthusiasm. However, the validation process is essential for new biomarkers to be introduced in routine clinical practice [5].

In this sense, this review critically discusses the importance of biomarkers in the diagnosis and treatment of human diseases, focusing mainly on cardiovascular diseases, cancer and viral infections, as well as describing the steps to validate such biomolecules, using some of the main validation techniques. This work also comments on the genomic, transcriptomic, proteomic and metabolomic strategies used in the biomarker discovery process.

2. Biomarkers: an overview

The term biomarker (contracted form of biological marker) emerged in the scientific sphere in 1989 as a medical term to indicate biological parameters (for example, the increase or decrease in the concentration of specific enzymes and hormones or the presence of a substance in the biological system) that allow them to be measured quantitatively, serving as an indicator of health and assessments related to physiology such as pregnancy, genetic dysfunction or effects of chemical exposure [4,18]. For the World Health Organization (WHO), biomarkers are defined as any specie, structure or process that can be measured in the body, or in its products and that allows to predict the influence or incidence of disease or results [18]. For the National Institute of Health (NIH) Working Group, biomarkers are a characteristic that is objectively measured and evaluated as an indicator of normal biological processes, pathogenic process, or pharmacological response to a therapeutic intervention [24]. Although there are different definitions to conceptualize what is a biomarker, in practice, everyone agrees that biomarkers are important tools that can help to understand the cause, diagnosis, progression or regression of symptoms and the outcome of treatment of certain diseases. The main sources of biomarkers are tissues, cells, and biological fluids[4]. However, fluid samples such as, blood (plasma or serum), cerebrospinal fluid (CSF), urine and saliva are the most used in research to discover biomarkers [19]. This fact is justified by the advantages that this type of sample presents, such as, easy accessibility, avoiding the risks of invasive tissue sampling through biopsy, relatively low cost of obtaining it, and its potential for the development of diagnostic/prognostic tests on a large -scale, since biological fluids are used in routine tests [25,26]. The desirable characteristics for a biomarker depend on its application. For the detection of human disease, for example, a biomarker must have (i) high sensitivity and specificity, (ii) adequate precision and accuracy, (iii) be robust and present low cost in its clinical tests [4,18,19].

2.1 Types of biomarkers

According to Wishart et al. [4], biomarkers can be classified as: exposure biomarkers, widely used in predicting risks of toxicological contamination; and effect (or disease) biomarkers used in the prognosis, diagnosis and monitoring (progression or regression) of a given disease [4]. Exposure biomarkers are used to assess and confirm individual or group exposure to a specific substance, establishing a link between external exposure and the quantification of internal exposure in the biological system [5]. Exposure biomarkers can reflect the amount absorbed immediately before sampling, such as the concentration of solvent in the air expelled by the lung or blood during the workday, as well as it can reflect the amount of solvent absorbed the previous day, collecting pulmonary air or blood 16 hours after the end of exposure, in addition, exposure biomarkers may reflect the amount of substance absorbed during months of exposure [24]. In this case, the substance must have a long half-life, as is the case with exposure to heavy metals. Disease biomarkers are biological parameters, which reflect the relationship of disease/biological system or disease/ pharmacological agent [24]. Most of the time, biochemical changes are strong candidates for biological markers [4]. Effect biomarkers have important applications in monitoring the health status of an organism. Among its applications include (i) use as a diagnostic tool to identify abnormal conditions and /or disease, such as, high concentration of glucose in the blood, aiding in the diagnosis of diabetes [27]; (ii) use as a tool for the identification of cancer, measuring carcinoembryonic antigen 125 (CA-125), marker of several cancers [28]; (iii)

help to classify the severity of a disease, as is the case of the assessment of the concentration of the prostate specific antigen (PSA) in the blood, this assessment reflects the degree of tumor growth and metastasis in the body [28]; (iv) use as an indicator of disease prognosis and monitoring of therapeutic response, performed by a clinical intervention, such as, the measurement of cholesterol concentration in the blood, determining the risk of developing cardiovascular diseases [29].

For this work, disease biomarkers will be the focus of discussion. Here, the importance of this type of biomolecule for the diagnosis of human disease will be discussed, as well as the main phases of discovery and validation of such biomolecules will be briefly reported.

2.2 Discovery of biomarkers

The first step to discovery biomarkers involves the application of strategies aimed detecting candidate biomolecules for biological markers [19]. In this sense, genomics, transcriptomics, proteomics and metabolomics are highlights, mainly, investigating possible changes in the gene, messenger RNA, protein, and metabolite that is characterized as a biological marker [4,5]. Doing a search of the last ten years in one of the main search website (Scopus) with the words: omic (genomic, transcriptomic, proteomic, metabolomic) clinical, there is a significant growth in published works, reporting studies to discovery candidate biomolecules to biomarker of diferente diseases in different types of samples. Table 1 presents some of these numbers. This fact shows the high investment by development agencies, as well as demonstrates the interest of the scientific community in conducting research with the objective of discovering biomarkers that help in the diagnosis and treatment of human diseases.

Table 1 | Number of scientific articles published per year, reporting the search for human diseases biomarker.

Omic	Publication/year					
	2009	2011	2013	2015	2017	2019
Genomic	310	441	649	1038	1381	1822
Transcriptomic	65	126	196	333	501	844
Proteomic	562	698	688	768	840	970
Metabolomic	177	317	515	835	1125	1544

2.2.1 Genomics

Genomics is the area of science that studies the genetic patterns that may exist in the genome of a given organism. Genomics allows to assessment of possible alterations in the DNA code that alone or in combination are associated with susceptibility, expression and evolution of the disease, also considering the therapeutic response [20]. Genomics has important tools for gene analysis, such as: the polymorphism of a single nucleotide (SNP) to analyze possible changes in the bases of genetic sequencing, characterizing candidate genes for biological markers of human diseases [20]. For example, in a study developed by Zou et al. SNP technique was used to identify possible changes in the gene extracted from the blood of patients with type 2 diabetes (n = 152). To do this, the gene extracted from the blood of healthy individuals (n = 120) was used as a control. In the study, the researchers identified high levels of methylation in the PRKCZ gene, indicating that PRKCZ may be involved in the pathogenesis of type 2 diabetes [30].

2.2.2 Transcriptomics

Transcriptomics is another omic approach used to discovery biomarker of human diseses. In this strategy, the set of messenger RNAs (mRNAs) of a given biological system is studied under different conditions, such as diseases [31]. Among the main ways to study gene expression are complementary DNA microarray (cDNA) and the reverse transcription polymerase chain reaction (RT-qPCR)[32]. The cDNA arrangement technique is based on the ability of mRNA to pair (hybridize) with the DNA molecule that gave rise to it, allowing to label in an arrangement form and subsequent identification and quantification. RT-qPCR technique allows quantifying the number of copies (cDNA) of the target sequence, comparatively analyzing the number of copies of cDNA and the amount of mRNA that generated it, a fact that allows a global analysis of the gene expression of the disease [32]. Zhang et al. [33] performed a transcriptomic study in the saliva of individuals with breast cancer to determine possible biomarkers of this disease. In the study, the complementary DNA microarray technique was used to assess the profile of women diagnosed with breast cancer (n=10) and healthy women (n=10). Eight mRNAs (S100A8, CSTA, GRM1, TPT1, GRIK1, H6PD, IGF2BP1, MDM4) were identified as differentially expressed and were suggested as candidates for the biomarker of breast cancer [33].

2.2.3 Proteomics

Proteomics studies the set of proteins in an organism under specific conditions [25,26]. One of the applications is the comparative study [12]. In this study, the protein profiles of at least two samples are compared to identify qualitative and quantitative differences between the molecules, which can result in a biomarker [26]. The combination of separation techniques, as for example, electrophoresis (gel and capillary) and liquid chromatography with mass spectrometry is widely used in proteomic studies, as it allows to separate, quantify and identify the possible differential proteins of the disease, for example [12,26]. In this sense, several proteomic studies have been development to discovery biomarkers. For example, a comparative study in human saliva between patients with oral cancer (n = 16) and healthy patients (n = 16) it was performed in order to verify

differential proteins that are candidates for biomarkers [34]. In the study, the liquid chromatography mass spectrometry tandem (LC-MS/MS) technique was used for fractionation and nano-liquid chromatography quadrupole time of flight (nLC-QTOF MS) for identification, both in reverse phase. Fractionation resulted in 35 fractions. The proteins of each fraction were reduced with dithiothreitol (DTT), oxidized with iodocetamide (IAA) and digested with trypsin, then they were analyzed by nLC-QTOF MS. Comparing the spectra obtained from the analysis by nLC-QTOF MS with the Mascot database (score> 25 and p <0.05), it was possible to identify four main proteins (CD59, involucrin, Ras-related protein Rab-7 and moesin) candidates to biological marker of oral cancer [34].

