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(54) Title: DETERMINATION OF THE MINIMUM DURATION OF A CONTRAST AGENT BOLUS AND LIMITATION OF INJECTION RATES

(57) Abstract: A method is provided for predetermining a maximal duration for administration of a contrast agent bolus at a first vessel position for achieving a minimal duration for the response thereto at a second vessel position in a region of interest of a patient for a contrast agent-enhanced imaging procedure, wherein a correlation between the maximal duration for the bolus administration for a patient group with known patient parameters and at least one blood flow parameter is ascertained. Relatedly, a method is provided for determining an ideal flow rate for a shortest possible bolus administration, wherein a maximal duration for the bolus administration for achieving a minimal duration for the response thereto is ascertained and, from this, the necessary flow rate for the administration of a predetermined amount (M_{KM}) of the contrast agent to be applied is determined. A magnetic resonance system for performing the above-mentioned methods is also provided.

DETERMINATION OF THE MINIMUM DURATION OF A CONTRAST AGENT BOLUS AND LIMITATION OF INJECTION RATES

FIELD OF THE INVENTION

[001] Method for determining a minimum duration of a contrast agent bolus and limiting injection rates, method for determining the ideal flow rate in a bolus application, and a magnetic resonance system

[002] The invention relates to a method for predetermining a maximum bolus application duration for achieving a minimum bolus response duration of a contrast agent bolus response at a second vessel position in a region of interest of a patient after an automated bolus application using a contrast agent applicator at a first vessel position for a contrast agent-enhanced imaging recording method.

[003] The invention further relates to a method for determining an ideal flow rate for a shortest possible automated bolus application of a contrast agent using a contrast agent applicator for a contrast agent-enhanced recording of a patient on the basis of a previously ascertained maximum bolus application duration for achieving a minimum bolus response duration.

[004] The invention also relates to a method for avoiding an incorrect setting of the flow rate and/or bolus application duration of a contrast agent applicator which has a processor and a memory or is connected thereto in order to execute at least one computer program present in the memory during operation.

[005] Besides the above-mentioned methods, the invention also relates to a magnetic resonance system for generating a contrast agent-enhanced MR recording using a, by a processor-controlled contrast agent injector, wherein computer and a memory for computer programs are present for performing said methods.

BACKGROUND OF THE INVENTION

[006] Magnetic resonance imaging (MRI) methods are well known in diagnostic imaging. A contrast agent is employed for highlighting the arterial vessels in relation to the remaining tissue, particularly for displaying blood vessels in magnetic resonance angiography (MRA). Such methods are referred to as

contrast agent-enhanced MR angiography (CE-MRA). If records are made of pictures of peripheral blood vessels, e.g. leg arteries such as the femoral or popliteal arteries, this is referred to as contrast agent-enhanced peripheral MR angiography (CE-pMRA).

[007] Compared to other imaging techniques not enhanced by contrast agents, CE-MRA constitutes the preferred technique for radiation-free, non-invasive vessel diagnostics in many clinical cases. It was performed for the first time about 20 years ago, the technique has been improved continuously since then and these days it constitutes an advanced diagnostic standard method in most countries.

[008] In most cases, the clinical questions require a visualization of the arterial vessel system that has the highest possible contrast in relation to the surrounding tissue, with the simultaneous visualization of the venous vessel system being generally considered to be an interfering superposition. In the case of such contrast agent-enhanced MR examinations in which only the first flooding-in phase of the contrast agent is used for imaging, i.e. so-called “first-pass” MR examinations, it is essential in many cases that the contrast agent flooding-in, i.e. the bolus response duration to an applied short contrast agent bolus, is also kept as short as possible in order to keep venous superpositions as little as possible. A bolus response duration that is as short as possible is particularly advantageous for other, non-angiographic applications too, such as MRT perfusion examinations, for example in the intra-cranial region.

[009] Despite significant technical progress in recent years, the ideal time synchronization of the contrast agent bolus in the target region (bolus timing) and the ideal use of the injected contrast agent bolus continue to remain a challenge for personnel, since much experience and basic physical understanding of the complicated imaging MRI method are required.

[0010] Especially the desire for a relatively short duration of a contrast agent bolus response (bolus response duration) leads in some cases to problems in the programming of a contrast agent applicator, since it has emerged that, in the case of short bolus times, there is by no means still a direct proportionality between the bolus application duration at a first vessel position and the bolus response duration at a second vessel position. It has been demonstrated here that unnecessarily

short injection times and hence unnecessarily high injection rates can occur, which can constitute an avoidable stress on the patient, for example due to the selection of excessively large injection needles, and a danger to the i.v. injection site due to excessively high pressures.

[0011] Besides the need to be able to predict the time profile of the contrast agent concentration after the administration of a bolus as accurately as possible, it is therefore also essential to understand the relationship between the bolus application duration and the bolus response duration so as to be able to achieve a bolus response duration that is as short as possible, without endangering more than necessary the contrast agent inlet during the application.

[0012] It is therefore an object of the invention to find a method for allowing the predetermination of a maximal achievable bolus application duration with a simultaneous minimum bolus response duration and, proceeding therefrom, a method for determining an ideal flow rate for a shortest possible bolus application of a contrast agent, a method for avoiding an incorrect setting of the flow rate and/or bolus application duration of a contrast agent applicator, and a magnetic resonance system for this purpose.

[0013] This object is achieved by the features of the independent claims. Advantageous developments of the invention are subject-matter of dependent claims.

SUMMARY

[0014] The inventors have recognized that, in the case of a contrast agent bolus application at a first vessel position, usually in the region of an arm vein, for generating a shortest possible bolus response duration, as a shortest possible rise in the contrast agent concentration in the blood flow, at another, usually arterial, vessel position in the circulatory system of a patient, it is not expedient to keep on reducing the bolus application duration, since the achievable minimum bolus response duration cannot be reduced as desired. On the contrary, with ever shorter bolus, the bolus response duration approaches a limit value of a minimum bolus application duration, which limit value – under otherwise constant conditions – cannot be fallen short of. Accordingly, a bolus profile in which the same amount

of contrast agent is injected with increasingly higher pressure within an increasingly shorter time is also counterproductive, since lesions on the vein can arise owing to the then momentary high injection amount. It is also possible that excessively high flow rates and, in particular, flow velocities of the injected contrast agent trigger flow effects which lead more to an unwanted broadening of the bolus response duration than to a shortening of the bolus response duration.

[0015] In addition, the inventors have also recognized that the minimal achievable bolus response duration at a bolus duration – more precisely bolus application duration – maximal therefor correlates with at least one blood flow parameter. In this connection, the blood flow parameter used can be a blood flow property or a function composed of one or more blood flow properties, it being possible to determine the blood flow properties optionally without the presence of contrast agent in the blood circulation, for example by means of a phase-contrast magnetic resonance measurement. In this connection, the simplest case of such a blood flow parameter is the direct use of a mean blood flow velocity at a predetermined relevant vessel position as blood flow property.

[0016] On the basis of this knowledge of the correlation between blood flow parameter determinable without contrast agent and the minimal achievable bolus response duration at bolus application duration maximal therefor, there is now the possibility of applying an ideal contrast agent bolus in which the minimal achievable bolus response time ensues, it being possible at the same time to also avoid counterproductive excessive flow velocities and flow rates. Since, in this connection, there is no need for a preceding contrast agent-enhanced measurement, there is at the time of the first flooding-in no further contrast agent in the blood circulation during the measurement, achieving an ideal contrast-to-noise ratio during the image generation and thus an ideal image quality.

[0017] According to a further aspect of the invention, this knowledge can also be used to avoid a misadjustment on a contrast agent injector, or to find the ideal setting of flow rate and bolus application duration.

[0018] Accordingly, the inventors propose a method for predetermining a maximum bolus application duration ($=T_{Bmax}[T_{Amin}]$) for achieving a minimum bolus response duration ($=T_{Amin}$) of a contrast agent bolus response at a second vessel

position in a region of interest (=ROI) of a patient after an automated bolus application using a contrast agent applicator at a first vessel position for a contrast agent-enhanced imaging recording method, wherein the following method steps are carried out:

- ascertaining a correlation between the maximum bolus application duration for a patient group with at least one known patient parameter, on the one hand, and at least one blood flow parameter, on the other, wherein the blood flow parameter is dependent on at least one blood flow property at a third vessel position,
- outputting a table (=LUT) or function of the correlation and/or storing a table or function of the correlation in an electronic memory for further use by a computer.

