Capturing Knowledge for Multimodality Processing:

Interpreting Brain Vascular Imaging and its Description

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Abstract—**Advancements in medical imaging led to increased amount of image data that needs to be post-processed and examined in order to determine a pathology and provide diagnosis. In particular, post-processing and analysis of magnetic resonance images of blood vessels in the brain requires advanced tools capable of representing the vessels network in 3D and eliminating errors caused by image artifacts and noise. An approach based on the knowledge of the anatomy and functions of the brain vasculature is considered. While state-of-the-art tools are designed to evaluate image intensity, the knowledge-based framework can use the information on the underlying vascular structures to map imaging data to ontological representation, thus allowing for annotation possibility and textual description understanding, as well as detect errors and separate them from abnormalities caused by vascular disease.**

Keywords-Ontology; Knowledge Representation; Medical Imaging; Blood vessels; cerebral circulation.

I. INTRODUCTION

The paper proposes using an ontology as the basis of relevant knowledge for the domain. It assembles and neatly arranges, in an online resource that could be open to use by any health professional, all knowledge and experience that is available to an experienced physician “intuitively,” thus upgrading any less experienced medical practitioner’s ability to diagnose and treat the patient. Needless to say, while the ontology is open to any user, an individual patient’s data are duly protected as required by the relevant laws.

For any individual domain, the ontology is an easy and affordable extension of the existing general and previously extended ontology. The extension is implemented semi-automatically, with the computer formatting the entry and *prompting* a moderately trained user for questions about the linguistic meaning of terms. The previous extensions, to the banking industry, information security, and to feelings in general and humor research in particular, all resulted to the addition of under 400 new concepts, usually developed as new branches and leaves under one existing concept (BANK, SECURITY, and FEELING, respectively).

The ontology in our Ontological Semantic Technology approach is much more than a typical government or industry ontology for various areas: those are often an inventory of terms, usually aiming in standardizing them and focusing on objects rather than objects and events, linked with an abundance of properties. It is common for many published ontologies to have hardly any properties beyond subsumption, which establishes the hierarchy.

The standard procedure starts with what was referred to in the 1980s as knowledge engineering that led to the creation of expert systems. The crucial difference is that we are aware of the semantics of the collected material rather than the syntax-oriented and, therefore, failing expert systems. We do have an expert in vascular system among us, so the following sections of the paper were written in the process of conversing with him or drafted by him. But, the standard extension procedure could have started from a well-indexed textbook or reference book. Another significant advantage is that, within our approach, any acquisition is guided by the ontology that, logically and consistently, develops the new branches and leaves where they belong.

The purpose of any ontological extension is to identify all the events and objects in the domain and the multiplicity of properties that link them to each other. The objects and events are the nodes in an ontology, and the links are its named edges. The central concept for this extension is, of course, blood VESSEL.

The paper is organized in the following order: section II introduces blood vessels from a human perspective and describes what a system should know about them; section III describes how this knowledge can be represented for computational purposes; section IV goes further into the details of ontological representations, describing the salient features that are useful for processing. Finally, section V demonstrates what happens when an image is analyzed.

II. BLOOD VESSELS 101: WHAT KNOWLEDGE SHOLD BE CAPTURED

A blood vessel can be characterized by its anatomy and function. In the current clinical practice, clinical decisions are often based on medical images visualizing vascular anatomy, thus neglecting valuable information that could be inferred from functional data. Vessel anatomy can be characterized by its location and geometry, with the former describing whether it is an artery or vein, and where it is located in the circulation. This also defines the “parent” vessel and the branches, i.e., a vessel from which the vessel of interest originated and all vessels emanating from the vessel of interest. Longer vessels, such as an internal carotid artery, are subdivided in segments, in order to precisely locate the regions of interest. The geometry is defined by the diameter, length, and tortuosity of the vessel – these can obviously vary for different segments of the same vessel. The purpose of circulation is to quickly deliver oxygen from the lungs to all the cells of various organs and tissues, thus large vessels delivering blood to a particular region of the body divide into subsequent branches with smaller diameter but larger cumulative area. This typically results in a gradual decrease of the vessel diameter (but not necessarily length!) as we proceed through the circulation. The vessels or their segments located closer to the heart are called "proximal", while those further away are called "distal". It should be noted that this is defined by the vessel relative location and not by the direction of blood flow. The vessels that are located above are called "superior" while those below are called "inferior". Finally, the vessels closer to the front of the body are named "anterior" and those closer to the back are "posterior".