2.2.4 Metabolomics

aIn addition to genomics, transcriptomics and proteomics, changes in the level of concentration of metabolites in an organism are also important data in the search for disease biomarkers [35]. The main tools used in this type of study involve, in addition to nuclear magnetic resonance (NMR) spectroscopy, the combination of separation techniques such as chromatography (gas or liquid) and capillary electrophoresis with mass spectrometry [35]. Daimon et al. [36]used the capillary electrophoresis time of flight (CE-TOF -MS) technique to identify differentially expressed metabolites with a potential biomarker for type 2 diabetes. For the study, the researchers collected blood serum from non-diabetic men (n = 19) and diabetics (n = 17). Samples of non- diabetic individuals were subdivided into individuals with low glycemia (n = 5) and individuals with tolerable normal glycemia (IGNT) (n = 14). Of the 560 metabolites identified, approximately 74 metabolites were quantified in all serum samples. Significant differences between diabetics and IGNT were observed in 24 metabolites, with glycerol-3-phosphate, being the metabolite with the highest concentration in the diabetic group when compared to the IGNT group [36].

3. Analytical validation of a biomarker

Although, significant investments have been made to discovery possible biomarkers of human diseases, the number of new biomarkers approved by the Food and Drug Administration (FDA) has remained extremely low [37]. A comparative survey of publications and biomarker patents between 2009 and 2019 carried out using Scopus and FDA website shows some of this reality (Figure 1).

Figure 1 shows a low number of biomarker patents when compared to publications. Numerous factors have contributed to this low number of biomarkers that reach the clinical assessment stage [24]. Validation is one of the decisive steps to ensure the clinical testing stage. It is responsible for assessing whether there is sufficient evidence for the clinical utility of the candidate biomolecule as a

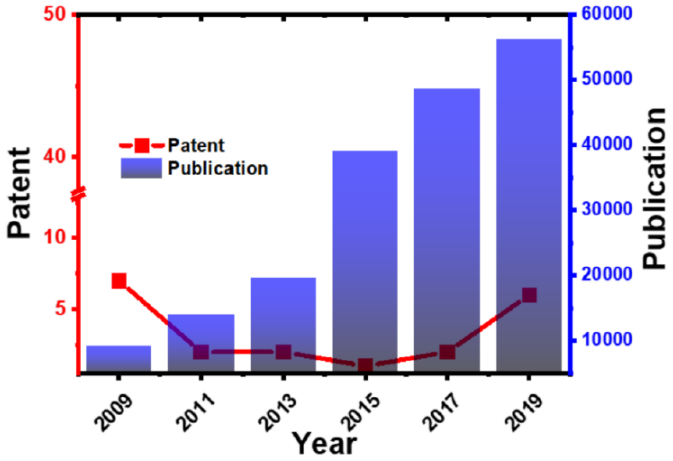

Figure 1 | Overview of the relationship between publications and patents involving biomarker.

biomarker [18,19]. Validation criteria are defined according to the purpose for which it is intended to validate. Generally, for the validation of a biomarker, the following points are used as essential criteria [10, 21]: (i) accuracy; (ii) precision; (iii) sensitivity; and (iv) specificity [18,19,21,22,38].

Accuracy is the proximity between the result of a measurement and the value considered true [38]. Limits for the minimum acceptable accuracy must be established before or during method development [39]. Standard reference materials (SRM) are used in assay validation to estimate intra- and inter-run accuracy [39]. Quality control reference materials are used to accept or reject assay runs [38,39]. Precision is defined as the proximity between measured quantity values obtained by replica measurements under specified conditions [38]. Analytical repeatability and reproducibility are requirements for the implementation of diagnostic tests and treatment. Measurement precision is usually expressed numerically by standard deviation, variance, or coefficient of variation under the specified measurement conditions [38]. Due the lack of well-characterized and well regulated "standard reference materials" or quantitative measures of immune analytes, reference materials often in the forms of biological samples are used to assess relative accuracy of an assay performance [38,39]. Sensitivity refers to the ability of the biomarker to reflect qualitatively and/or quantitatively a change in the biological system through a certain stimulus, such as disease, that is, it measures the probability of obtaining a positive result when the disease is present. Sensitivity is usually assessed experimentally in research groups (patients). Specificity indicates the probability of obtaining a negative result when the individual has no disease, that is, measures the ability to rule out a disease when it is not present. Specificity is assessed, experimentally, in control (healthy) groups [38]. The selectivity/specificity relationship is usually assessed by the receiver operation characterization curve (ROC). The ROC curve allows the quantitative description of the performance of a diagnostic test, resulting in the confirmation or discard of a procedure, in this case: the

validation of a biomolecule as a biomarker [4,38]. In addition to the validation step, it is also necessary to evaluate important aspects of the feasibility of applying the biomarker in clinical practice, such as: validity and availability of the biomarker, agility, simplicity and cost of the experiments [18,19,37].

3.1 Main techniques applied for biomarker validation and their challenges

A precise method to quantify the gene biomarker is the RT -qPCR[32]. With this method it is possible to quantify unique genes or multiple gene sets in a run [40]. PCR is an assay that amplify a DNA (or RNA) target rather than a signal. Using qPCR arrays, up to 384 different transcripts can be analyzed in parallel [40]. There are also other methods available for a holistic screen of gene-expression changes. Until recently, microarray analysis has been the screening method of choice for most gene-expression experiments at the mRNA and miRNA and miRNA level. However, RNA sequencing (RNA-Seq) has been gaining space. RNA-Seq is a new method that allows the sequencing and the quantification of the whole transcriptome of a biological sample. It is a sensitive approach. In addition, a single transcript of a given gene is detectable, and since it is free from guesswork, it is also possible to discover new transcripts or unknown splice variants [41].

Although, RT-qPCR is the current gold standard for sensitive and reproducible miRNA gene-expression analysis, the nature of miRNA molecules poses a challenge for reliable analyses, as for example, (i) members of a miRNA family (e.g., let 7 family) usually differ by only one nucleotide, mainly at the 3'end of the sequence; (ii) the combination of short length of mature miRNAS (~22nt) and a heterogeneous content poses a challenge for cDNA synthesis and primer and probe design since these results in significant difference in the melting temperatures of different miRNAs; (iii) There are no specific guidelines for analyzing and normalizing miRNA expression data [39]. However, strategies to deal with these challenges have been published and are being intensely discussed [38,39,41]. Not only are molecules properties challenging for established technical procedures, but sample matrices also present additional problems [41].

Immunohistochemistry (IHC) is a multi-step process that requires standardized conditions for samples collection, fixation and processing, preparation of the IHC slide, and interpretation of staining results [38]. Tissues are typically the most used sample in the IHC assay. Tissue-based biomarkers can be measured in freshly frozen (FF) samples or formalin fixed paraffin embedded (FFPE) tissue [39]. FFPE tissue blocks often available as archival materials as part of bio-bank samples for conventional IHC, which is the most widely used platform for evaluating biomarker in diagnostic surgical pathology and for retrospective research. However, protein and nucleic acid damage usually occurs though fixation, incorporation, and prolonged storage of FFPE samples [39]. Therefore, to control the pre-analytical requirements of assay performance, it is recommended to run the test on a series of in-house tissues with known IHC performance characteristics, representing known positive and negative tissues (references samples) [38,39].

Another technique used to validate biomarker of human disease is those based on antibodies, such as, enzyme-linked immunosorbent assays (ELISA) and Western blotting [42]. Although different immunoassay formats are available, the sandwich ELISA is the most common assay used in biomarker analysis due to its high specificity and sensitivity [42,43]. In this format, the target protein will be detected using two different antibodies (capture and detection antibodies). However, for many of the candidate biomarkers, a commercially available assay will not exist and specific antibodies against the target of interest and/or the corresponding ELISA need to be developed [43]. The development and optimization of an ELISA assay requires a careful design, as a wide range of variables, ranging from antibody specificity to the concentration and composition of different reagents, can affect the result and therefore the validity of the candidate [42,43]. Jou et al. [44]. Suggested protein transferrin as a biomarker of early-stage oral cancer. In this comparative proteomics study, the researchers used two-dimensional electrophoresis and matrix-assited laser desorption/ionization mass spectrometry (MALDI-TOF MS) to discover differential proteins between saliva of patients diagnosed with oral cancer (n = 11) and healthy patients (n=30). Transferrin was confirmed using ELISA and Western blotting as validation techniques. The specificity and selectivity of the biomarker, according to the authors, were 100% for both criteria [44].

More recently, strategies based on targeted mass spectrometry have been developed to validate biomarker involved in different diseases, offering an alternative [45]. The great advantage of this methodologies on targeted mass spectrometry-based is that they allow the simultaneous accurate and specific quantification of several biomarkers (multiplexing) [45]. Peptides are used as protein surrogates, measured using triple quadrupole instruments in selected reaction monitoring/multiple reaction monitoring (SRM/ MRM) analysis [46]. SRM is an MS-based method performed in two stage of mass analysis [47]. An ion of a specific mass is selected to be detected in the first stage of mass spectrometer an a product ion after fragmentation of the precursor ion is selected in a second detection step [45–47]. MRM is the application of selected reaction monitoring for multiple product ions of one or more precursor ions [45]. The pair of m/z values corresponding to the precursor and fragment ions is called a transition. The intensity of this pair (transition) is recorded and used for absolute quantification [47]. However, the applications of SRM/MRM assays are still in the beginning, therefore, there are, still, limitation, but it is believed that improved automated sample preparation and mass spectrometry technology

(faster instruments with higher selectivity) could make SRM/MRM methods the diagnostic tool of the future [45]. In the work carried out by by Ahn et al. [48], glycoproteins were evaluated to identify possible biomarkers of lung cancer. In the study, using plasma from healthy patients (n = 30) and patients with lung cancer (n = 30), the researchers validated, by SRM-MS, alpha-1-acid glycoprotein and ceruloplasmin as biomarkers of such neoplasia. The specificities and sensitivity of the identified biomarkers were 0.75 and 0.80, respectively [48].