[0019] The provision of such a correlation table or correlation function, in which the variables taken into account are, firstly, the various patient parameters, whereby comparable patients and patient groups are considered, and, secondly, the blood flow parameter from which it is then possible to read off or calculate the associated maximum bolus application duration of the particular patient for achieving a minimum bolus response duration, provides qualified personnel with a means to avoid unnecessary, time-consuming and patient-stressing experiments for achieving a minimum bolus response time in an examination region.

[0020] Preferably, the second vessel position and/or the region of interest selected can be a region situated, in terms of flow, after the pulmonary vessels, for example in the region of the carotid arteries and of the head. In most cases, the first vessel position selected is a position in the arm vein.

[0021] Since the at least one blood flow property can be ascertained even in the absence of contrast agent, preferably by a phase-contrast magnetic resonance measurement, there is also no administration of contrast agent to the blood circulation as a result of these measurements, and so, in subsequent measurements during a first flooding-in, there is also no need to fear “background noise” due to contrast agent remnants in the blood circulation from previous measurements and, in the actual measurement, an improved contrast-to-noise ratio can thus be achieved.

[0022] With regard to the patient parameters to be used for making the tested patient clientele and the results obtained therefrom comparable with a patient currently under examination, it is proposed that at least one patient parameter, preferably multiple patient parameters, of the following list is/are used:

- sex
- weight,
- height,
- age,
- heart rate,
- BMI,
- typing of physique,
- distance between predetermined vessel positions.

[0023] As blood flow properties to be advantageously examined, it is proposed that the at least one blood flow property used is at least one of the following properties:

- maximum, minimum or mean blood flow velocity at at least one predetermined position in the vessel cross section at the vessel position;
- maximum, minimum or mean blood flow velocity at at least one predetermined position in the vessel cross section at the vessel position at a given heart or pulse phase;
- maximum, minimum or mean blood flow velocity at at least one predetermined position in the vessel cross section at the vessel position at a given heart or pulse phase over a predetermined measurement time period;
- maximum, minimum or mean blood flow volume at at least one predetermined position in the vessel cross section at the vessel position;
- maximum, minimum or mean blood flow volume at at least one predetermined position in the vessel cross section at the vessel position at a given heart or pulse phase;
- maximum, minimum or mean blood flow volume at at least one predetermined position in the vessel cross section at the vessel position at a given heart or pulse phase over a predetermined measurement time period;

- a geometric property of a velocity profile over the vessel cross section at the vessel position;
- net forward volume over a predetermined period of time or per heartbeat.

[0024] In a particularly simple embodiment of the method, the blood flow parameter itself can be used as the blood flow property.

[0025] Furthermore, the blood flow parameter used can be an absolute or percentage difference between the blood flow property at the third vessel position in relation to the same blood flow property at a fourth vessel position.

[0026] The favourable first vessel position should satisfy at least one of the following locations or conditions:

- the first vessel position lies in a venous vessel,
- the first vessel position lies in an arm vein,
- the first vessel position lies on the back of the hand,
- the first vessel position lies on a central venous catheter,
- the first vessel position lies between the back of the hand and the axillary vein,
- the first vessel position lies between the foot and the great saphenous vein,
- the first vessel position lies in a central venous vessel.

[0027] Furthermore, it is proposed that the second vessel position satisfies at least one of the following locations or conditions:

- the second vessel position lies in an arterial vessel,
- the second vessel position lies in a leg artery,
- the second vessel position lies downstream of the third vessel position the second vessel position lies downstream of the bifurcation of the aorta,
- the second vessel position lies in a peripheral artery, preferably in the knee region,
- the second vessel position lies in the arm region,
- the second vessel position lies in the neck region,
- the second vessel position lies in the head region.

[0028] The third vessel position should satisfy at least one of the following locations or conditions:

- the third vessel position is the second vessel position the third vessel position lies in the thoracic aorta,
- the third vessel position lies in the abdominal aorta,
- the third vessel position lies in the ascending aorta,
- the third vessel position lies between the thoracic aorta and the third vessel position lies upstream of the bifurcation,
- the third vessel position lies between the bifurcation and the second vessel position.

[0029] Lastly, at least one of the following locations or conditions is satisfied for the fourth vessel position:

- the fourth vessel position lies upstream of the third vessel position,
- the fourth vessel position lies downstream between the third vessel position and the second vessel position,
- the fourth vessel position lies downstream of the second vessel position.

[0030] As shown above, it is thus possible to determine the maximum bolus application duration for achieving a minimal possible bolus response duration, preferably without contrast agent and without stressing the patient with ionizing radiation. On the basis of such knowledge, it is then possible to determine an ideal flow rate and duration of an automated bolus application which, firstly, keeps the flow rate as low as possible and, secondly however, generates a shortest possible bolus response duration in the examination region.

[0031] Accordingly, there is proposed a method for determining an ideal flow rate for a shortest possible automated bolus application of a contrast agent using a contrast agent applicator for a contrast agent-enhanced recording of a patient, comprising at least the following method steps:

- ascertaining a maximum bolus application duration for achieving a minimum bolus response duration of a contrast agent bolus response at a second vessel position in a region of interest of a patient after an automated bolus application using a contrast agent applicator at a first vessel position,

- calculating a flow rate to be set at a contrast agent injector for a contrast agent bolus in the case of the predetermined maximum bolus application duration for applying a predetermined contrast agent amount to be applied,
- storing the calculated flow rate and the bolus application duration in a memory of the contrast agent injector for use for a contrast agent bolus injection to be carried out.

[0032] In this case, at least the following method steps can be carried out in order to ascertain the bolus application duration where $T_B = T_{Bmax}[T_{Amin}]$:
- performing a contrast agent-free measurement of at least one blood flow property on the patient currently under examination,
- determining at least one blood flow parameter on the basis of the at least one blood flow property measured,
- ascertaining the maximum bolus application duration for achieving a minimum bolus response duration using a predetermined correlation between the at least one blood flow parameter and the maximum bolus application duration taking into account at least one patient parameter.

[0033] Preferably, the method outlined above can be used to ascertain the correlation between the at least one blood flow parameter and the maximum bolus application duration for achieving a minimum bolus response duration, wherein it is self-evidently preferred that, in the measurements to determine the correlation and in the later measurements on the patient currently under examination, the same blood flow properties at the same vessel positions and hence the same blood flow parameters are determined, wherein the reference patient clientele with its patient parameters should be in line with the patient currently under examination as far as possible.

[0034] The method according to the invention is especially proposed in order that an application of the contrast agent using a contrast agent applicator takes place using the ascertained flow rate over the predetermined bolus application duration where $T_B = T_{Bmax}[T_{Amin}]$ and at least one image of at least the region of interest of the patient is generated by a contrast agent-enhanced imaging method. Preferably, the generation of the at least one image should be done by means of a magnetic resonance examination or using a magnetic resonance imaging system.

[0035] The described method is especially advantageous for an examination in which a first flooding-in of contrast agent in the examination region is imaged. Accordingly, it is proposed that the contrast agent-enhanced generation of a recording of the examination area, preferably in the head/brain region, is only done during the first flooding-in of the contrast agent in the examination area.

[0036] On the basis of the knowledge of the maximum bolus application duration $T_{Bmax}[T_{Amin}]$, there is additionally also proposed a method for avoiding an incorrect setting of the flow rate and/or bolus application duration of a contrast agent applicator, said applicator having a processor and a memory or being connected thereto in order to execute at least one computer program present in the memory during operation, and the at least one computer program having a process routine which ensures that an inputted bolus application duration is identical to or greater than a previously ascertained maximum bolus application duration for achieving a minimum bolus response duration of a contrast agent bolus response at a second vessel position in a region of interest of a patient after an automated bolus application using a contrast agent applicator at a first vessel position.

[0037] Preferably, in the case of this method too, the maximum bolus application duration for achieving a minimum bolus response duration should be ascertained on the current patient at the same vessel positions using the same blood flow parameters and patient parameters which are also used to ascertain the correlation, wherein the positions already proposed above may preferably be used.

[0038] Furthermore, it is also possible in this case to ascertain the maximum bolus application duration for achieving a minimum bolus response duration of the patient currently examined by means of a contrast agent-free phase-contrast magnetic resonance determination of at least one blood flow property, wherein the method described above is preferably carried out.

[0039] Besides the method according to the invention, the inventors also propose an imaging medical examination system, preferably a magnetic resonance system for generating a contrast agent-enhanced MR recording, wherein said system is provided with a processor-controlled contrast agent injector and wherein computer

and a memory for computer programs are present, and computer programs which execute the method according to the invention during operation are stored.

