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Arterial patterns of the human upper limb: update of anatomical variations and embryological development

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SUMMARY

The arterial pattern of the upper limb is one of the systems that shows a large number of variations in the adult human body. However, embryological explanations for these variations have been subject to much debate. Recent studies have provided a new classification of the arterial variations in the upper limb, as well as a new model of arterial development based on the study of large anatomical and embryological samples.

In the present article, we offer a review of the embryological and morphological data obtained in adults, contrasting them with those found in a new sample of adult material.

Key words: Arteries – Upper limb – Arm – Forearm – Variations – Embryology

INTRODUCTION

Arterial variations in the upper limb have been the subject of much controversy since Von Haller mentioned their existence for the first time in the eighteenth century (Von Haller, 1813).

On one hand, the objectives of the different studies differed widely. Whereas studies based on large samples focused mainly on presenting data about the incidence of the different variant patterns, although frequently omitting many morphological details –such as the origin, course, relationships, incidence by sex and side–, other studies based on casual findings provided detailed morphological descriptions, but failed to provide data of statistical value.

On the other hand, a terminological controversy arose since some authors adopted a topographical criterion to name the arteries –brachial and antebrachial– while other authors believed that the arterial variations should be considered as individual entities, therefore adopting a single name regardless of the topographical area.

Furthermore, to explain the existence of arterial variations in the upper limb of the adult, several hypotheses have been advanced based on findings from adult corpses, taking into account that these variations represent a transitory embryonic stage (Moncayo-Marques, 1941; Wankoff, 1961, 1962; Kadanoff and Balkansky, 1966; Poteat, 1986; Rodríguez-Baeza et al., 1995; Fadel and Amonoo-Kuofi, 1996; Anagnostopoulou and Venieratos, 1999; Nakatani et al., 1999). However, few embryological studies exist, probably due to the difficulty involved in obtaining human embryonic material.

The largest classical embryological studies are those of DeVriese (1902) and Müller (1903). Nevertheless, the accepted theory until now has been that of Singer (1933), based on findings from adult corpses and the embryological data published in a Congress' Proceedings (Senior, 1926). Singer (1933) stated that the adult pattern develops from a main axial trunk, which extends from the axilla to the fingers and represents the brachial and interosseous artery. The different arteries arise via sprouting angiogenesis: first the

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median artery, then the ulnar, then the superficial brachial and, finally, an anastomosis at elbow level between the brachial and superficial brachial arteries, which eventually become the initial part of the radial artery, whereas the proximal segment regresses to form the definitive adult pattern (Fig. 1).

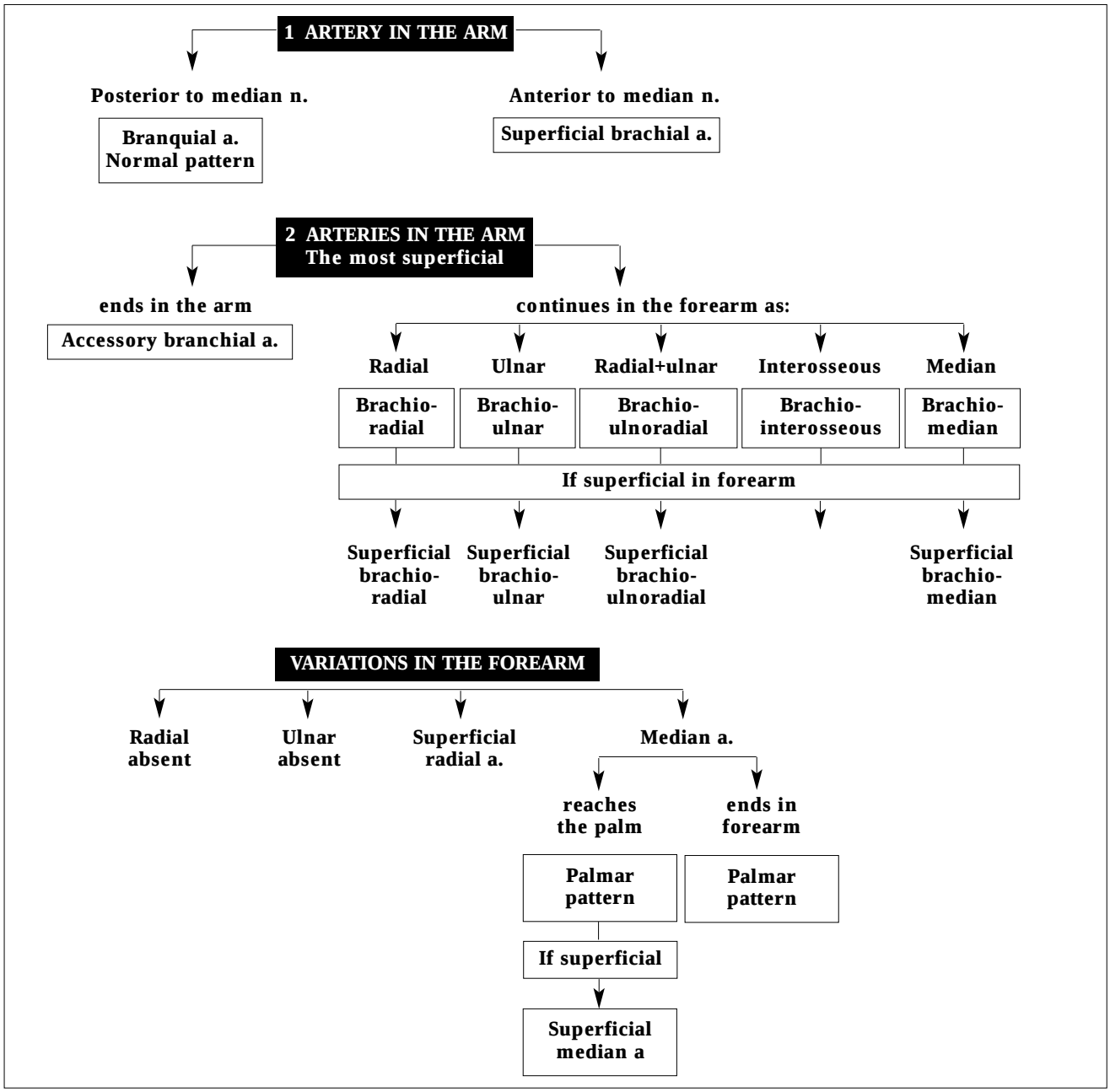
This theory was able to explain those cases in which the radial artery originated above the elbow level, but was unable to explain other variations; for example, an ulnar artery arising above the elbow level (Quain, 1844).