A vessel affected by cardiovascular disease typically has a local change in its diameter, such as an abnormal constriction, named "stenosis" or dilation, named "aneurysm". Medical images showing stenosis may indicate atherosclerotic plaques obstructing blood flow and potentially decreasing the amount of blood delivered to the distal vascular territory supplied by this vessel. An aneurysm of a brain vessel may grow and rupture, causing hemorrhage in the brain.

The functional information can be obtained with advanced images that can either visualize the transport of an injected contrast agent or directly measure blood flow velocities. These characteristics of the vessel include the blood flow rate, the pulsatility of the flow (how much it is changing through the cardiac cycle), the velocity distribution in the vessel or simply the average or maximum velocity, and the pressure drop, i.e., the difference between the pressure at two different points in the vessel. For example, a stenosis resulting in a minimal pressure drop is likely to present less risk than that causing a larger pressure drop, even if both are characterized by the same degree of the vessel's obstruction. In addition, there are numerous flow-derived metrics that can characterize the vessel's function and, in some cases, help with diagnostics and risk stratification of patients. These include wall shear stress -- a frictional force exerted on the vessel wall by flowing blood, flow residence time -- the relative time blood dwells at a given location and other, more complex flow descriptors.

A healthy vessel is characterized by approximately the same or gradually changing diameter and relatively smooth distribution of velocities, faster in the core of the flow and slower near the wall. This also results in a very minimal pressure drop along the vessels and an optimal range of wall shear stress for all arteries of similar size. A diseased artery, affected by a stenosis or aneurysm is characterized by local changes of the diameter and curvature, as well as by complex flow patterns affecting other flow-derived descriptors. A narrowing of the vessel results in a high velocity jet and region of disturbed, slowly recirculated flow. The flow residence time in these disturbed regions is typically increased. These features may cause various image artifacts, such as a loss of signal or insufficient resolution to detect the smaller section of the diseased vessel. An aneurysm is also characterized by disturbed flow with jets and regions of flow recirculation, affecting wall shear stress and flow residence time. This may, in turn, affect the quality of medical images, e.g., cause the loss of MRI (Magnetic Resonance Imaging) signal in regions of stagnant flow which occur in larger aneurysms.

Depending on the size of blood vessel or whether it is affected by disease, the flow through it may be also "Newtonian" or "non-Newtonian". Since blood is not a homogeneous fluid but a suspension of cells in plasma, blood viscosity (resistance to flow) depends on the interactions of these cells. In a vessel that is comparable in size to these cells or in regions of disturbed flow, blood viscosity can increase due to aggregation of cells. In addition, blood may form clots consisting of aggregated cells and cell fragments. Blood clotting is important for preventing leaks through injured regions of the vessel wall. At the same time, a clot formed in a vessel may travel to the smaller vessel downstream and block it, causing a stroke.

It should be mentioned that the vessels are also characterized by the wall thickness and properties. While vessel walls in the brain are typically too thin to be detected with existing imaging modalities, it is crucial to understand their anatomy and function in health and in disease. A vessel wall is composed of three layers with different characteristics and properties. The inner layer, the intima, is a layer of endothelial cells providing a barrier between the flowing blood and stationary tissue. The other two layers, media and adventitia, are composed of elastic tissue reinforced by collagen fibers which determines its elastic properties. A diseased vessel may contain plaques with necrotic (dead) tissues, calcifications and intraplaque hemorrhage. Advanced vessel wall imaging techniques, such as those developed by David Saloner at UC San Francisco [1], aimed at detecting various components of the wall. A healthy wall thickness is typically 10% of the vessel's diameter, while a diseased wall can be either abnormally thin or inflated. While a healthy wall is compliant, and moves corresponding to heart pulse, a diseased wall may become rigid, affecting both the flow and pulse wave propagation.