[0040] In a related aspect, the invention provides a method for predetermining a maximum duration ($T_{Bmax}[T_{Amin}]$) for administration of a contrast agent bolus at a first vessel position (P1) for achieving a minimum duration (T_{Amin}) of a response thereto having profile (K(t)) at a second vessel position (P2) in a region of interest (ROI) of a patient (P) wherein the administration of the contrast agent bolus having a profile (B(t)) at the first vessel position (P1) is carried out using an automated contrast agent injector (5) in connection with a contrast agent-enhanced imaging procedure. The method includes determining a correlation between the maximum duration ($T_{Bmax}[T_{Amin}]$) for the administration of the contrast agent bolus for a patient group with at least one known patient parameter (P_P) and at least one blood flow parameter (P_B) of the patient (P), wherein the at least one blood flow parameter (P_B) of the patient (P) is dependent on at least one blood flow property (E_B) at a third vessel position (P3) of the patient (P). The method also includes outputting a table (LUT) and/or function of the correlation and storing the table and/or function of the correlation in an electronic memory for further use by a computer.

[0041] In certain non-limiting embodiments of the aforementioned method, the second vessel position (P2) and the region of interest (ROI) are situated, in terms of flow, after pulmonary vessels of the patient. The at least one blood flow property (E_B) is determined in the absence of contrast agent by a phase-contrast magnetic resonance measurement. At least one of the following variables may be used as the least one patient parameter (P_P): sex, weight, height, age, heart rate, body mass index, typing of physique, and distance between the vessel positions. The at least one blood flow property (E_B) used may be at least one of the following properties: (a) maximum, minimum or mean blood flow velocity (v_G) at at least one predetermined position in a cross section of the blood at the vessel position; (b) maximum, minimum or mean blood flow velocity (v_G) at at least one predetermined position in a cross section of the blood vessel at the vessel position at a given heart or pulse phase; (c) maximum, minimum or mean blood flow velocity (v_G) at at least one predetermined position in a cross section of the blood vessel at the

vessel position at a given heart or pulse phase over a predetermined measurement time period; (d) maximum, minimum or mean blood flow volume at at least one predetermined position in a cross section of the blood vessel at the vessel position; (e) maximum, minimum or mean blood flow volume at at least one predetermined position in a cross section of the blood vessel at the vessel position at a given heart or pulse phase; (f) maximum, minimum or mean blood flow volume at at least one predetermined position in a cross section of the blood vessel at the vessel position at a given heart or pulse phase over a predetermined measurement time period; (g) geometric property of a velocity profile over a cross section of the blood vessel at the vessel position; and (h) net forward volume over a predetermined period of time or per heartbeat.

[0042] In certain non-limiting embodiments of the aforementioned method, the at least one blood flow parameter (P_B) used may be the at least one blood flow property (E_B) itself. The at least one blood flow parameter (P_B) used may be an absolute or percentage difference between the at least one blood flow property (E_B) at the third vessel position (P3) in relation to the at least one blood flow property (E_B) of a same type at a fourth vessel position (P4). The first vessel position (P1) satisfies at least one of the following locations or conditions: (a) the first vessel position (P1) lies in a venous vessel; (b) the first vessel position (P1) lies in a vein of an arm; (c) the first vessel position (P1) lies on a back of a hand; (d) the first vessel position (P1) lies on a central venous catheter; (e) the first vessel position (P1) lies between the back of the hand and an axillary vein; (f) the first vessel position (P1) lies between a foot and a great saphenous vein; and (g) the first vessel position (P1) lies in a central venous vessel. The second vessel position (P2) satisfies at least one of the following locations or conditions: (a) the second vessel position (P2) lies in an arterial vessel; (b) the second vessel position (P2) lies in an artery of a leg; (c) the second vessel position (P2) lies downstream of the third vessel position (P3); (d) the second vessel position (P2) lies downstream of the bifurcation of the aorta; (e) the second vessel position (P2) lies in a peripheral artery, preferably in a region of a knee; (f) the second vessel position (P2) lies in a region of an arm; (g) the second vessel position (P2) lies in a region of the head; and (h) the second vessel position (P2) lies in a region of the

neck. The third vessel position (P3) satisfies at least one of the following locations or conditions: (a) the third vessel position (P3) is the second vessel position (P2); (b) the third vessel position (P3) lies in the thoracic aorta; (c) the third vessel position (P3) lies in the abdominal aorta; (d) the third vessel position (P3) lies in the ascending aorta; (e) the third vessel position (P3) lies between the thoracic aorta and the second vessel position (P2); (f) the third vessel position (P3) lies upstream of the bifurcation of the aorta; and (g) the third vessel position (P3) lies between the bifurcation of the aorta and the second vessel position (P2). The fourth vessel position (P4) satisfies at least one of the following locations or conditions: (a) the fourth vessel position (P4) lies upstream of the third vessel position (P3); (b) the fourth vessel position (P4) lies downstream between the third vessel position (P3) and the second vessel position (P2); and (c) the fourth vessel position (P4) lies downstream of the second vessel position (P2).

[0043] In certain non-limiting embodiments of the aforementioned method, the contrast agent injector (5) has a memory for storing at least one computer program in which the method is embodied and a processor for executing the at least one computer program in connection with a magnetic resonance system (1) for generating a contrast agent-enhanced image of the region of interest (ROI).`

[0044] In another aspect, the invention provides a method for determining an ideal flow rate (F) for a shortest possible application of a contrast agent (KM) bolus using an automated contrast agent injector (5) in connection with a contrast agent-enhanced imaging procedure of a patient (P). The method includes determining a maximum duration ($T_{Bmax}[T_{min}]$) for application of a contrast agent bolus for achieving a minimum duration (T_{Amin}) of a response K(t)) thereto at a second vessel position (P2) in a region of interest (ROI) of a patient (P) after an application of the contrast agent (KM) bolus having a profile (B(t)) at a first vessel position (P1) using the automated contrast agent injector (5). The method also includes calculating a flow rate (F) for the contrast agent bolus to be set at the contrast agent injector (5) at the predetermined maximum duration ($T_{Bmax}[T_{Amin}]$) for applying a predetermined amount (M_{KM}) of the contrast agent; and storing the calculated flow rate (F) and the predetermined maximum duration (T_B =

$T_{Bmax}[T_{Amin}]$) in a memory of the contrast agent injector (5) for use for a contrast agent bolus injection to be carried out.

[0045] In certain non-limiting embodiments of the aforementioned method, at least the following steps are carried out to determine the duration ($T_B = T_{Bmax}[T_{Amin}]$) for the application of the contrast agent bolus: (a) performing a contrast agent-free measurement of at least one blood flow property (E_B) of the patient (P) currently under examination; (b) determining at least one blood flow parameter (P_B) on the basis of the at least one blood flow property (E_B) measured; and (c) determining the maximum duration ($T_{Bmax}[T_{min}]$) for application of a contrast agent bolus for achieving a minimum duration (T_{Amin}) of a response thereto using a predetermined correlation between the at least one blood flow parameter (P_B) and the maximum duration ($T_{Bmax}[T_{min}]$) for application of a contrast agent bolus taking into account at least one patient parameter (P_P). The predetermined correlation may be determined according to any of the ways disclosed above. For the determination of the maximum duration ($T_{Bmax}[T_{min}]$) for application of a contrast agent bolus, the at least one blood flow parameter (P_B) and the at least one patient parameter (P_P) are determined at the same vessel positions (P1 to P4) used for determining the correlation according to either of the aspects of the invention disclosed above.

[0046] In certain non-limiting embodiments of the aforementioned method, the following steps are carried out: (a) applying the contrast agent at the calculated flow rate (F) using the contrast agent injector (5) over the predetermined maximum duration ($T_B = T_{Bmax}[T_{Amin}]$) for applying the predetermined amount (M_{KM}) of the contrast agent; and (b) generating at least one image of at least the region of interest (ROI) of the patient (P) using a contrast agent-enhanced imaging procedure. The at least one image may be generated by means of a magnetic resonance examination or using a magnetic resonance imaging system. The contrast agent-enhanced imaging procedure used to generate the at least one image of the region of interest (ROI) is preferably performed during a flooding-in of the contrast agent (KM) in the region of interest (ROI), and the region of interest (ROI) is preferably in a head/brain region.

[0047] In certain non-limiting embodiments of the aforementioned method, the memory of the contrast agent injector (5) is also used for storing at least one

computer program in which the method is embodied, the contrast agent injector (5) further having a processor for executing the at least one computer program in connection with a magnetic resonance system (1) for generating a contrast agent-enhanced image of the region of interest (ROI).