4 General classes of biomarker assays

The American Association of Pharmaceutical Scientists (AAPS) and the US Clinical Ligand Society have listed four general classes of biomarker assays [38]: (i) qualitative assay; (ii) semi-quantitative assay; (iii) relative quantitative assay; (iv) a definitive quantitative assay. Table 2 show a summary of the general classes of biomarker assays, highlighting the performance characteristics required to be evaluated for each type of assay.

A qualitative assay generates categorical data lacks proportionality to the amount of analyte in a sample [49]. Data can be ordinal in the sense that the assay is based on discrete scoring scales such as those often used for IHC or nominal such as the presence or absence of a gene producto [38]. Qualitative assays are only needed to show that they are sufficiently sensitive and specific to detect the target analyte [50]. A semi-quantitative assay does not use a calibration standard but has a continuous response that is expressed in terms of a characteristic of the test sample [49]. Precision can be validated, but not accuracy [38]. A relative quantitative assay uses a concentration-response calibration with reference standards that are not fully representative of the biomarker [49]. As the calibration curve can use a non-certified standard or surrogate matrix or both, studies on parallelism and dilution linearity are necessary [50]. Precision can be validated but accuracy can only be estimated [50]. A definitive quantitative assay makes uses of calibrators and a regression model to calculate absolute quantitative values for unknown samples [49]. The reference standard must be well defined and fully representative of the biomarker [38]. This type of assay can be validated to be accurate and precise [38,49,50].

5. Human diseases and the importance of biomarkers in their diagnosis

According to WHO data, cardiovascular disease, cancer, and viral infection are, at the moment, the diseases that most affect and kill in the world. Thus, in the following topics, a brief description of these diseases is presented, highlighting some of the validated biological markers and their potential biochemical pathways in the biological systems that can be used in the diagnosis and/or treatment of these disease.

5.1 Main techniques applied for biomarker validation and their challenges

Cardiovascular diseases (CVD) are diseases characterized by affecting the circulatory system, that is, the blood vessels and the heart [51]. There are several types of CVD, including myocardial infarction, ischemia, atherosclerosis, and strokes [10,51]. According to the WHO, CVDs are the main cause of mortality in the world, making a total of 7.2 million deaths each year [10]. The incidence of CVDs is related to lifestyle, as well as genetic susceptibility [29]. Thus, studies have provided important information about biological markers that play a role in the diagnosis of CVDs, for example, the LTA and LGALS2 genes and the 5-lipoxygenase and 4D-phosphodiesterase proteins, among others. These biomolecules have been found to be overexpressed in comparative studies with cardiac patients [51,52]. Several molecular mechanism mediate hypertension-induced vascular remodeling [9,10,20,52]. One of the main mechanisms is shown in Figure 2 [51].

The mechanical stretching force exerted by hypertension on the vascular wall promotes the production of reactive oxygen species (ROS) [53], which in turn induce Vascular Smooth Muscle Cell (VSMC) remodeling [54,55]. Hypertension-mediated excessive stretch force also causes changes in the extracellular matrix, activating the RhoA pathway, which in turn promotes actin cytoskeleton remodeling in VSMC [51]; hypertension-induced activation of extracellular signal- regulated kinases 1 and 2 (ERK1/2) and protein kinase B (AKT) also results in vascular remodeling [56,57]. Furthermore, caveolae, which are lipid raft investigations in the plasma membrane, mediate the modeling of hypertension induced VSMC via endothelial nitric oxide synthase (eNOS) and endothelin receptor type A (ETA) [58,59]. Studies have also shown that angiotensin II type 1 receptor (AT1), platelet-derived growth factor receptor (PDGF-R), and specific ion channels, such as voltage-gated calcium channels, are implicated in hypertension-induced VSMC remodeling [60,61]. The forces

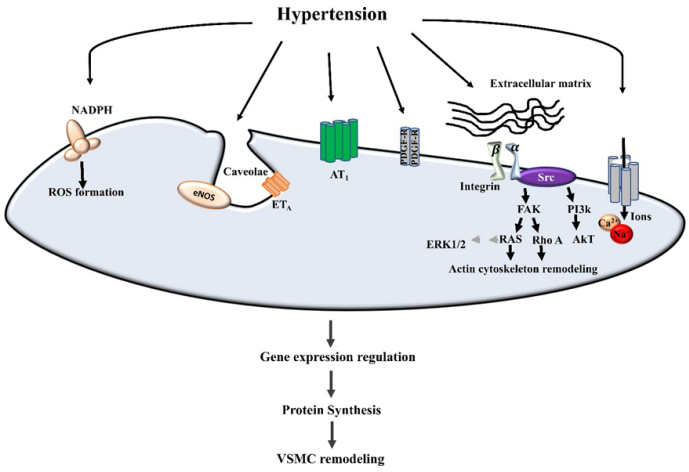

Figure 2 | Scheme of vascular smooth muscle cell (VSMC) remodeling in response to hypertension .

Table 2 | Overview of the general classes of biomarker assays, highlighting the performance characteristics that should be evaluated for each type of assay

Assay type	Definition	Examples	Assay performance characteristics			
			Accuracy	Precision	Sensitivity	Specificity
Qualitative	No calibration standards, and the bioanalytical results are expressed in terms of test discrete sample characteristic (discontinuous) and reported in any ordinal or nominal formats.	Immunohistochemistry (IHC), imaging	-	+	+	+
Semi-quantitative	Does not use a reference standard (or calibration curve). However, the analytical response is continuous (numeric), and the bioanalytical result are expressed in terms of a characteristic of the test sample.	Enzymatic assays (where activity might be expressed per unit volume); Anti-drug antibody assays (where the readout is a titer or % bound).	-	+	+	+
Relative quantitative	Reference standard that is not well characterized, not available in a purified form, or not fully representative of the endogenous biomarker; The results of these assays are expressed in continuous numeric units of the relative reference standard; Most biomarker assays provide "relative" quantification of the analyte. The interest is in the temporal changes of the marker rather than the absolute concentration.	Quantitative -PCR, flow cytometry	+	+	+	+
Definitive quantitative	Reference standard is well defined or characterized and is representative of the endogenous biomarker; Assay results are absolute quantitation of the analyte and are expressed in continuous numerical units of the definitive reference standard.	Human insulin or a steroid assay, small molecule, LC-MS	+	+	+	+

exerted by hypertension cause endothelial damage and dysfunction, resulting in reduced production on nitric oxide (NO) [51]. Consequently, blood pressure-induced vasodilation is compromised. In addition, hypertension-mediated endothelial dysfunction promotes the development of atherosclerosis, which is associated with the accumulation of na atheromatous plaque. Atherosclerosis is primarily composed of oxidized low-density lipoprotein (LDL) and macrophages inside the artery walls [51,52]. It is a risk factor for coronary artery disease, myocardial infarction (MI), hypertension, stroke, and peripheral arterial disease. When blood pressure is low, endothelial cells secrete several vasoactive molecules, such as, endothelin- 1, angiotensin II, prostanoids, and ROS, which act on VSMCs to promote VSMC concentration and subsequent vasoconstriction [51,54]. In contrast, when blood pressure increases, vasodilating substances, such as NO, prostacyclin, and endothelium-derived hyperpolarization factor are produced by endothelial cells [62]. Arterial calcification is associated with atheroma progression and alters the mechanical properties of the vascular wall, thus increasing the risk of atherosclerotic plaque rupture [51,60,61].

5.2 Biomarkers and cancer

Cancer is caused by an excessive multiplication of cells in certain regions of the body [63].

It is the second leading cause of death in the worldwide, second only to cardiovascular disease [64]. The most common types of cancer are skin cancer [65], breast cancer [66], lung cancre [67], prostate cancer [68] among others. Strong evidence supports the concept that cancer is a genetic disease that involves the abnormal growth of transformed cells, and this abnormal growth is triggered in combination with extrinsic factors (lifestyle, environmental aspect) [63,65–68]. Characterizing early-stage tumor cells, researchers have reported important genetic markers for different cancers, such as breast cancer (RAD21, PCTAIRE, CDC25B, CENPF, VEGF, PGK1 and others) [69], prostate cancer (PSA, PSM) [68], pancreatic cancer (KRAS, TP53, DPC4) [70] and others [71] that allow for early diagnosis and monitoring (progression, regression) of such disease. Figure 3 shows intracellular signaling via the P13K-AKT-mTOR pathways that is dysregulated pathway in human cancers [7].