III. ONTOLOGICAL VIEW

We take a general ontology that we have developed [2] as a reference point. Our general ontology contains concepts and their properties and has been formally described in its crisp [3]-[5] and fuzzy [2], [6], [7] flavors. Here, we will continue with the fuzzy approach, and we will demonstrate that it is most suitable for this domain. As [2] states, given a set of objects D, where D is the disjoint union of D_c (concepts) and D_d (literals), and given its interpretation function $\mathcal{J}$, for every fuzzy concept C, object x is an element of C with some degree $\mathcal{J}[C](x)\rightarrow[0, 1]$; for every relation R, $\mathcal{J}[R](x, y)\subseteq D_c \text{ x } D_c\rightarrow[0, 1]$; for every attribute A; $\mathcal{J}[A](x, a)\subseteq D_c \text{ x } D_d\rightarrow[0, 1]$.

We assume that $x\in C$ if $\mathcal{J}[C](x)\rightarrow(0, 1]$. With this in mind, the following is true for concepts C_1 and C_2:

$\mathcal{J}[C_1\ C_2](x) = \max\{\mathcal{J}[C_1](x), \mathcal{J}[C_2](x)\};$

$\mathcal{J}[\text{and } C_1\ C_2](x) = \min\{\mathcal{J}[C_1](x), \mathcal{J}[C_2](x)\};$

$\mathcal{J}[((C))](x)= \max_{y\in C}\{\mathcal{J}[R](y, x)\};$

$\mathcal{J}[(R(\text{and } C_1\ C_2))](x) = \min\{\mathcal{J}[(C_1)](x), \mathcal{J}[(C_2)](x)\};$

$\mathcal{J}[R(C_1\ C_2)](x) = \max\{\mathcal{J}[R(C_1)](x), \mathcal{J}[R(C_2)](x)\};$

$\mathcal{J}[C_1(R(C_2))](x) = \min\{\mathcal{J}[C_1](x), \mathcal{J}[R(C_2)](x)\}$;

$\mathcal{J}[C(R_1(C_1))(R_2(C_2))](x) =$

$=\min\{\mathcal{J}[C(R_1(C_1))](x), \mathcal{J}[C(R_2(C_2))](x)\}$;

A. Vessel domain ontologies

Many terminological descriptions of blood vessels that resemble ontologies exist today. We take an approach here that an ontology should capture most useful properties of the domain of application, and thus, a hierarchy with a handful of properties is not an ideal ontological representation. With this in mind, lattices of blood vessels' anatomy are a useful starting point.

The second point worth making is that we are only interested in the details of the cerebral vessels, which means that while we cannot completely discard the rest, a special attention is paid to the description of the brain area. Finally, we treat an ontological hierarchy as a good starting point due to its mathematical properties, such as inheritance. We will assume, then, that it is sufficient to describe properties of a parent concept in this paper with a full understanding that they will propagate to the children concepts. We assume that inheritance of properties is carried though IS-A relationship. We also allow transitive and symmetric properties in our representation:

$\forall c_1, c_2 \in C, r_s \in R: c_1(r_s(c_2)) \Leftrightarrow c_2(r_s(c_1))$, where c_1, c_2 are concepts and r_s is a symmetric property;

$\forall c_1, c_2, c_3 \in C, r_t \in R: c_1(r_t(c_2)), c_2(r_t(c_3)) \Rightarrow c_1(r_t(c_3))$, where c_1, c_2, c_3 are concepts and r_t is a transitive property.

We are going to start with anatomical description of the vessel and then continue with its functional characteristics.