[0048] In a further aspect, the invention provides a method for avoiding an incorrect setting of at least one of a flow rate (F) of and a bolus application duration (T_B) for a contrast agent (KM) on a contrast agent injector (5). The contrast agent injector (5) has a processor and a memory in which at least one computer program embodying the method, at least in part, is present during operation of the contrast agent injector (5). The method includes ensuring that the duration (T_B) for application of the contrast agent bolus inputted into the contrast agent injector (5) is identical to or greater than a previously determined maximum duration ($T_{Bmax}[T_{Amin}]$) of a contrast agent bolus application for achieving a minimum duration (T_{Amin}) of a response K(t)) to a contrast agent bolus at a second vessel position (P2) in a region of interest (ROI) of a patient (P) after the application of the contrast agent (KM) bolus having a profile (B(t)) at a first vessel position (P1) using the contrast agent injector (5).

[0049] In certain non-limiting embodiments of the aforementioned method, for the patient at issue, the maximum duration ($T_{Bmax}[T_{Amin}]$) is determined at vessel positions (P1 to P4) identical to, and with blood flow parameters (P_B) and patient parameters (P_P) the same as, those used to determine the correlation according to the related aspect of the invention disclosed above. The maximum duration ($T_{Bmax}[T_{Amin}]$), for the patient (P) at issue, is determined by means of a contrast agent-free phase-contrast magnetic resonance determination of at least one blood flow property (E_B). The at least one computer program is stored in the memory of the contrast agent injector (5) and useable in connection with a magnetic resonance system (1) for generating a contrast agent-enhanced image of the region of interest (ROI).

[0050] The invention will be described in more detail below by means of the figures, with only the features required for understanding the invention being depicted. Specifically:

DETAILED DESCRIPTION OF THE DRAWINGS

[0051] **FIG. 1** shows an illustration of an MRI system according to the invention;

[0052] **FIG. 2** shows an illustration of a circulation of a patient;

[0053] **FIG. 3** shows an illustration of a profile of a bolus application at a first vessel position and of the corresponding profile of a bolus response at a second vessel position;

[0054] **FIG. 4** shows an illustration of three bolus applications of differing bolus application duration at the same first vessel position and respective resultant bolus response profiles at the same second vessel position;

[0055] **FIG. 5** shows an illustration of a relationship between the bolus at a first vessel position with the bolus application duration T_B and the bolus response duration T_A of a subsequent bolus response at a second vessel position of a patient with resultant minimum bolus response duration T_{Amin} and maximum bolus duration $T_{Bmax}[T_{Amin}]$ possible therefor;

[0056] **FIG. 6** shows an illustration of the correlation between a blood flow parameter P_B and a minimum bolus response duration T_{Amin} with the maximum bolus duration $T_{Bmax}[T_{Amin}]$ possible therefor.

DETAILED DESCRIPTION OF THE INVENTION

[0057] **Figure 1** schematically depicts a magnetic resonance imaging system (MRI system) 1. In this MRI system 1, magnetic coils 2 for generating a strong main magnetic field are situated in a housing 6, as a result of which magnetic field the hydrogen nuclei in the body of the patient 7, in accordance with the spin thereof, are aligned parallel or antiparallel to the magnetic field lines. By exciting the atomic nuclei with an alternating electromagnetic field at the resonant frequency of the atomic nuclei, the atomic nuclei vibrate. After switching off the excitation frequency, the atomic nuclei return to their position and emit their vibrational energy in the form of electromagnetic vibrational energy, which is measured with the aid of reception coils 3, which are arranged, where possible, in the vicinity of an ROI to be observed on the patient 7. A weak magnetic field with a defined field gradient is generated by additional magnetic coils 4, as a result of which the signals emitted by the nuclei contain spatial information, by means of which the

position of the emitted signal is definable. The control and computer unit 8 controls this system 1, evaluates the measurement signals and, in the memory thereof, has programs 9 which, in addition to control and image calculation, can also execute the method according to the invention during operation.

[0058] For an improved representation of blood vessels, it is sometimes necessary to briefly enrich the blood circulation of the patient with contrast agent, for the purposes of which use is usually made of a contrast agent injector 5 which generates under electronic control – either by the computer unit 8 or by a separate processor – the volume flow of a contrast agent to be applied for the measurement (=bolus), in which the flow (volume per time) or the time profile thereof and the flow duration T_B is appropriately predetermined.

[0059] With the aid of such an MRI system, it is possible, even when using a plurality of reception antennas, to obtain blood flow properties, such as e.g. flow velocities, velocity profiles or volume flows, without the application of a contrast agent. In this respect, reference is made, merely by way of example, to the document DE 102013204994 A1.

[0060] For an improved understanding of the invention, **Figure 2** shows a very schematically depicted blood circulation of a patient. This closed circulation is divided into a venous circulation (dashed lines) and an arterial circulation (full lines) and is substantially operated by the pumping action of the heart. In the pulmonary circulation – in contrast to the remaining blood circulation – the arterial blood has a low oxygen content and the venous blood has a high oxygen content. In accordance with such a natural profile and the relatively easily producible and usable accesses in the venous zone, for example at an arm or hand vein, contrast agents are usually applied through such accesses, usually with the aid of automatically controlled contrast agent injectors. Accordingly, a bolus placed there initially passes the right cardiac chambers (not depicted in any more detail), is guided by the pulmonary vessels to the left chambers of the heart (likewise not depicted here) and from there it reaches the regions of the body which are intended to be imaged with an MR recording and which are of interest in relation to the invention; in particular, it also reaches the peripheral vessel regions.

[0061] In the schematic illustration of Figure 2, the essential vessel positions P1 to P4 and the examination region ROI to be at least imaged are marked at exemplary and typical positions. As already mentioned, the application usually occurs in the zone of the venous circulation, corresponding to the inscribed vessel position P1 at a peripheral vessel, e.g. of an arm or hand vein.

[0062] The region of interest ROI, which is to be examined by imaging, can – as drawn in here – for example lie in the region of a leg artery or else in the head region, where the vessel position P2 is then also situated. The further measurement positions, at which blood flow properties are then determined, generally lie in the arterial vessel system between the left atrium of the heart and the ROI. However, reference is made to the fact that positioning of the measurement points at vessel positions which, as seen in the flow direction, are arranged downstream of the ROI or P2 is also possible.

[0063] A bolus application with contrast agent that is applied at a first vessel position P1 usually has a bolus profile B(t), as drawn in in the upper part of **Figure 3**. There, the volume flow of the bolus B with a bolus application duration T_B is plotted over time t, the exceeding of the contrast agent concentration profile K(t) above a contrast agent concentration level, in this case the half maximal value $K^{max}/2$ for determining the full width at half maximum, being considered to be the criterion for determining the bolus response duration. Such a bolus profile B(t) can – as depicted here – assume a rectangular profile, but it can also reproduce any desired function by means of appropriate setting on a contrast agent injector. Such a volume flow B is selected dependent upon the employed contrast agent (e.g. Gadovist® or Magnevist®) and specific patient properties in order to achieve a desired contrast agent concentration at the location of examination in the vessel to be depicted. As shown in Figure 2, after application in the venous vessel zone, such a bolus passes at least the heart twice and the lung with significant branching of the vessels in between. At the bottom of Figure 3, the contrast agent concentration profile K(t) of a bolus response with a bolus response duration T_A at a vessel position P2 is shown in an exemplary manner.

[0064] Three different and typical values of a bolus application duration T_B in comparison with the resultant values for the respective resulting bolus response

durations T_A are depicted in **Figure 4**. Fundamentally, there is a range of proportionality for the bolus application duration T_B, in which an ever larger or ever smaller bolus application duration T_B also leads to correspondingly ever larger or ever smaller bolus response duration T_A. In relation to ever shorter times of the bolus application duration T_B, the bolus response duration T_A reaches a limit value of a minimal achievable bolus response duration T_{Amin}, which limit value cannot be fallen short of by a bolus application duration T_B, however short. This situation is especially due to the pulmonary vessels and additionally occurring turbulences, non-laminar flows and velocity differences across the vessel cross section including due to dilution effects in the venous system, which generate a more or less strong dispersion of the applied contrast agent bolus. Presumably, in this case, dilution effects are significant both in the cardiac chambers and in the large pulmonary void volume. In this connection, the cardiac and pulmonary system behaves like a blood reservoir, into which a small contrast agent volume is rapidly introduced and is then discharged in a diluted manner over a relatively long time period.