The P13K-AKT-mTOR signaling pathway is one of the main unregulated pathways in human cancers [7]. The P13K -AKT–mTOR pathway is triggered by the activation of various growth factor receptor tyrosine kinases or G protein-coupled receptors [72–74]. The class I PI3K proteins are recruited to the plasma membrane by adapter proteins, such as insulin receptor substrate (IRS) family members, that interact with these activated cell-surface receptors, leading to phosphorylation ofphosphatidylinositol 4,5-bisphosphate (PIP2) to generate phosphatidylinositol 3,4,5-trisphosphate

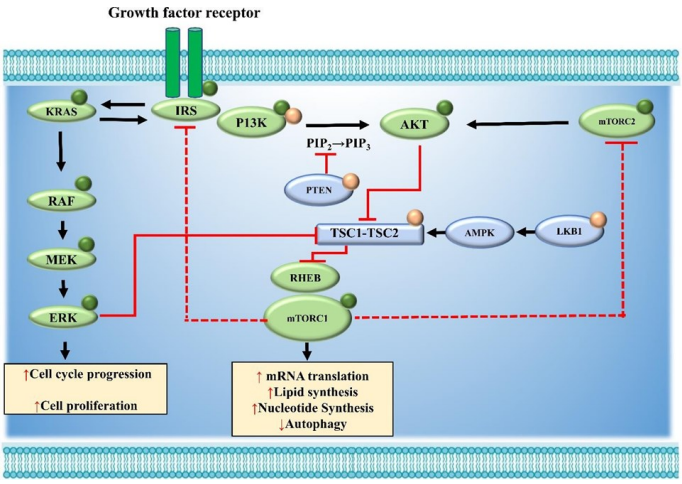

Figure 3 | Schematic of dysregulated pathway in human cancers involving intracellular signaling via the P13K-AKT-mTOR pathway.

(PIP3) [75–77]. PIP3 is a second messenger that activates the AKT kinases, which can phosphorylate tuberous sclerosis protein 1 (TSC1) and TSC2, dissociating, thus, the TSC1-TSC2 complex [77]. The TSC1–TSC2 complex down-regulates the mTOR kinase activity; and, therefore, AKT results in the activation of the mTOR complex 1 (mTORC1), increasing protein and lipid synthesis and decreased autophagy, which supports cell growth and proliferation [7,73,74,76,77]. Notably mTORC1 is involved in a negative feedback loop that serves to avoid overactivation of AKT (dashed red lines in the Figure 3) [78]. The PI3K- AKT-mTOR pathway can be upregulated by activating molecular changes in the PI3K subunits (such as PI3K catalytic subunit α isoform, encoded by PIK3CA), AKT, and mTOR (represented by green circles in the Figure 3) or by loss of function changes in regulatory subunits of PI3K (such as PI3K regulatory subunit-α, encoded by PIK3R1), PTEN, TSC1, TSC2, and LKB1 (also known as STK11) (depicted by orange circles in the Figure 3)[74,76]. In parallel, activation of the growth factor receptor tyrosine kinases and G protein-coupled receptors induces KRAS-RAF- MEK-ERK signaling, and ERK activation may further contribute to mTORC1 activation trough dissociation of the TSC1-TSC2 complex [78]. KRAS can also increase PI3K activation [7,74,76,77]. Notably, the KRAS-RAF-MEK-ERK pathway can also be constitutively activated by gain of function changes in components kinases or cell-surface receptors (green circles in the Figure 3) [7,73].

5.3 Biomarkers and infection diseases

Infectious diseases are categorized as diseases caused by pathogenic microorganism such as viruses [79]. These diseases have been major threat worldwide and have a great impact on public health and the world economy [80,81]. Among the different types of infectious diseases, human immunodeficiency virus (HIV) [82–84], tuberculosis [85,86], and malaria [87] are known as the leading causes of deaths globally [79]. In addition, several types of neglected tropical diseases, such as dengue [88,89], yellow fever [90,91], zika virus [92,93], and chikungunya [94] are also considered to be major global threats. Although such diseases emerge in tropical and subtropical regions, the risk of these infectious diseases may be worldwide due to the global economy and migration [95]. Recently, the WHO declared a pandemic state due to viral infection caused by a new virus of the Coronaviridae family: SRAS-CoV-2. Coronavirus disease (COVID-19) is currently one of the main causes of death in the world [79], causing about four million deaths in June 2021. In this sense, the search for the ideal biomarkers in infectious diseases (with high sensitivity, specificity, and predictive capacity) should be focused on the detection and identification of the infectious agent, monitoring the clinical response, and guiding the duration of treatment [95], as in the case of procalcitonin (PCT) assay, which can discriminate between a viral and a bacterial infection and has been approved by FAD [95]. Currently, the SARS-CoV-2 RNA genome serves as a major biomarker for direct viral detection and the primary COVID-19 diagnosis [96-98]. Viral proteins encoded by SARS-CoV-2 could theoretically serve as alternative biomarkers for viral detection, but due to the complexity of protein detection and the significantly greater number of biological samples required, they are often impractical targets [80,99]. Many of these viral proteins, however, can serve as potential targets for antiviral drugs or biomarkers of drug development for COVID-19 treatment [95,98]. Immune defense cells or T-lymphocytes (particularly CD4þ and CD8þ cells) are among the first human cells to respond to the threat of SARS-CoV-2 [98,100,101]. In a recent study, all twenty of the COVID-19 patients produced CD4þ T-cells and antibodies (IgG, IgM and IgA) targeting the viral S-protein, and 70% of cases produced measurable CD8þ T-cells [98] (Figure 4). These results confirm that the human imune system can mount a substantial and long-lasting response to the new coronavirus [79,99]. On the other hand, lymphopenia has also observed in COVID-19 patients, in which, levels of CD4þ and CD8þ T -cells were decreased in severe patients in comparison with mild cases but restored when the viral infection was cleared [79,95,98]. Cytokine release syndrome (CRS) is a major

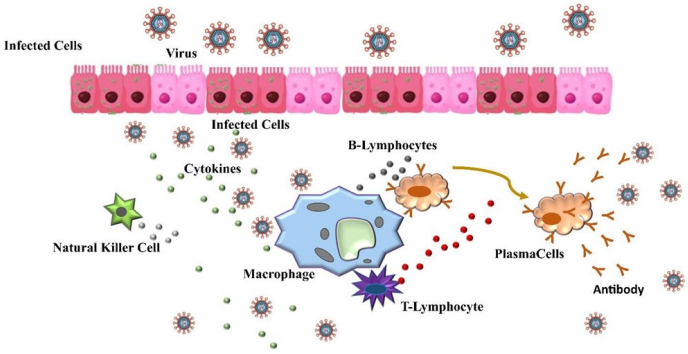

Figure 4 | Immune system scheme during a viral infection involving cytokines, macrophages, natural killer cells, and B and T cells and antibodies that constitute the lines of defense of the immune system.

cause of multiple organ injury and fatal outcome induced by SARS-CoV-2 infection in severe COVID-19 patients. Xiao et al. [102] investigated cytokines/chemokine profiles in the serum of healthy controls, patients with mild and severe COVID-19. Correlation analyses show close associations between metabolites and pro-inflammatory cytokines/ chemokines, such as IL-6, M-CSF, IL-1α, IL-1β, and imply a potential regulatory crosstalk between arginine, tryptophan, purine metabolismo and hyperinflammation [102]. In addition, it has been shown that targeting metabolism markedly modulates the release of pro-inflammatory cytokines by peripheral blood mononuclear cells isolated from SARS-CoV-2 rhesus monkeys infected ex vivo, suggesting that exploiting metabolic changes may be a potential strategy for the treatment of fatal CRS in COVID-19 [102]. In another study, Huang et al. [103] investigated cytokines in the serum of patients infected with the dengue virus during the Guangdong outbreak in 2014, in which more than 50,000 dengue cases were reported and 6 patients died. They found that the levels of CCL17 and CXCL5 were significantly lower than controls, while several pro-inflammatory cytokines such as CXCL9, IP-10, CXCL11, IL-8, and IL-10 were highly upregulated in patients after dengue infection. These results determine the association of clinical routine indices and inflammatory cytokines and would be useful to understand the interplay between the virus and the host responses during the acute stage of dengue infection [103].

6. Linking the biomarker to the clinical endpoint

The relationship of a biomarker to clinical outcome requires a firm promise of reliability for surrogate endpoints through a structured approach and a substantial body of evidence [5,104]. Three clinical features are required to obtain a surrogate marker of success: (i) efficiency, (ii) linkage and (iii) congruence [105]. To be considered efficient, the surrogate marker must exhibit superior accessibility in terms of technical and temporal acquisition allowing acquisition of accurate information in shorter time intervals and clinical trials with fewer resources and less subject participation. By linkage, it means that a plausible underlying relationship between surrogate marker and clinical endpoint must be demonstrated and substantiated by comprehensive scientific evidence. For congruence, the surrogate must produce parallel estimates of risk and benefit as endpoints. In addition, there must be a clear difference in surrogate marker measurements between individuals with and without the disease. In intervention studies, the expected clinical benefits must be deductible from the observed changes in the surrogate marker [5,104,105].