B. Anatomical Properties of Blood Vessels

As mentioned before, anatomical characteristics can be described in terms of location and geometry. While the location of the vessel may be reflected in its name, it is still crucial to represent this information mathematically. We thus have the following location properties, all with a domain of the vessel:

- RELATIVE-LOCATION-TO-HEART, with a range of {proximal, distal};
- RELATIVE-VERTICAL-POSITION, with a range of {superior, inferior};
- RELATIVE-FRONTAL-POSITION, with a range of {anterior, posterior};
- RELATIVE-SIDE-POSITION, with a range of {left, right};
- INFLOW-VESSEL, with a range of names of vessels that (blood) flow into a given one;
- OUTFLOW-VESSEL, with a range of names of vessels that (blood) flow out of a given one.

Both INFLOW-VESSEL and OUTFLOW-VESSEL properties are transitive.

Geometry properties can be summarized as follows:

- DIAMETER, with a range of being dependent on a particular vessel, relative to the aorta of that individual;
- LENGTH, with a range of being dependent on a particular vessel, not relative to the aorta;
- TORTUOSITY, with a range of true of false, dependent on a particular patient, rather than on a type of a vessel.

DIAMETER and LENGTH must be greater than zero.

Based on the properties above, the following concepts can be defined:

- STENOSIS: a portion of artery of variable length where diameter of the lumen is decreased relative to the diameter the proximal or distal segment of the same vessel;
- ANEURYSM: a segment of a vessel with a significantly dilated diameter, relative to proximal or distal diameter of the same vessel.

An ANEURYSM has additional properties that a healthy vessel does not need to have, such as:

- diameter of a neck of an aneurysm (NECK-DIAMETER), which is a diameter of the opening between the aneurysm and a parent vessel;
- number of lobes (LOBES-NO), which is a number of separate convex shapes in an aneurysm;
- volume of an aneurysm (VOLUME);
- area of an aneurysm (AREA), measured by wall surface area;
- height of an aneurysm (HEIGHT), which is a maximum distance from the neck to the wall.
- diameter of the aneurysm (DIAMETER), which is the largest dimension between any two points in the aneurysm;
- aneurysm angle (ANGLE), which is an angle between its diameter and flow direction;

The range of all of these additional properties is a rational number. Additionally, two types of aneurysms can be described: a SACCULAR aneurism is an aneurysm that appears on one side of a vessel; and a FUSIFORM, which bulges out on circumference of the vessel. It is possible to create new child concepts for these two types or create a property, reflecting its relative location as a property, TYPE, with the range corresponding to the type names.

C. Functional Properties of Blood Vessels

Functional properties of vessels correspond to properties that are usually captured with advanced imaging methods. These properties, while descriptive of a vessel, may be selectively obtained. However, it should be noted that the values correspond to each voxel of an image, and thus, each vessel is explicitly represented in three dimensional coordinates. The properties that describe the vessels are then spatiotemporal distributions with values in each of the (existing) points in the coordinates, not the properties of vessel as a hole. The properties of interests are:

- blood flow velocity (VELOCITY);
- blood flow rate (FLOW-RATE): exists in a given cross-section, not in a voxel;
- pulsatility of the flow (PULSATILITY): how much it is changing through the cardiac cycle;

- pressure (PRESSURE): pressure measurement at any point in a vessel;
- wall sheer stress (WSS): a frictional force exerted on the vessel wall by flowing blood;
- flow residence time (FRT): the relative time the blood dwells at a given location.

It is tempting to consider mereology (a study of parts and holes) when considering mathematical properties of the descriptions above. However, for the purposes of this paper, it is sufficient to treat each of these points independently, although in reality there is a strong dependence between them.