[0065] In **Figure 5**, a typical relationship between the duration of a bolus application T_B at a first vessel position and the resulting duration of a bolus response T_A is plotted against one another. As can be seen, the curve $T_A(T_B)$ runs, coming from the right, firstly approximately proportionally in an approximately 40° angle towards smaller values of the bolus application duration T_B. This is followed by a curved region in which the broadening effect which occurs starts to dominate, followed by a limit value for the bolus response duration T_{Amin}, below which a bolus response duration – under the prerequisite of otherwise identical conditions – cannot be shortened even with any desired short bolus application. Accordingly, it is also necessary to determine a maximum value of a bolus application duration $T_{Bmax}[T_{Amin}]$, from which the minimum bolus response duration T_{Amin} is achieved.

[0066] The relationships described here between maximum bolus application duration $T_{Bmax}[T_{Amin}]$ for achieving a minimum bolus response duration T_{Amin} apply under fundamentally identical flow conditions, which in turn generate identical blood flow parameters. In accordance with the knowledge of the inventors, it is, however, also possible to find a correlation or unambiguous relationship between

such blood flow property-based blood flow parameters and the above-described maximum bolus application duration $T_{Bmax}[T_{Amin}]$. Accordingly, under the prerequisite of a comparable patient clientele, i.e. patients with largely agreeing patient parameters, it is possible by determining the blood flow parameters to predict the maximum bolus application duration $T_{Bmax}[T_{Amin}]$ for given application positions of the bolus and observation positions of the bolus response, which leads to a minimal possible bolus response duration T_{Amin}.

[0067] By way of example, **Figure 6** shows the ascertained correlation between the blood flow parameter P_B corresponding to a mean flow velocity of the blood at a typical vessel position P3 of a patient collective having similar to identical patient parameters concerning sex, weight, height, age, heart rate and BMI, on the one hand, and the maximum bolus application duration $T_{Bmax}[T_{Amin}]$ ascertained under these conditions for a first vessel position P1 of a bolus application and observation positions of the bolus response at a second vessel position P2 predict, which leads to a minimal possible bolus response duration T_{Amin}. According to the graphical illustration, it is possible from the diagram in Figure 6, proceeding from a in the case of a patient under examination whose patient parameter agrees with the patient collective used here, to initially read off a value on the upper curve, which leads to a maximum bolus response duration $T_{Bmax}[T_{Amin}]$ on the abscissa. Proceeding further perpendicularly downward from there gives a value on the lower curve, from which it is possible, proceeding horizontally to the left to the ordinate, to read off the value for the minimum bolus response duration T_{Amin} achievable under these conditions.

[0068] It is self-evident that the correlations depicted here graphically can also be described by means of a corresponding look-up table (LUT) or corresponding mathematical functions.

[0069] Altogether, the invention thus proposes a method for predetermining a maximum – in the sense of a maximal possible – bolus application duration for achieving a minimal possible bolus response duration of a contrast agent bolus response at a second vessel position in a region of interest of a patient at a first vessel position for a contrast agent-enhanced imaging recording method, wherein, to this end, a correlation is ascertained between the maximal possible bolus

application duration for a patient group with known patient parameters and at least one blood flow parameter.

[0070] Moreover, there is also proposed a method for determining an ideal flow rate for a shortest possible bolus application, wherein the maximal achievable bolus application duration with a simultaneous shortest possible bolus response duration is ascertained and, from this, the necessary flow rate for the application of a predetermined contrast agent amount to be applied is determined.

[0071] Although the invention has been illustrated and described in more detail in detail by means of the preferred exemplary embodiment, the invention is not restricted by the disclosed examples and other variations can be derived therefrom by a person skilled in the art without departing from the scope of protection of the invention. In particular, the invention is not limited to the combinations of features specified here; on the contrary, it is also possible to form other combinations and partial combination of the disclosed features that are clearly implementable for a person skilled in the art. Furthermore, the invention is not restricted to the claim categories used in the claims; on the contrary, it also encompasses the disclosed features in conjunction with all other claim categories familiar to a person skilled in the art.

[0072] List of reference signs

1	Magnetic resonance imaging system (MRI system)
2	Magnetic coils
3	Reception coil
4	Magnetic coils
5	Contrast agent injector
6	Housing
7	Patient
8	Control and computer unit / computer with memory and display
9	Computer programs
B	Bolus
B(t)	Bolus time profile
K	Contrast agent concentration
K(t)	Contrast agent concentration time profile / contrast agent bolus response
$K^{max}/2$	Half maximal value of the contrast agent concentration
P_B	Blood flow parameter
P1	First vessel position
P2	Second vessel position
P3	Third vessel position
P4	Fourth vessel position
ROI	Examination area
t	Time
T_A	Bolus response duration
T_B	Bolus application duration
$T_{Bmax}[T_{Amin}]$	Maximum bolus application duration for achieving a minimum bolus response duration
T_{Amin}	Minimum bolus response duration

THE INVENTION CLAIMED IS:

1. A method for predetermining a maximum duration ($T_{Bmax}[T_{Amin}]$) for administration of a contrast agent bolus at a first vessel position (P1) for achieving a minimum duration (T_{Amin}) of a response thereto having profile (K(t)) at a second vessel position (P2) in a region of interest (ROI) of a patient (P) wherein the administration of the contrast agent bolus having a profile (B(t)) at the first vessel position (P1) is carried out using an automated contrast agent injector (5) in connection with a contrast agent-enhanced imaging procedure, the method comprising:

determining a correlation between the maximum duration ($T_{Bmax}[T_{Amin}]$) for the administration of the contrast agent bolus for a patient group with at least one known patient parameter (P_P) and at least one blood flow parameter (P_B) of the patient (P), wherein the at least one blood flow parameter (P_B) of the patient (P) is dependent on at least one blood flow property (E_B) at a third vessel position (P3) of the patient (P); and

outputting at least one of a table (LUT) and function of the correlation and storing the at least one of the table and function of the correlation in an electronic memory for further use by a computer.

2. The method according to claim 1, wherein at least one of the second vessel position (P2) and the region of interest (ROI) are situated, in terms of flow, after pulmonary vessels of the patient.

3. The method according to claim 1, wherein the at least one blood flow property (E_B) is determined in the absence of contrast agent by a phase-contrast magnetic resonance measurement.

4. The method according to claim 1, wherein at least one of the following variables is used as the least one patient parameter (P_P): sex, weight, height, age, heart rate, body mass index, typing of physique, and distance between the vessel positions.

5. The method according to claim 1, wherein the at least one blood flow property (E_B) used is at least one of the following properties:

(a) maximum, minimum or mean blood flow velocity (v_G) at at least one predetermined position in a cross section of the blood at the vessel position;

(b) maximum, minimum or mean blood flow velocity (v_G) at at least one predetermined position in a cross section of the blood vessel at the vessel position at a given heart or pulse phase;

(c) maximum, minimum or mean blood flow velocity (v_G) at at least one predetermined position in a cross section of the blood vessel at the vessel position at a given heart or pulse phase over a predetermined measurement time period;

(d) maximum, minimum or mean blood flow volume at at least one predetermined position in a cross section of the blood vessel at the vessel position;

(e) maximum, minimum or mean blood flow volume at at least one predetermined position in a cross section of the blood vessel at the vessel position at a given heart or pulse phase;

(f) maximum, minimum or mean blood flow volume at at least one predetermined position in a cross section of the blood vessel at the vessel position at a given heart or pulse phase over a predetermined measurement time period;

(g) a geometric property of a velocity profile over a cross section of the blood vessel at the vessel position; and

(h) net forward volume over a predetermined period of time or per heartbeat.

6. The method according to claim 1, wherein the at least one blood flow parameter (P_B) used is the at least one blood flow property (E_B) itself.

7. The method according to claim 1, wherein the at least one blood flow parameter (P_B) used is an absolute or percentage difference between the at least one blood flow property (E_B) at the third vessel position (P3) in relation to the at least one blood flow property (E_B) of a same type at a fourth vessel position (P4).

8. The method according to claim 1, wherein the first vessel position (P1) satisfies at least one of the following locations or conditions:

(a) the first vessel position (P1) lies in a venous vessel;

(b) the first vessel position (P1) lies in a vein of an arm;

(c) the first vessel position (P1) lies on a back of a hand;

(d) the first vessel position (P1) lies on a central venous catheter;

(e) the first vessel position (P1) lies between the back of the hand and an axillary vein;

(f) the first vessel position (P1) lies between a foot and a great saphenous vein; and

(g) the first vessel position (P1) lies in a central venous vessel.