7. Outlook

As a perspective on biomarker validation of human disease, we highlight development of imaging technologies with accuracy, precision, specificity and sensitivity to validate a biomarker. For example, the use of both positron emission tomography and near-infrared imaging has been reported to quantitatively monitor the initial trafficking of vaccine to drain lymph nodes after intramuscular injection in non-human primates [106]. To do this, the researcher previously labeled a messenger RNA vaccine model a probe for both techniques. They used near-infrared fluorescence and flow cytometry to validate tissue extracted from sacrificed animals [106]. In another study, the intratumoral metabolic heterogeneity of breast cancer patients were determined via photoacoustic microscopy, measuring the oxygen consumption rates of single cells taken from the tissue after it was homogenized in a single-cell suspension and the cells deposited in microwell arrays [107]. Heterogeneity has also been observed in how tissues and even single cells metabolize glucose in cancer progression by using Raman spectroscopy and stimulated Raman scattering to trace deuterated glucose in living mice [108]. The research validated their quantitative measurements of Raman intensity using nuclear magnetic resonance spectra of tissue lipid extracts [108]. This optical multiplexing imaging of glucose metabolites may in the future, discover new metabolic biomarkers of disease or be used for the metabolic phenotyping of biopsied tissues from patients.

In addition, as the volume of biomarker data continues to grow, the scientific discovery of biomarkers based on artificial intelligence can be a complementary approach to classical strategies. In some cases, machine learning algorithms can be leveraged to classify biomolecules that accurately contribute to the prediction of a disease state, for example, or treatment, thus generating new and testable assays. However, additional information needs to be considered for better diagnostic alignment, such as standardization of protocols and equipment, large-scale cross- validation, multicenter trials controlling for age, gender and culture variables, definition of end points and use cases, cost-effective and easy to use.

8. Concluding remarks

Different types of human diseases are related to lifestyle and genetic susceptibility, which determine exposure to various risk factors and constitute a determining element in the emergence and development of human diseases. The risk of suffering health deterioration can be assessed using biomarkers that express the likelihood that an unwanted effect will occurs due to exposure to environmental aspects or gene dysfunction. Although their findings present great challenges, biomarkers are an important tool in the prediction, diagnosis, and treatment of human diseases, as they can reflect possible changes in the biological system, allowing the unequivocal specification of such disease. However, it is important to recognize the need for a detailed and a rigorous path to discovery and validation of human disease biomarkers in research and clinical settings,

considering important parameters, such as accuracy, precision, specificity, and sensitivity. Obviously, several challenges are observed during these processes.

Conflicts of interest

The authors declare no conflict of interest

Author contributions

Both authors (J.R.J and M.A.Z.A) contributed equally to the writing of this work.

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Abbreviation

AAPS - american Association of Pharmaceutical Scientists
AKT – protein kinase B
AT1 – angiotensin II type 1 receptor
CA-125 - carcinoembryonic antigen 125
cDNA – complementary DNA
CE-TOF-MS – capillary electrophoresis time of flight
COVID-19 - Coronavirus disease
CSF – cerebrospinal fluid
CVD – cardiovascular diseases
DTT dithiothreitol
ELISA – enzyme-linked immunosorbent assays
eNOS – endothelial nitric oxide synthase
ERK1/ - extracellular signal-regulated kinases 1and 2
ETA – endothelin receptor type A
FDA – Food and Drug Administration
FF – Freshly frozen
FFPE – formalin fixed paraffin embedded
HIV - human immunodeficiency virus
IAA – iodocetamide
IGNT - tolerable normal glycemia
IHC - Immunohistochemistry
IRS – insulin receptor substrate
LDL – low-density lipoprotein
MALDI – TOF MS – matrix-assisted laser desorption/ ionization mass spectrometry
MI - myocardial infarction
mRNAs - messenger RNAs
mTORC1 - mTOR complex 1
NIH - National Institute of Health
nLC-QTOF MS - nano-liquid chromatography quadrupole time of flight
NMR - nuclear magnetic resonance
NO – nitric oxide
PCT – procalcitonin
PDGF-R – platelet-derived growth factor receptor
PIP2 – phosphorylation of phosphatidylinositol 4,5-bisphosphate
PIP3 – phosphatidylinositol 3,4,5- trisphosphate
RNA-Seq – RNA sequencing
ROC – receiver operation characterization curve
ROS – reactive oxygen species ROS - reactive oxygen species
RT-qPCR - real-time reverse transcription polymerase chain reaction
SNP – single nucleotide
SRM/MRM – selected reaction monitoring/multiple reaction monitoring
TSC1 - tuberous sclerosis protein 1
VSMC – Vascular Smooth Muscle Cell
WHO – World Health Organization

References

[1] V.C. Sgarbieri, M.T.B. Pacheco, Brazilian Journal of Food Technology. 20 (2017) 1-23. https://doi.org/10.1590/1981-6723.00717.

[2] F.A.S. Addor, Clinical, Cosmetic and Investigational Dermatology. 11 (2018) 437–443. https://doi.org/10.2147/CCID.S177448.

[3] Y. Yoshida, N. Matsunaga, T. Nakao, K. Hamamura, H. Kondo, T. Ide, H. Tsutsui, A. Tsuruta, M. Kurogi, M. Nakaya, H. Kurose, S. Koyanagi, S. Ohdo, Nature Communications. 12 (2021) 1-17. https://doi.org/10.1038/s41467-021-23050-x.

[4] D.S. Wishart, B. Bartok, E. Oler, K.Y.H. Liang, Z. Budinski, M. Berjanskii, A. Guo, X. Cao, M. Wilson, Nucleic Acids Research. 49 (2021) 259–267. https://doi.org/10.1093/nar/gkaa1067.

[5] K.D. Davis, N. Aghaeepour, A.H. Ahn, M.S. Angst, D. Borsook, A. Brenton, M.E. Burczynski, C. Crean, R. Edwards, B. Gaudilliere, G.W. Hergenroeder, M.J. Iadarola, S. Iyengar, Y. Jiang, J.T. Kong, S. Mackey, C.Y. Saab, C.N. Sang, J. Scholz, M. Segerdahl, I. Tracey, C. Veasley, J. Wang, T.D. Wager, A.D. Wasan, M.A. Pelleymounter, Nature Reviews Neurology. 16 (2020) 381–400. https://doi.org/10.1038/s41582- 020-0362-2.

[6] G. Jung, E. Hernández-Illán, L. Moreira, F. Balaguer, A. Goel, Nature Reviews Gastroenterology and Hepatology. 17 (2020) 111–130. https://doi.org/10.1038/s41575-019-0230-y.

[7] F. Janku, T.A. Yap, F. Meric-Bernstam, Nature Reviews Clinical Oncology. 15 (2018) 273–291. https://doi.org/10.1038/nrclinonc.2018.28.

[8] T. Powles, D. Carroll, S. Chowdhury, G. Gravis, F. Joly, J. Carles, A. Fléchon, P. Maroto, D. Petrylak, F. Rolland, N. Cook, A. v. Balar, S.S. Sridhar, M.D. Galsky, P. Grivas, A. Ravaud, R. Jones, J. Cosaert, D. Hodgson, I. Kozarewa, R. Mather, R. McEwen, F. Mercier, D. Landers, Nature Medicine. (2021). https://doi.org/10.1038/s41591- 021-01317-6.

[9] T. Hirata, Y. Arai, S. Yuasa, Y. Abe, M. Takayama, T. Sasaki, A. Kunitomi, H. Inagaki, M. Endo, J. Morinaga, K. Yoshimura, T. Adachi, Y. Oike, T. Takebayashi, H. Okano, N. Hirose, Nature Communications. 11 (2020) 1-17. https://doi.org/10.1038/s41467-020-17636-0.

[10] F. Genre, J. Rueda-Gotor, S. Remuzgo-Martínez, V. Pulito-Cueto, A. Corrales, V. Mijares, L. Lera-Gómez, V. Portilla, R. Expósito, C. Mata, R. Blanco, J. Llorca, V. Hernández-Hernández, E. Vicente, C. Fernández-Carballido, M.P. Martínez-Vidal, D. Castro-Corredor, J. Anino- Fernández, C. Rodríguez-Lozano, O. Gualillo, J.C. Quevedo-Abeledo, S. Castañeda, I. Ferraz- Amaro, R. López-Mejías, M. González-Gay, Scientific Reports. 10 (2020) 9636. https://doi.org/10.1038/s41598-020-66816-x.

[11] J.R. Jesus, M.A.Z. Arruda, Rapid Communications in Mass Spectrometry. (2020) 1–10. https://doi.org/10.1002/rcm.8798.

[12] J.R. de Jesus, R.M. Galazzi, T.B. de Lima, C.E.M. Banzato, L.F. de Almeida Lima e Silva, C. de Rosalmeida Dantas, F.C. Gozzo, M.A.Z. Arruda, Clinical Biochemistry. (2017) 1118-1125. https://doi.org/10.1016/j.clinbiochem.2017.06.009.