IV. ACCEPTABLE RANGE OF VALUES

While location features of blood vessels are tedious to construct, there is no mystery to their verification of correctness: any anatomical atlas can be constructed for information as to whether something is correct or not. For example, if one is to describe branches of BASILAR-ARTERY, and fill its location properties, one would describe them as:

- LEFT-ANTERIOR-INFERIOR-CEREBELLAR ARTERY
- RIGHT-ANTERIOR-INFERIOR-CEREBELLAR ARTERY
- LEFT-SUPERIOR-CEREBELLAR ARTERY
- RIGHT-SUPERIOR-CEREBELLAR ARTERY
- LEFT-POSTERIOR-CEREBRAL ARTERY
- RIGHT-POSTERIOR-CEREBRAL ARTERY

Since all of these are branches of the BASILAR-ARTERY, the flow of all of the above vessels would be provided by the BASILAR-ARTERY, and thus, BASILAR-ARTERY is an INFLOW-VESSEL for each of them, and each of them is an OUTFLOW-VESSEL for BASILAR-ARTERY.

A. Geometric Properties of a Concept VESSEL

Selecting the correct range of values of the geometric properties for a given vessel is slightly more complex. We will start with a description of DIAMETER values for a vessel. These values are best described as fuzzy membership functions [8], where a perfect range corresponds to a maximum value of membership function, but then there is a gradual decline in the values that corresponds to less than maximal, yet still acceptable membership value. We will call these acceptable values a HEALTHY fuzzy set. There are some deviations from healthy range, some more severe than others, but, these values should still be physically possible. We will call this an unhealthy range, corresponding to UNHEALTHY fuzzy set. Finally, there will be some values that can only be achieved as a result of a measuring error or an artifact of a method, we will call this set ARTIFACT set. A graphical representation is shown Figure 1.

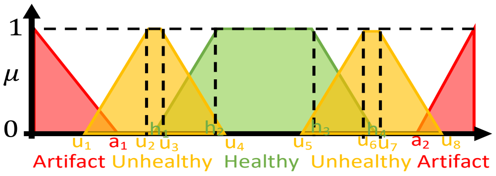

Figure 1. Fuzzy sets as DIAMETER values (sets are not drawn to scale)

HEALTHY = {x, $\mu_{\text{HEALTHY}}(x)$ | x∈X}, where X is all possible values received for a given property.

UNHEALTHY = {x, $\mu_{\text{UNHEALTHY}}(x)$ | x∈X}, where X is all possible values received for a given property.

ARTIFACT = {x, $\mu_{\text{ARTIFACT}}(x)$ | x∈X}, where X is all possible values received for a given property.

$$\mu_{\text{HEALTHY}}(x) = \begin{cases} 0, (x < h1)\ or\ (x > h4) \\ \frac{x-h1}{h2-h1},\ h1 \le x \le h2 \\ 1,\ h2 \le x \le h3 \\ \frac{h4-x}{h4-h3},\ h3 \le x \le h4 \end{cases}$$

By convention, a trapezoidal fuzzy set HEALTHY can be expressed as [h1, h2, h3, h4].

$$\mu_{\text{UNHEALTHY}}(x) = \begin{cases} 0, (x < u1)\ or\ (u4 < x < u5) \\ \frac{x-u1}{u2-u1},\ u1 \le x \le u2 \\ \frac{x-u5}{u6-u5},\ u5 \le x \le u6 \\ 1,\ (u2 \le x \le u3)\ or\ (u6 \le x \le u7) \\ \frac{u4-x}{u4-u3},\ u3 \le x \le u4 \\ \frac{u8-x}{u8-u7},\ u7 \le x \le u8 \end{cases}$$

We will notate UNHEALTHY as [u1, u2, u3, u4] ∪ [u5, u6, u7, u8].

$$\mu_{\text{ARFIFACT}}(x) = \begin{cases} 0, (x < a2)\ or\ (x > a1) \\ \frac{x-a1}{0-a1},\ x \le a1 \\ 1,\ x = a1\ or\ x = a2 \\ \frac{a2-x}{a2},\ a2 \le x \end{cases}$$