9. The method according to claim 1, wherein the second vessel position (P2) satisfies at least one of the following locations or conditions:

(a) the second vessel position (P2) lies in an arterial vessel;

(b) the second vessel position (P2) lies in an artery of a leg;

(c) the second vessel position (P2) lies downstream of the third vessel position (P3);

(d) the second vessel position (P2) lies downstream of the bifurcation of the aorta;

(e) the second vessel position (P2) lies in a peripheral artery, preferably in a region of a knee;

(f) the second vessel position (P2) lies in a region of an arm;

(g) the second vessel position (P2) lies in a region of the head; and

(h) the second vessel position (P2) lies in a region of the neck.

10. The method according to claim 1, wherein the third vessel position (P3) satisfies at least one of the following locations or conditions:

(a) the third vessel position (P3) is the second vessel position (P2);

(b) the third vessel position (P3) lies in the thoracic aorta;

(c) the third vessel position (P3) lies in the abdominal aorta;

(d) the third vessel position (P3) lies in the ascending aorta;

(e) the third vessel position (P3) lies between the thoracic aorta and the second vessel position (P2);

(f) the third vessel position (P3) lies upstream of the bifurcation of the aorta; and

(g) the third vessel position (P3) lies between the bifurcation of the aorta and the second vessel position (P2).

11. The method according to claim 7, wherein the fourth vessel position (P4) satisfies at least one of the following locations or conditions:

(a) the fourth vessel position (P4) lies upstream of the third vessel position (P3);

(b) the fourth vessel position (P4) lies downstream between the third vessel position (P3) and the second vessel position (P2); and

(c) the fourth vessel position (P4) lies downstream of the second vessel position (P2).

12. A method for determining an ideal flow rate (F) for a shortest possible application of a contrast agent (KM) bolus using an automated contrast agent injector (5) in connection with a contrast agent-enhanced imaging procedure of a patient (P), the method comprising:

determining a maximum duration ($T_{Bmax}[T_{min}]$) for application of a contrast agent bolus for achieving a minimum duration (T_{Amin}) of a response K(t)) thereto at a second vessel position (P2) in a region of interest (ROI) of a patient (P) after an application of the contrast agent (KM) bolus having a profile (B(t)) at a first vessel position (P1) using the automated contrast agent injector (5);

calculating a flow rate (F) for the contrast agent bolus to be set at the contrast agent injector (5) at the predetermined maximum duration ($T_{Bmax}[T_{Amin}]$) for applying a predetermined amount (M_{KM}) of the contrast agent; and

storing the calculated flow rate (F) and the predetermined maximum duration ($T_B = T_{Bmax}[T_{Amin}]$) in a memory of the contrast agent injector (5) for use for a contrast agent bolus injection to be carried out.

13. The method according to claim 12, wherein at least the following steps are carried out to determine the duration ($T_B = T_{Bmax}[T_{Amin}]$) for the application of the contrast agent bolus:

(a) performing a contrast agent-free measurement of at least one blood flow property (E_B) of the patient (P) currently under examination;

(b) determining at least one blood flow parameter (P_B) on the basis of the at least one blood flow property (E_B) measured; and

(c) determining the maximum duration ($T_{Bmax}[T_{min}]$) for application of a contrast agent bolus for achieving a minimum duration (T_{Amin}) of a response thereto using a predetermined correlation between the at least one blood flow parameter (P_B) and the maximum duration ($T_{Bmax}[T_{min}]$) for application of a contrast agent bolus taking into account at least one patient parameter (P_P).

14. The method according claim 13, wherein the predetermined correlation is determined according to any of claim 1.

15. The method according to claim 14, wherein, for the determination of the maximum duration ($T_{Bmax}[T_{min}]$) for application of a contrast agent bolus, the at least one blood flow parameter (P_B) and the at least one patient parameter (P_P) are determined at the same vessel positions (P1 to P4) used for determining the correlation according to claim 1.

16. The method according to claim 12, wherein the following steps are carried out:

(a) applying the contrast agent at the calculated flow rate (F) using the contrast agent injector (5) over the predetermined maximum duration ($T_B = T_{Bmax}[T_{Amin}]$) for applying the predetermined amount (M_{KM}) of the contrast agent; and

(b) generating at least one image of at least the region of interest (ROI) of the patient (P) using a contrast agent-enhanced imaging procedure.

17. The method according to claim 16, wherein generation of at least the at least one image is done by means of a magnetic resonance examination or using a magnetic resonance imaging system.

18. The method according to claim 16, wherein the contrast agent-enhanced imaging procedure used to generate the at least one image of the region of interest (ROI) is preferably performed during a flooding-in of the contrast agent (KM) in the region of interest (ROI), and the region of interest (ROI) is preferably in a head/brain region.

19. A method for avoiding an incorrect setting of at least one of a flow rate (F) of and a bolus application duration (T_B) for a contrast agent (KM) on a contrast agent injector (5), the contrast agent injector (5) having a processor and a memory in which at least one computer program embodying the method at least in part is present during operation of the contrast agent injector (5), the method comprising ensuring that the duration (T_B) for application of the contrast agent bolus inputted into the contrast agent injector (5) is one of identical to and greater than a previously determined maximum duration ($T_{Bmax}[T_{Amin}]$) of a contrast agent bolus application for achieving a minimum duration (T_{Amin}) of a response K(t)) to a contrast agent bolus at a second vessel position (P2) in a region of interest (ROI) of a patient (P) after the application of the contrast agent (KM) bolus having a profile (B(t)) at a first vessel position (P1) using the contrast agent injector (5).

20. The method according to claim 19, wherein, for the patient at issue, the maximum duration ($T_{Bmax}[T_{Amin}]$) is determined at vessel positions (P1 to P4) identical to, and with blood flow parameters (P_B) and patient parameters (P_P) the same as, those used to determine the correlation according to claim 1.

21. The method according to claim 20, wherein, for the patient (P) at issue, the maximum duration ($T_{Bmax}[T_{Amin}]$) is determined by means of a contrast agent-free phase-contrast magnetic resonance determination of at least one blood flow property (E_B).

22. The method according to claim 19, wherein the at least one computer program is stored in the memory of the contrast agent injector (5) and useable in connection with a magnetic resonance system (1) for generating a contrast agent-enhanced image of the region of interest (ROI).

23. The method according to claim 1, wherein the contrast agent injector (5) has a memory for storing at least one computer program in which the method is embodied and a processor for executing the at least one computer program in connection with a magnetic resonance system (1) for generating a contrast agent-enhanced image of the region of interest (ROI).

24. The method according to claim 12, wherein the memory of the contrast agent injector (5) is also used for storing at least one computer program in which the method is embodied, the contrast agent injector (5) further having a processor for executing the at least one computer program in connection with a magnetic resonance system (1) for generating a contrast agent-enhanced image of the region of interest (ROI).