[13] G.D.S. Pessôa, J.R. de Jesus, T.S. Balbuena, M. Aurélio, Z. Arruda, Rapid Communications in Mass Spectrometry 34 (2020) e8698. https://doi.org/10.1002/rcm.8698.

[14] J.R. de Jesus, (2019) 39– 58. https://doi.org/10.1007/978-3-030-29473-1_3.

[15] S. Paramasivan, S.S. Adav, S.F.C. Ngan, R. Dalan, M.K.S. Leow, H.H. Ho, S.K. Sze, Scientific Reports. 10 (2020) 1-12. https://doi.org/10.1038/s41598-020-62341-z.

[16] S. Park, S. Chon, S.Y. Park, S. Yun, S.H. Baik, J.T. Woo, S.Y. Rhee, Y.K. Pak, S.H. Kim, Scientific Reports. 11 (2021) 1-9. https://doi.org/10.1038/s41598-021-82794-0.

[17] J.R. Wang, W.N. Gao, R. Grimm, S. Jiang, Y. Liang, H. Ye, Z.G. Li, L.F. Yau, H. Huang, J. Liu, M. Jiang, Q. Meng, T.T. Tong, H.H. Huang, S. Lee, X. Zeng, L. Liu, Z.H. Jiang, Nature Communications. 8 (2017) 1-14. https://doi.org/10.1038/s41467-017-00662-w.

[18] N. Goossens, S. Nakagawa, X. Sun, Y. Hoshida, Translational Cancer Research. 4 (2015) 256–269. https://doi.org/10.3978/j.issn.2218- 676X.2015.06.04.

[19] V.B. Kraus, Nature Reviews Rheumatology. 14 (2018) 354–362. https://doi.org/10.1038/s41584-018-0005-9.

[20] M. v. Holmes, T.G. Richardson, B.A. Ference, N.M. Davies, G. Davey Smith, Nature Reviews Cardiology. 18 (2021) 1-19. https://doi.org/10.1038/s41569-020-00493-1.

[21] E.E. Redei, J.D. Ciolino, S.L. Wert, A. Yang, S. Kim, C. Clark, K.B. Zumpf, K.L. Wisner, Translational Psychiatry. 11 (2021) 1-9. https://doi.org/10.1038/s41398- 020-01188-4.

[22] T.L. Whiteside, Validation of plasma-derived small extracellular vesicles as cancer biomarkers, Nature Reviews Clinical Oncology. 17 (2020)719–720. https://doi.org/10.1038/s41571-020-00433-5.

[23] X. Zheng, T. Chen, A. Zhao, Z. Ning, J. Kuang, S. Wang, Y. You, Y. Bao, X. Ma, H. Yu, J. Zhou, M. Jiang, M. Li, J. Wang, X. Ma, S. Zhou, Y. Li, K. Ge, C. Rajani, G. Xie, C. Hu, Y. Guo, A. Lu, W. Jia, W. Jia, 9 Nature Communications. 12 (2021) 1487. https://doi.org/10.1038/s41467-021-21744-w. 10

[24] R.M. Califf, Experimental Biology and Medicine. 243 (2018) 213–221. https://doi.org/10.1177/1535370217750088.

[25] J.R. de Jesus, G. de S. Pessôa, A. Sussulini, J.L.C. Martínez, M.A.Z. Arruda, Journal of Proteomics. 145 (2016) 187–196. https://doi.org/10.1016/j.jprot.2016.04.034.

[26] J.R. de Jesus, B.K. de Campos, R.M. Galazzi, J. Luis, C. Martinez, Analytical and Bioanalytical Chemistry (2014) 661 –667. https://doi.org/10.1007/s00216-014-8341-3.

[27] T. Huo, S. Cai, X. Lu, Y. Sha, M. Yu, F. Li, Journal of Pharmaceutical and Biomedical Analysis. 49 (2009) 976–82. https://doi.org/10.1016/j.jpba.2009.01.008.

[28] A. aroon Lertkhachonsuk, S. Buranawongtrakoon, N. Lekskul, N. Rermluk, W.W. Wee- Stekly, C. Charakorn, Journal of Obstetrics and Gynaecology Research. 46(2020) 2287–2291. https://doi.org/10.1111/jog.14427.

[29] Y. ho Lee, S.G. Lee, M.H. Lee, J.H. Kim, B.W. Lee, E.S. Kang, H.C. Lee, B.S. Cha, Journal of the American Heart Association. 3 (2014) 1-13. https://doi.org/10.1161/JAHA.113.000650.

[30] L. Zou, S. Yan, X. Guan, Y. Pan, X. Qu, Journal of Diabetes Research. (2013) 1-5. https://doi.org/10.1155/2013/721493.

[31] L. Larsson, J. Frisén, J. Lundeberg, Nature Methods. 18 (2021) 15–18. https://doi.org/10.1038/s41592-020-01038-7.

[32] Y. Mo, R. Wan, Q. Zhang, Methods Mol. Bio. (2012) 99–112. https://doi.org/10.1007/978-1-62703-002-1_7.

[33] L. Zhang, H. Xiao, S. Karlan, H. Zhou, J. Gross, D. Elashoff, D. Akin, X. Yan, D. Chia, B. Karlan, D.T. Wongiomarkers for the non- invasive detection of breast cancer, PLoS ONE. 5 (2010) 1-7. https://doi.org/10.1371/journal.pone.0015573.

[34] S. Hu, M. Arellano, P. Boontheung, J. Wang, H. Zhou, J. Jiang, D. Elashoff, R. Wei, J.A. Loo, D.T. Wong, Clinical Cancer Research. 14 (2008) 6246–6252. https://doi.org/10.1158/1078-0432.CCR-07-5037.

[35] L. Perez de Souza, S. Alseekh, F. Scossa, A.R. Fernie, Nature Methods. (2021) 1-14. https://doi.org/10.1038/s41592-021-01116-4.

[36] M. Daimon, T. Soga, A. Hozawa, T. Oizumi, W. Kaino, K. Takase, S. Karasawa, Y. Jimbu, K. Wada, W. Kameda, S. Susa, T. Kayama, K. Saito, M. Tomita, T. Kato, Internal Medicine. 51 (2012) 545–551. https://doi.org/10.2169/internalmedicine.51.6612.

[37] Food and Agriculture Department. www.fda.gov/drugs/biomarker-qualification-program/list-qualified-biomarkers (accessed at 28th of may 2021)

[38] L. Fang, C. Su, Springer International Publishing, 2019. https://doi.org/10.1007/978-3-030-31503-0.

[39] K.K. Dobbin, A. Cesano, J. Alvarez, R. Hawtin, S. Janetzki, I. Kirsch, G. v. Masucci, P.B. Robbins, S.R. Selvan, H.Z. Streicher, J. Zhang, L.H. Butterfield, M. Thurin, Journal for Immuno Therapy of Cancer. 4 (2016) 1-14. https://doi.org/10.1186/s40425-016-0179-0.

[40] L. Antoury, N. Hu, L. Balaj, S. Das, S. Georghiou, B. Darras, T. Clark, X.O. Breakefield, T.M. Wheeler, Nature Communications. 9 (2018) 1-16. https://doi.org/10.1038/s41467-018-06206-0.

[41] Henry Erlich (Ed), PCR Technology, Palgrave Macmillan, UK, 1989, pp 1-246.

[42] M. del Campo, W. Jongbloed, H.A.M. Twaalfhoven, R. Veerhuis, M.A. Blankenstein, C.E. Teunissen, Frontiers in Neurology. 6 (2015) 1-10. https://doi.org/10.3389/fneur.2015.00202.

[43] E. Sheikhzadeh, S. Eissa, A. Ismail, M. Zourob, Talanta. 220 (2020) 1-17. https://doi.org/10.1016/j.talanta.2020.121392.

[44] Y.J. Jou, C. der Lin, C.H. Lai, C.H. Chen, J.Y. Kao, S.Y. Chen, M.H. Tsai, S.H. Huang, C.W. Lin, Analytica Chimica Acta. 681 (2010) 41–48. https://doi.org/10.1016/j.aca.2010.09.030.

[45] G. Mermelekas, A. Vlahou, J. Zoidakis, Expert Review of Molecular Diagnostics. 15 (2015) 1441–1454. https://doi.org/10.1586/14737159.2015.1093937.

[46] P. Picotti, R. Aebersold, Nature Methods. 9 (2012) 555–566. https://doi.org/10.1038/nmeth.2015.

[47] Y. Jin Kim, Z. Zaidi-Ainouch, S. Gallien, B. Domon, Nature Protocols. 7 (2012) 859–871. https://doi.org/10.1038/nprot.2012.023.

[48] Y.H. Ahn, E.S. Ji, N.R. Oh, Y.S. Kim, J.H. Ko, J.S. Yoocancer, Journal of Proteomics. 106 (2014) 221–229. https://doi.org/10.1016/j.jprot.2014.04.031.