The range of acceptable values of inflow vessel have to be propagated to the outflow vessel. The values can be assumed to be the same, unless the inflow vessel is branching out into a number of outflow vessels. In the described example of BASILAR ARTERY, it has 6 branches that serve as its outflow vessels: LEFT-ANTERIOR-INFERIOR-CEREBELLAR ARTERY, RIGHT-ANTERIOR-INFERIOR-CEREBELLAR ARTERY, LEFT-SUPERIOR-CEREBELLAR ARTERY, RIGHT-SUPERIOR-CEREBELLAR ARTERY, LEFT-POSTERIOR-CEREBRAL ARTERY, RIGHT-POSTERIOR-CEREBRAL ARTERY. Common sense dictates that the diameter of these arteries should not be the same, and thus it is important to provide a model that is close to a real world. We will take a previously defined HEALTHY fuzzy set [h1, h2, h3, h4] as a starting point. We will assume that each of the branches *i* have their own HEALTHY_i [$h1_i$, $h2_i$, $h3_i$, $h4_i$] fuzzy set such that for any branch *i*, $h1_i$<h1, $h2_i$<h2 $h3_i$<h3, $h4_i$<h4. Moreover,

$$(h2 - h1)^2 \le \sum_i (h2_i - h1_i)^2 \approx 1.2(h2 - h1)^2.$$

Thus, the DIAMETER values of the branching vessels can be verified compared to the parent vessel.

LENGTH and TORTUOSITY values of vessel are independent on factors other than the actual vessel. While the LENGTH still varies from person to person, and should be described as a fuzzy number, there are no other dependencies other than that of a TORTUOSITY.

B. Geometric Properties of the Concept ANEURYSM

Let us now consider the properties of SACCULAR and FUSIFORM aneurysms. As stated earlier, the difference between these types is that the former appears to the side of the vessel, and the latter to bulges out on the circumference. Most properties defined for an aneurism are applicable for both types, however some differences should be pointed out.

The first properties, NECK-DIAMETER, describes an opening between a parent vessel and an aneurysm. It follows from a definition of FUSIFORM aneurysm that its NECK-DIAMETER could be equal to the diameter of the vessel, whoever this parameter is not typically used in medical practice. Similarly, HEIGHT is not of much use for FUSIFORM aneurysm, although, technically, could be defined. A NECK-DIAMETER and HEIGHT of the SACCULAR aneurysm can vary and thus are useful parameters.

Number of lobes is typically applicable to SACCULAR aneurysms, but there is no reason why it would not be applicable for both. VOLUME and AREA are useful parameters for both types, and can vary in values. A DIAMETER of an aneurism should not be confused with a DIAMETER of a vessel. Since DIAMETER of an aneurysm is defined as a largest distance between any two points of an aneurysm, it is always greater than the vessel DIAMETER for FUSIFORM aneurysms. However, it is possible that it could be greater or less than the vessel DIAMETER for SACCULAR aneurysms.

With these restrictions in mind, the next section will demonstrate how an ontology could be used to annotate an image.

V. INTERPRETING AN IMAGE

Figure 2 shows an image used by [9] as an example of image segmentation errors. While it is possible to assume from this picture that an aneurysm is connected to two arteries, the ontology would reject such interpretation.

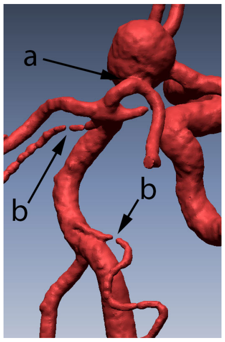

Figure 2. Image segmentation errors [9]: separate blood vessels are blended together a) cerebral aneurysm pressing on posterior cerebral artery; b) two disconnected arteries.