FIG 1

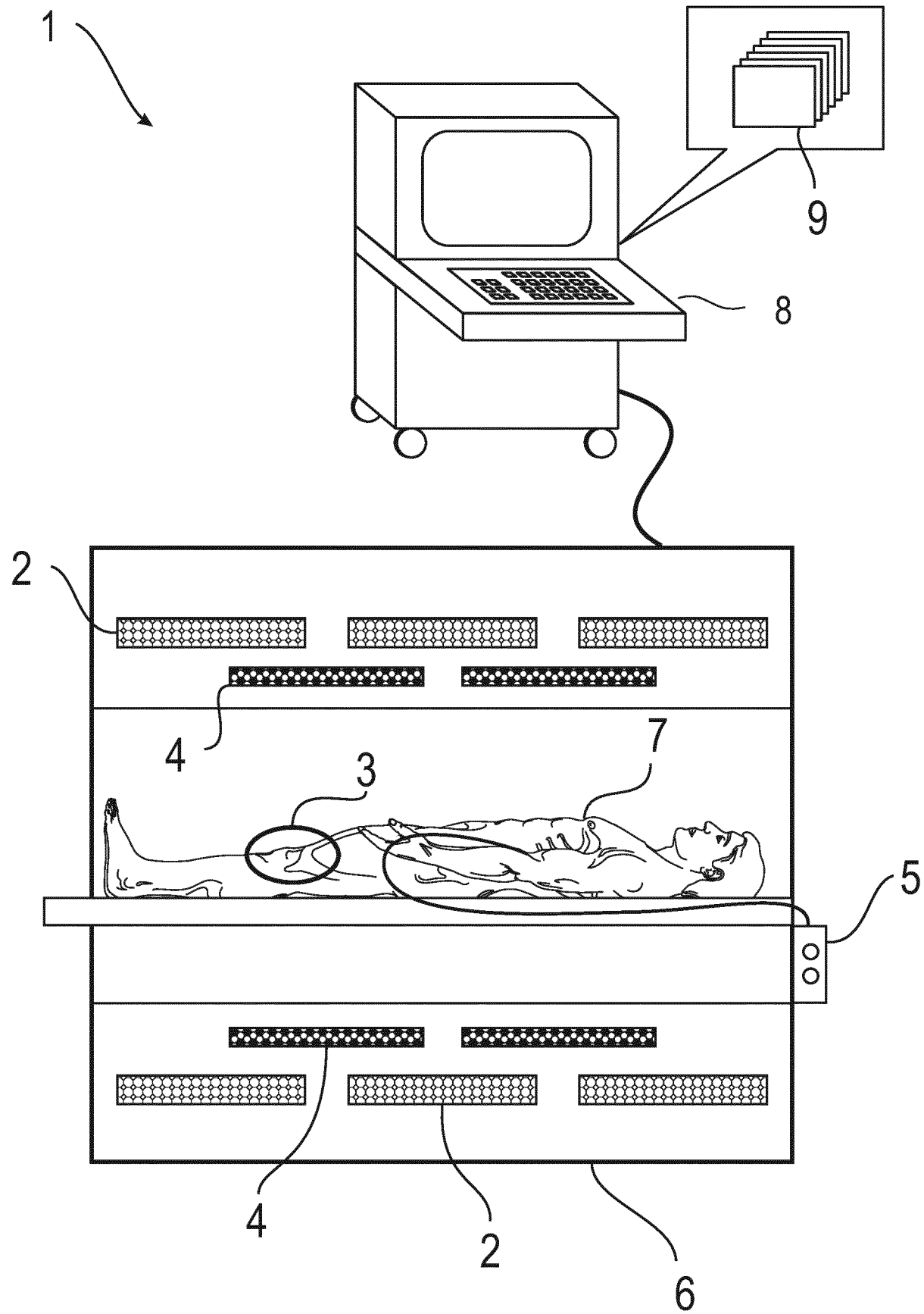

FIG 2

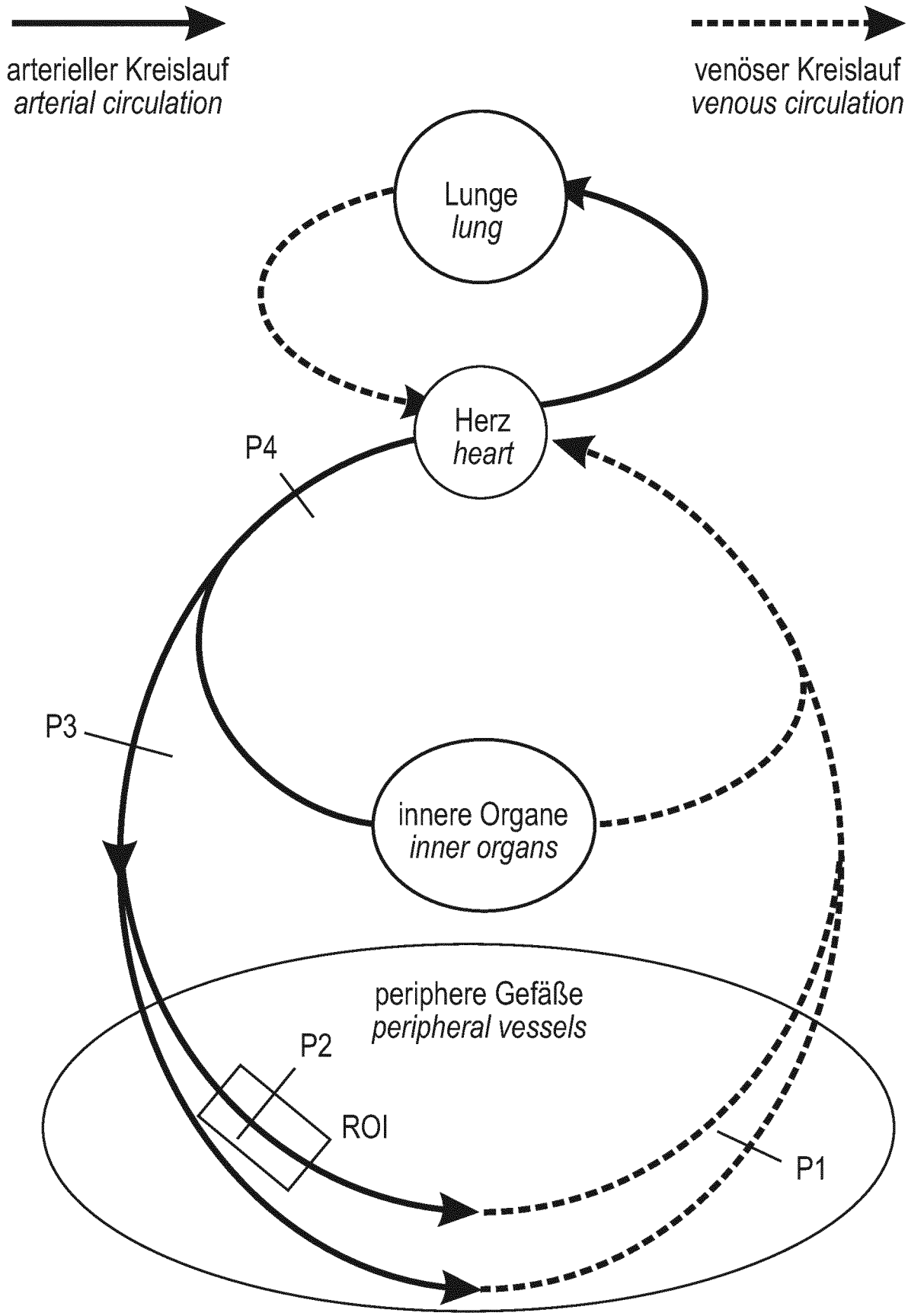
arterieller Kreislauf
arterial circulation
venöser Kreislauf
venous circulation
Lunge
lung
Herz
heart
P4
P3
innere Organe
inner organs
periphere Gefäße
peripheral vessels
P2
ROI
P1

FIG 3

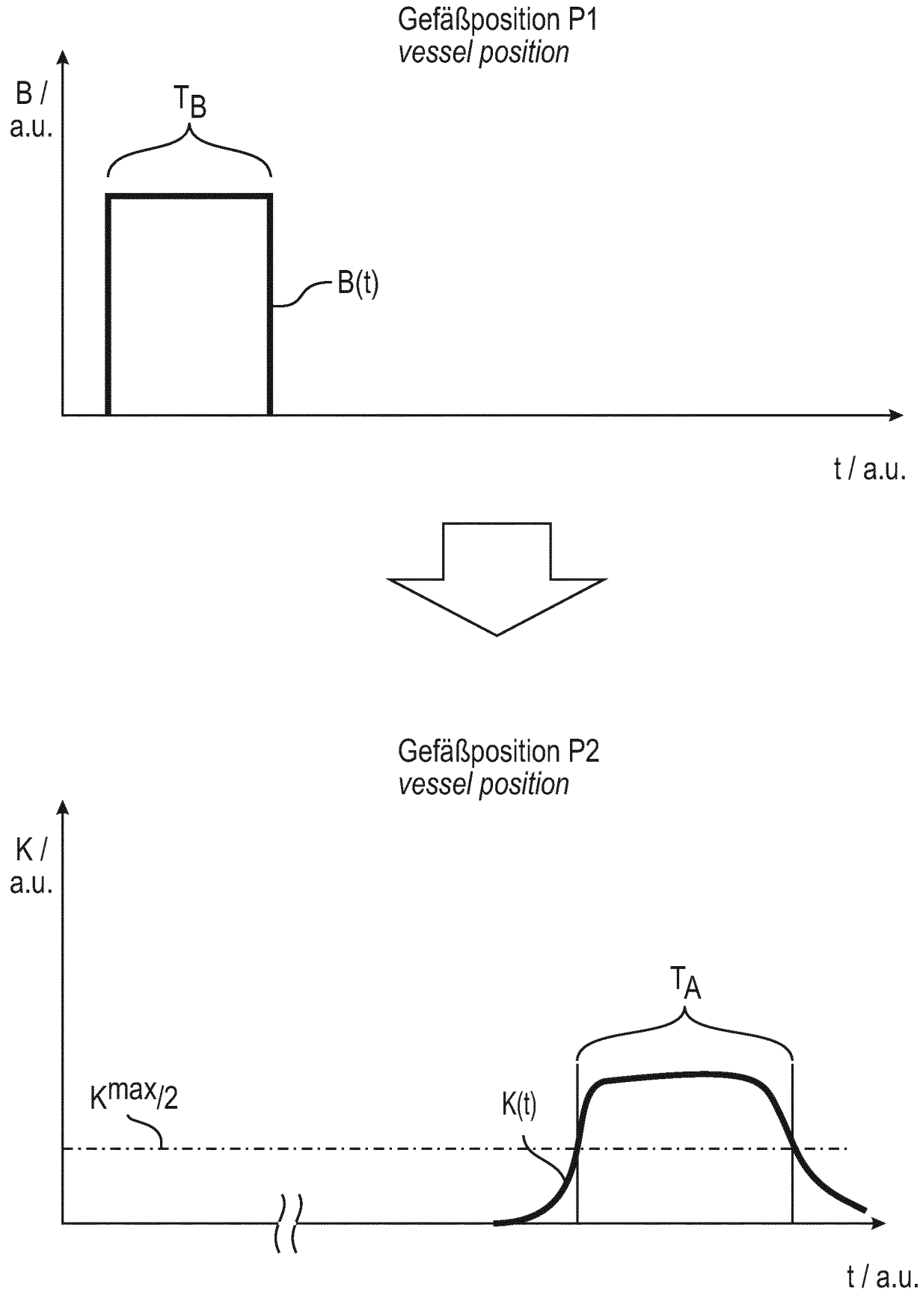
Gefäßposition P1
vessel position
B / a.u.
T_B
B(t)
t / a.u.
Gefäßposition P2
vessel position
K / a.u.
$K^{max}/2$
K(t)
T_A
t / a.u.