[49] J.W. Lee, V. Devanarayan, Y.C. Barrett, R. Weiner, J. Allinson, S. Fountain, S. Keller, I. Weinryb, M. Green, L.

Duan, J.A. Rogers, R. Millham, P.J. O'Brien, J. Sailstad, M. Khan, C. Ray, J.A. Wagner, Pharmaceutical Research, 23 (2006) 312–328. https://doi.org/10.1007/s11095-005-9045-3.

[50] J. Cummings, F. Raynaud, L. Jones, R. Sugar, C. Dive, British Journal of Cancer. 103 (2010) 1313–1317. https://doi.org/10.1038/sj.bjc.6605910.

[51] C.M. Ghantous, L. Kamareddine, R. Farhat, F.A. Zouein, S. Mondello, F. Kobeissy, A. Zeidan, Biomedicines. 8 (2020) 1–19. https://doi.org/10.3390/biomedicines8120552.

[52] G. Wang, S.D. Grosse, M.W. Schooley, American Journal of Preventive Medicine. 53 (2017) S115–S117. https://doi.org/10.1016/j.amepre.2017.08.005.

[53] C.M. Ghantous, F.H. Kobeissy, N. Soudani, F.A. Rahman, M. Al-Hariri, H.A. Itani, R. Sabra, A. Zeidan, Frontiers in Pharmacology. 6 (2015) 1-14. https://doi.org/10.3389/fphar.2015.00240.

[54] Y. Zhou, M.J. Zhang, B.H. Li, L. Chen, Y. Pi, Y.W. Yin, C.Y. Long, X. Wang, M.J. Sun, X. Chen, C.Y. Gao, J.C. Li, L.L. Zhang, PLoS ONE. 11 (2016) 1-14. https://doi.org/10.1371/journal.pone.0154720.

[55] W. Nour-Eldine, C.M. Ghantous, K. Zibara, L. Dib, H. Issaa, H.A. Itani, N. El-Zein, A. Zeidan, Frontiers in Pharmacology. 7 (2016) 1-15. https://doi.org/10.3389/fphar.2016.00086.

[56] P. Liu, Y. Gu, J. Luo, P. Ye, Y. Zheng, W. Yu, S. Chen, Experimental Cell Research. 380 (2019) 36–46. https://doi.org/10.1016/j.yexcr.2019.02.022.

[57] M. Yoshizumi, Y. Kyotani, J. Zhao, K. Nakahira, Annals of Translational Medicine. 8 (2020) 157–157. https://doi.org/10.21037/atm.2019.12.145.

[58] X. Lian, C. Matthaeus, M. Kaßmann, O. Daumke, M. Gollasch, Pathophysiological Role of Caveolae in Hypertension, Frontiers in Medicine. 6 (2019) 1-9. https://doi.org/10.3389/fmed.2019.00153.

[59] S.J. Forrester, K.J. Elliott, T. Kawai, T. Obama, M.J. Boyer, K.J. Preston, Z. Yan, S. Eguchi, V. Rizzo, Hypertension. 69 (2017) 79–86. https://doi.org/10.1161/HYPERTENSIONAHA.116.08278.

[60] I.A.M. Brown, L. Diederich, M.E. Good, L.J. Delalio, S.A. Murphy, M.M. Cortese-Krott, J.L. Hall, T.H. Le, B.E. Isakson, Arterioscler Thromb Vasc Biol. 38 (2018) 1969–1985. https://doi.org/10.1161/ATVBAHA

[61] A. Jaminon, K. Reesink, A. Kroon, L. Schurgers, International Journal of Molecular Sciences. 20 (2019) 1-29. https://doi.org/10.3390/ijms20225694.

[62] G. Jia, W. Durante, J.R. Sowers, Diabetes. 65 (2016) 2118–2120. https://doi.org/10.2337/dbi16-0026.

[63] K. Pantel, R.H. Brakenhoff, Nature Reviews Cancer. 4 (2004) 448–456. https://doi.org/10.1038/nrc1370.

[64] World Health Organization – www.who.int/news-room/fact-sheets/detail/the-top-10- causes-of-death (accessed in 28th of may 2021).

[65] J. Ock, T. Kim, S. Lee, T.S. Yang, M. kim, W. Jeong, J. Choi, N. Kim, Scientific Reports. 11 (2021). https://doi.org/10.1038/s41598-021-88287-4.

[66] S.J. Rodgers, L.M. Ooms, V.M.J. Oorschot, R.B. Schittenhelm, E. v. Nguyen, S.A. Hamila, N. Rynkiewicz, R. Gurung, M.J. Eramo, A. Sriratana, C.G. Fedele, F. Caramia, S. Loi, G. Kerr, H.E. Abud, G. Ramm, A. Papa, A.M. Ellisdon, R.J. Daly, C.A. McLean, C.A. Mitchell, Nature Communications. 12 (2021) 3140. https://doi.org/10.1038/s41467-021-23241-6.

[67] J. Ju, A. Chen, Y. Deng, M. Liu, Y. Wang, Y. Wang, M. Nie, C. Wang, H. Ding, B. Yao, T. Gui, X. Li, Z. Xu, C. Ma, Y. Song, M. Kvansakul, K. Zen, C.Y. Zhang, C. Luo, M. Fang, D.C.S. Huang, C.D. Allis, R. Tan, C.K. Zeng, J. Wei, Q. Zhao, Nature Communications. 8 (2017) 1-14. https://doi.org/10.1038/s41467-017-00988-5.

[68] R. J. Rabello; C. Oing; K. E. Knudsen; S. Loeb; D.C. Johnson; R.E.Reither; S. Gillssen; T. Van der Kwast; R. Bristow, Nature Reviews Disease Primers. 7 (2021) 1-27. https://doi.org/10.1038/s41572-021-00249-2.

[69] L. J. van't Veer; H. Day; M. J. Van de Vijver; Y. D. He; A.A.M. Hart; M. Mao; H.L. Peterse et al, Nature. 415 (2002) 530-536. https://doi:10.1038/415530a.

[70] S. Dhara, S. Chhangawala, H. Chintalapudi, G. Askan, V. Aveson, A.L. Massa, L. Zhang, D. Torres, A.P. Makohon-Moore, N. Lecomte, J.P. Melchor, J. Bermeo, A. Cardenas, S. Sinha, D. Glassman, R. Nicolle, R. Moffitt, K.H. Yu, S. Leppanen, S. Laderman, B. Curry, J. Gui, V.P. Balachandran, C. Iacobuzio-Donahue, R. Chandwani, C.S. Leslie, S.D. Leach, Nature Communications. 12 (2021) 3044. https://doi.org/10.1038/s41467-021-23237-2.

[71] N. Kosaka, H. Iguchi, T. Ochiya, Cancer Science. 101 (2010) 2087–2092. https://doi.org/10.1111/j.1349-7006.2010.01650.x.

[72] F. Janku, Cancer Treatment Reviews. 59 (2017) 93–101. https://doi.org/10.1016/j.ctrv.2017.07.005.

[73] J. Polivka, F. Janku, Pharmacology and Therapeutics. 142 (2014) 164–175. https://doi.org/10.1016/j.pharmthera.2013.12.004.

[74] D.A. Fruman, C. Rommel, Nature Reviews Drug Discovery. 13 (2014) 140–156. https://doi.org/10.1038/nrd4204.

[75] D.M. Hyman, L.M. Smyth, M.T.A. Donoghue, S.N. Westin, P.L. Bedard, E.J. Dean, H. Bando, A.B. El-Khoueiry, J.A. Pérez-Fidalgo, A. Mita, J.H.M. Schellens, M.T. Chang, J.B. Reichel, N. Bouvier, S.D. Selcuklu, T.E. Soumerai, J. Torrisi, J.P. Erinjeri, H. Ambrose, J.C. Barrett, B. Dougherty, A. Foxley, J.P.O. Lindemann, R. Mcewen, M. Pass, G. Schiavon, M.F. Berger, S. Chandarlapaty, D.B. Solit, U. Banerji, J. Baselga, B.S. Taylor, Journal of Clinical Oncology AKT Inhibition in Solid Tumors With AKT1 Mutations, J Clin Oncol. 35 (2017) 2251– 2259. https://doi.org/10.1200/JCO.

[76] F. Janku, D.S. Hong, S. Fu, S.A. Piha-Paul, A. Naing, G.S. Falchook, A.M. Tsimberidou, V.M. Stepanek, S.L. Moulder, J.J. Lee, R. Luthra, R.G. Zinner, R.R. Broaddus, J.J. Wheler, R. Kurzrock, Cell Reports. 6 (2014) 377–387. https://doi.org/10.1016/j.celrep.2013.12.035.

[77] D.J. Kwiatkowski, T.K. Choueiri, A.P. Fay, B.I. Rini, A.R. Thorner, G. de Velasco, M.E. Tyburczy, L. Hamieh, L. Albiges, N. Agarwal, T.H. Ho, J. Song, J.C. Pignon, P.M. Barrios, M.D. Michaelson, E.M. van Allen, K.M. Krajewski, C. Porta, S.K. Pal, J. Bellmunt, D.F. McDermott, D.Y.C. Heng, K.P. Gray, S. Signoretti, Clinical Cancer Research. 22 (2016) 2445–2452. https://doi.org/10.1158/1078-0432.CCR-15-2631.