Before we get to a reasoning step, however, let us consider information presented to us. There are 8 vessels that can be identified “under” the aneurysm in this image. Let us start at the bottom of the figure, with the large vessel at the center, let us identify it as v_1. There is another vessel on the left of v_1, let us call it v_2, that merges with v_1 to form v_3 (in Figure 2, v_3 actually looks like a continuation of v_1). A fourth vessel, v_4, branches off v_3. Since we know that a diameter of a vessel has to be greater than 0, v_4 should not have an empty segment next to the right b-arrow. A similar error is seen where another vessel, v_5, branches off v_3. Three more vessels branch off of v_3, we will call them v_6, v_7, v_8. The following can be observed:

- v_1 and v_2 flow into v_3, which means that
    - ○ v_1 and v_2 are INFLOW-VESSELS for v_3,
    - ○ and v_3 is an OUTFLOW-VESSEL for v_1 and v_3
- v_3 flows into v_4, which means that
    - ○ v_3 is an INFLOW-VESSEL for v_4,
    - ○ and v_4 is an OUTFLOW-VESSEL from v_3;
- v_3 flows into v_5, v_6, v_7, v_8, which mean that
    - ○ v_3 is an INFLOW-VESSEL for v_5, v_6, v_7, v_8;
    - ○ and v_5, v_6, v_7, v_8 are OUTFLOW-VESSELS for v_3
- since INFLOW-VESSEL and OUTFLOW-VESSEL properties are transitive, we can conclude that
    - ○ v_1 and v_2 are INFLOW-VESSELS for v_4, v_5, v_6, v_7, v_8
    - ○ v_4, v_5, v_6, v_7, v_8 are OUTFLOW VESSELS for v_1 and v_2

Looking at the location properties, and comparing them with possible ontological interpretations, v_1 corresponds to LEFT-VERTBRAL-ARTERY, v_2 corresponds to RIGHT-VERTBRAL-ARTERY, v_3 corresponds to BASILAR-ARTERY, v_4 corresponds to POSTERIOR-INFERIOR-CEREBELLAR-ARTERY, v_5 and v_6 to LEFT and RIGHT SUPERIOR CEREBELLAR ARTERIES, v_7 and v_8 to LEFT and RIGHT POSTERIOR CEREBRAL ARTERIES.

Let us now address the geometric properties. All of these vessels have TORTUOSITY value of false, with the exception of v_4. The diameter calculation for healthy vessels should be as follows:

$$1.2 * \text{DIAMETER (BASILAR-ARTERY)}^2 \approx$$
$$\approx \text{DIAMETER(RIGHT-POSTERIOR-CEREBRAL-ARTERY)}^2 +$$
$$+ \text{DIAMETER (LEFT-POSTERIOR-CEREBRAL-ARTERY)}^2$$

While the total area of the branches should exceed that of the parent vessel, an abrupt increase in the area could make the vessel unhealthy, at the flow would separate from the wall resulting in a swirl or recirculation.

Finally, there is an aneurysm that is seemingly located on a side of v_8, thus it is a SACCULAR aneurysm. Its DIAMETER is considerably greater than the DIAMETER of v_8. Its NECK-DIAMETER appears to be quite large, and a person not familiar with brain vessel anatomy may not detect that it is also connected to another, yet unlabeled, vessel. A person familiar with anatomy (or a computer program?) may detect the connection. It follows that this SACCULAR aneurysm is connected on its two sides to two arteries, which is not possible according to our current definition. Further analysis could indicate that even if it was possible for an aneurism to be connected to more than one vessel, there is no blood-flow either from v_8 to the unlabeled artery with aneurysm or from it to v_8. Such determination can be done through transitive properties INFLOW-VESSEL and OUTFLOW-VESSEL, thus flagging the imaging error, which, in this case, is due to an artifact. In reality, the aneurysm is supplied by the anterior cerebral artery; the large aneurysm size resulted in its wall contacting the v_8, without any flow exchange.

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VI. CONCLUSION

The knowledge-based approach for visualization and analysis of MR angiography data was formulated and verified on an example dataset containing cerebral aneurysm. This approach can help in reliable representation of the vascular anatomy in 3D, thus helping in flow analysis and treatment planning. Moreover, the knowledge-based methods can be invaluable for automatic screening of large image datasets in order to flag pathologies that require human intervention.

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