FIG 4

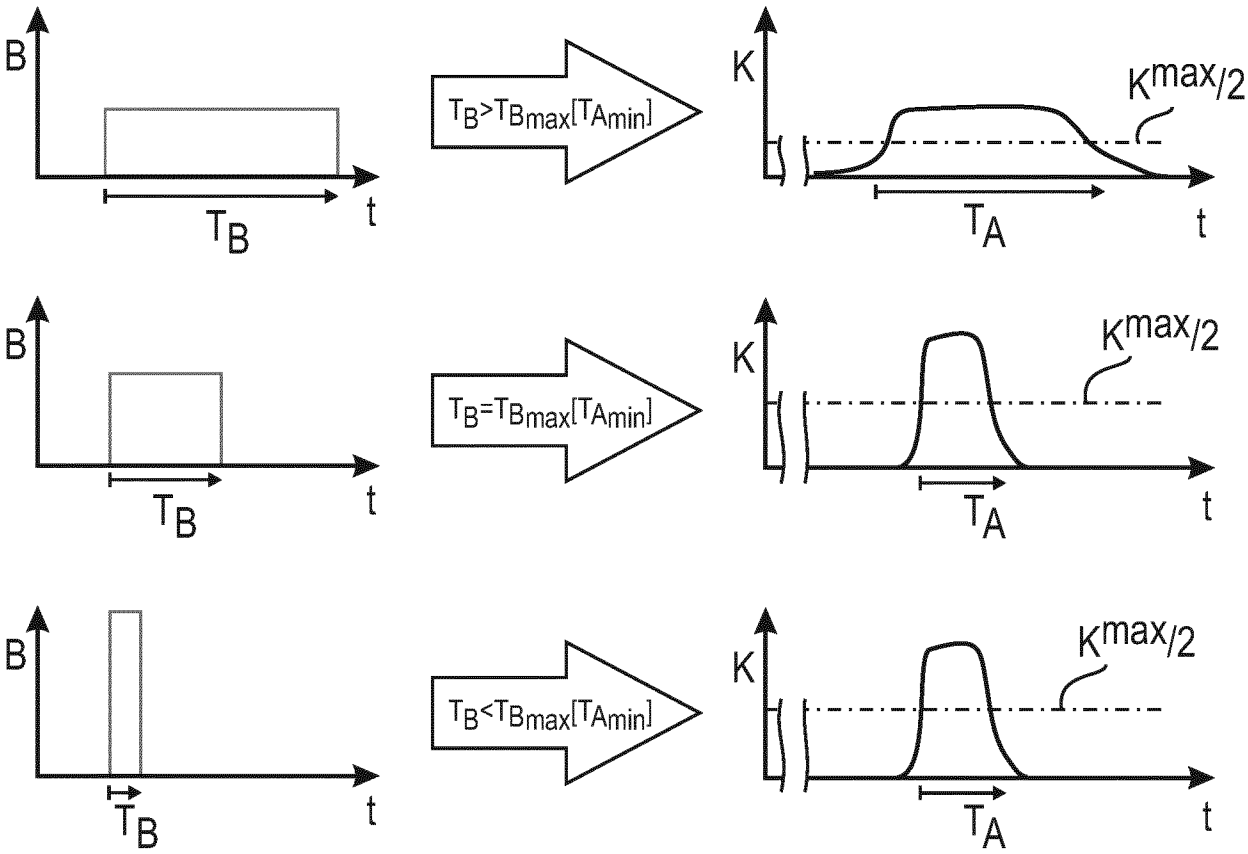
B
t
T_B
$T_B > T_{Bmax}[T_{Amin}]$
$T_B = T_{Bmax}[T_{Amin}]$
$T_B < T_{Bmax}[T_{Amin}]$
K
$K^{max}/2$
T_A

FIG 5

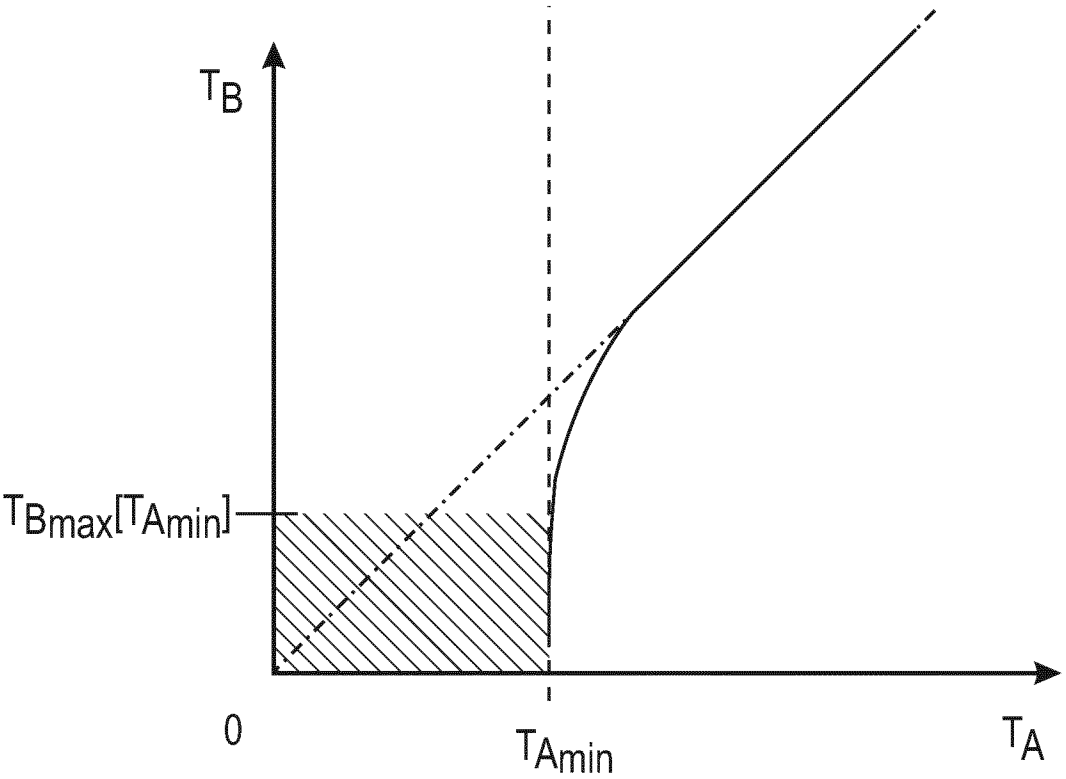
T_B
$T_{Bmax}[T_{Amin}]$
0
T_{Amin}
T_A

FIG 6