[78] H. Cheng, Y. Zou, J.S. Ross, K. Wang, X. Liu, B. Halmos, S.M. Ali, H. Liu, A. Verma, C. Montagna, A. Chachoua, S. Goel, E.L. Schwartz, C. Zhu, J. Shan, Y. Yu, K. Gritsman, R. Yelensky, D. Lipson, G. Otto, M. Hawryluk, P.J. Stephens, V.A. Miller, B. Piperdi, R. Perez- Soler, Cancer Discovery. 5 (2015) 1262–1270. https://doi.org/10.1158/2159-8290.CD-14-0971.

[79] J.R. de Jesus, T. de Araújo Andrade, Metallomics. 12 (2020) 1912–1930. https://doi.org/10.1039/d0mt00220h.

[80] X. Ou, Y. Liu, X. Lei, P. Li, D. Mi, L. Ren, L. Guo, R. Guo, T. Chen, J. Hu, Z. Xiang, Z. Mu, X. Chen, J. Chen, K. Hu, Q. Jin, J. Wang, Z. Qian, Nature Communications. 11 (2020) 1-12. https://doi.org/10.1038/s41467-020-15562-9.

[81] A. Tsatsakis, D. Petrakis, T.K. Nikolouzakis, A.O. Docea, D. Calina, M. Vinceti, M. Goumenou, R.N. Kostoff, C. Mamoulakis, M. Aschner, A.F., Food and Chemical Toxicology. 141 (2020) 1-15. https://doi.org/10.1016/

j.fct.2020.111418.
[82] N. Khan, X. Chen, J.D. Geiger, Viruses. 12 (2020) 1-25. https://doi.org/10.3390/v12040471.
[83] G.A. Heeren, J.B. Jemmott, L. Sidloyi, Z. Ngwane, J.C. Tyler, Vulnerable Children and Youth Studies. 7 (2012) 47–54. https://doi.org/10.1080/17450128.2012.656733.
[84] M. Li, W. Liu, T. Bauch, E.A. Graviss, R.C. Arduino, J.T. Kimata, M. Chen, J. Wang, Nature Communications. 11 (2020) 1-15. https://doi.org/10.1038/s41467-020-17753-w.
[85] B.E. Feleke, T.E. Feleke, D. Mekonnen, M.B. Beyene, Clinical Nutrition ESPEN. 31 (2019) 56–60. https://doi.org/10.1016/j.clnesp.2019.03.001.
[86] A. Tapley, N. Switz, C. Reber, J.L. Davis, C. Miller, J.B. Matovu, W. Worodria, L. Huang, D.A. Fletcher, Journal of Clinical Microbiology. 51 (2013) 1774–1778. https://doi.org/10.1128/JCM.03432-12.
[87] A. Ayanlade, I.J. Nwayor, C. Sergi, O.S. Ayanlade, P. di Carlo, O.D. Jeje, M.O. Jegede, Scientific Reports. 10 (2020) 1-13. https://doi.org/10.1038/s41598-020-71094-8.
[88] M.G. Guzman, D.J. Gubler, A. Izquierdo, E. Martinez, S.B. Halstead, Nature Reviews Disease Primers. 2 (2016) 1-25. https://doi.org/10.1038/nrdp.2016.55.
[89] J. Lee, Y.E. Kim, H.Y. Kim, M. Sinniah, C.K. Chong, H.O. Song, Scientific Reports. 5 (2015) 1-10. https://doi.org/10.1038/srep18077.
[90] J.M. Dietz, S.J. Hankerson, B.R. Alexandre, M.D. Henry, A.F. Martins, L.P. Ferraz, C.R. Ruiz-Miranda, Scientific Reports. 9 (2019) 1-13. https://doi.org/10.1038/s41598-019-49199-6.
[91] M.S. Cunha, R.M. Tubaki, R.M.T. de Menezes, M. Pereira, G.S. Caleiro, E. Coelho, L. del C. Saad, N.C.C. de A. Fernandes, J.M. Guerra, J.S. Nogueira, J.L. Summa, A.A.C. Coimbra, T. Zwarg, S.S. Witkin, L.F. Mucci, M. do C.S.T. Timenetsky, E.C. Sabino, J.T. de Deus, Scientific Reports. 10 (2020) 1-8. https://doi.org/10.1038/s41598-020-72794-x.
[92] A.F. Versiani, E.M.N. Martins, L.M. Andrade, L. Cox, G.C. Pereira, E.F. Barbosa- Stancioli, M.L. Nogueira, L.O. Ladeira, F.G. da Fonseca, Scientific Reports. 10 (2020) 1-17. https://doi.org/10.1038/s41598-020-68357-9.
[93] M.I. Giraldo, H. Xia, L. Aguilera-Aguirre, A. Hage, S. van Tol, C. Shan, X. Xie, G.L. Sturdevant, S.J. Robertson, K.L. McNally, K. Meade-White, S.R. Azar, S.L. Rossi, W. Maury, M. Woodson, H. Ramage, J.R. Johnson, N.J. Krogan, M.C. Morais, S.M. Best, P.Y. Shi, R. Rajsbaum, Nature. (2020) 1-23. https://doi.org/10.1038/s41586-020-2457-8.
[94] N.A. Prow, L. Liu, M.K. McCarthy, K. Walters, R. Kalkeri, J. Geiger, F. Koide, T.H. Cooper, P. Eldi, E. Nakayama, K.R. Diener, P.M. Howley, J.D. Hayball, T.E. Morrison, A. Suhrbier, Npj Vaccines. 5 (2020) 1-10. https://doi.org/10.1038/s41541-020-0191-8.
[95] H. Hwang, B.Y. Hwang, J. Bueno, Disease Markers. 2018 (2018) 1-2. https://doi.org/10.1155/2018/8509127.
[96] J.F.W. Chan, K.H. Kok, Z. Zhu, H. Chu, K.K.W. To, S. Yuan, K.Y. Yuen, Emerging Microbes and Infections. 9 (2020) 221–236. https://doi.org/10.1080/22221751.2020.1719902.
[97] Y.J. Tan, S.G. Lim, W. Hong, Antiviral Research. 65 (2005) 69–78. https://doi.org/10.1016/j.antiviral.2004.10.001.
[98] L. Zhang, H. Guo, Advances in Biomarker Sciences and Technology. 2 (2020) 1–23. https://doi.org/10.1016/j.abst.2020.08.001.
[99] N. le Bert, A.T. Tan, K. Kunasegaran, C.Y.L. Tham, M. Hafezi, A. Chia, M.H.Y. Chng, M. Lin, N. Tan, M. Linster, W.N. Chia, M.I.C. Chen, L.F. Wang, E.E. Ooi, S. Kalimuddin, P.A. Tambyah, J.G.H. Low, Y.J. Tan, A. Bertoletti, Nature. 584 (2020) 457–462. https://doi.org/10.1038/s41586-020-2550-z.
[100] A.C. Walls, Y.J. Park, M.A. Tortorici, A. Wall, A.T. McGuire, D. Veesler, Structure, Cell. 181 (2020) 281-292.e6. https://doi.org/10.1016/j.cell.2020.02.058.
[101] E. Andreano, R. Rappuoli, Nature Medicine. 27 (2021) 759–761. https://doi.org/10.1038/s41591-021-01347-0.
[102] N. Xiao, M. Nie, H. Pang, B. Wang, J. Hu, X. Meng, K. Li, X. Ran, Q. Long, H. Deng, N. Chen, S. Li, N. Tang, A. Huang, Z. Hu, Nature Communications. 12 (2021) 1-13. https://doi.org/10.1038/s41467-021-21907-9.
[103] J. Huang, W. Liang, S. Chen, Y. Zhu, H. Chen, C.K.P. Mok, Y. Zhou, Serum Cytokine Profiles in Patients with Dengue Fever at the Acute Infection Phase, Disease Markers. (2018) 1-8. https://doi.org/10.1155/2018/8403937.
[104] D.J. Hunter, E. Losina, A. Guermazi, D. Burstein, M.N. Lassere, V. Kraus, Current Drug Targets. 11 (2010) 536-545.
[105] V.O. Puntmann, Postgraduate Medical Journal. 85 (2009) 538–545. https://doi.org/10.1136/pgmj.2008.073759.
[106] K. E. Lindsay et al, Nature Biomedical Engineering. 3 (2019) 371-380. https://doi.org/10.1038/s41551-019-0378-3.
[107] A.J. Walsh, J.T. Sharick, M.C. Skala, Nature Biomedical Engineering. 3 (2019) 333–334. https://doi.org/10.1038/s41551-019-0398-z.
[108] L. Zhang, L. Shi, Y. Shen, Y. Miao, M. Wei, N. Qian, Y. Liu, W. Min, Nature Biomedical Engineering. 3 (2019) 402–413. https://doi.org/10.1038/s41551-019-0393-4.