The objective of this review is to offer not only an overview of the latest studies concerning the morphology of the arterial patterns in human adults (Wood et al., 1997; Sañudo et al., 1998; Rodríguez-Niedenführ et al., 1999, 2000, 2001a), but also the results of a new sample of 48 corpses, forming an overall sample of 240 (480 arms). The embryological theories about the development of the arterial pattern and its variations are also reviewed (Rodríguez-Niedenführ et al., 2001b).

THE TERMINOLOGICAL PROBLEM

Some authors have applied a topographical criterion that names the arteries regionally. Thus, a second artery in the arm was termed the brachialis superficialis, but once it crossed the elbow, it was re-named based on its course; either radial, ulnar, superficial ulnar or interosseous (Adachi, 1928; Wankoff, 1962;

Table 1.- Proposed terminology following the criteria of Barkow (1869) and completed in our recent study (Rodríguez-Niedenführ et al., 2001a).



Skopakoff, 1959). Accordingly, the brachialis superficialis and the variations of the forearm arteries were analysed separately, generating –first– an overlapping of the results since the information was repeated both in the chapters of arm variations and forearm variations and –secondly– omitting some important information (Quain, 1844; Adachi, 1928; Skopakoff, 1959). Thus, when the origin of the brachialis superficialis was analyzed, its continuation in the forearm was omitted (Skopakoff, 1959) and when a variant artery was detected in the forearm, no detailed description of its origin was provided.

In later attempts to simplify and unify criteria, subsequent authors considered the variant artery as a complete entity in the arm and forearm, therefore maintaining the same name both in the arm and forearm (McCormack et al., 1953). Accordingly, the information about the origin of the artery in the arm, as well as its course in the forearm, was considered and no overlapping of results occurred. The authors proposed different terminologies, such as superficial radial, superficial ulnar, high origin of the radial or high origin of ulnar, but these were considered improper names because there are no such radial or ulnar regions in the arm (Schwalbe, 1898).

We propose a simple terminology that, following the criteria of Barkow (1869), unifies the topographical criteria (Adachi, 1928; Skopakoff, 1959) and considers the arterial variation as a complete entity throughout its course, but does not use improper names for referring to the vessel when it courses in different regions (McCormack et al., 1953). Based on this criterion and terminology, we have unified previous classifications and subclassifications, which are summarized in Table 1.

INCIDENCE OF ARTERIAL VARIATIONS

It is important to note that careful analysis of arterial variations with homogeneous criteria over the years has allowed us to confirm that they appear every year with very similar incidences.

The overall incidences of arterial variations observed in the arm and forearm are shown in Table 2.

MORPHOLOGY OF ARTERIAL VARIATIONS IN HUMAN EMBRYOS AND ADULT UPPER LIMBS

For clarify in the morphological description, this has been split into three sections dedicated to variations located exclusively in the arm, arm and forearm, and forearm and hand.

1. Variations located exclusively in the arm

Two variations are reported: the superficial brachial artery and the accessory brachial artery (Table 2).

The *superficial brachial artery* represents a brachial artery, which instead of coursing deep to the median nerve runs in front of it after adopting its superficial course. This variation does not present any further deviation from the norm and at the elbow it branches into the forearm arteries. This variation was observed in 4.8% of cases (Table 2).

The *accessory brachial artery* represents a second artery in the arm that originates from the brachial or axillary arteries and rejoins the brachial artery in the distal third of the arm before the latter divides into the usual forearm arteries (Quain 1844; McCormack et al., 1953;

Table 2.- Arterial variations observed in this study and previous adult and embryo based samples (Rodríguez-Niedenführ et al., 1999, 2001b)

	Embryo	Adult
Arm		
Superficial brachial	7.7% (13/168)	4.8% (23/480)
Accessory brachial	0.7% (1/168)	0.2% (1/480)
Arm & Forearm		
Brachioradial	14% (21/150)	14.2% (68/480)
Superficial brachioradial	<0.7% (<1/150)	<0.2% (<1/480)
Brachioulnar	<0.7% (<1/150)	0.2% (1/480)
Superficial brachioulnar	4.7% (7/150)	3.75% (18/480)
Brachioulnoradial	-	-
Superficial brachioulnoradial	0.7% (1/150)	0.6% (3/480)
Brachiomedian	-	-
Superficial brachiomedian	0.7% (1/150)	<0.2% (<1/480)
Brachiointerosseous	<0.7% (<1/150)	<0.2% (<1/480)
Forearm		
Median (palmar pattern)	18.7% (28/150)	12% (29/240)
Superficial median	<0.7% (<1/150)	<0.2% (<1/480)
Superficial radial	<0.7% (<1/150)	0.4% (2/480)
Radial absent	<0.7% (<1/150)	<0.2% (<1/480)
Ulnar absent	<0.7% (<1/150)	<0.2% (<1/480)

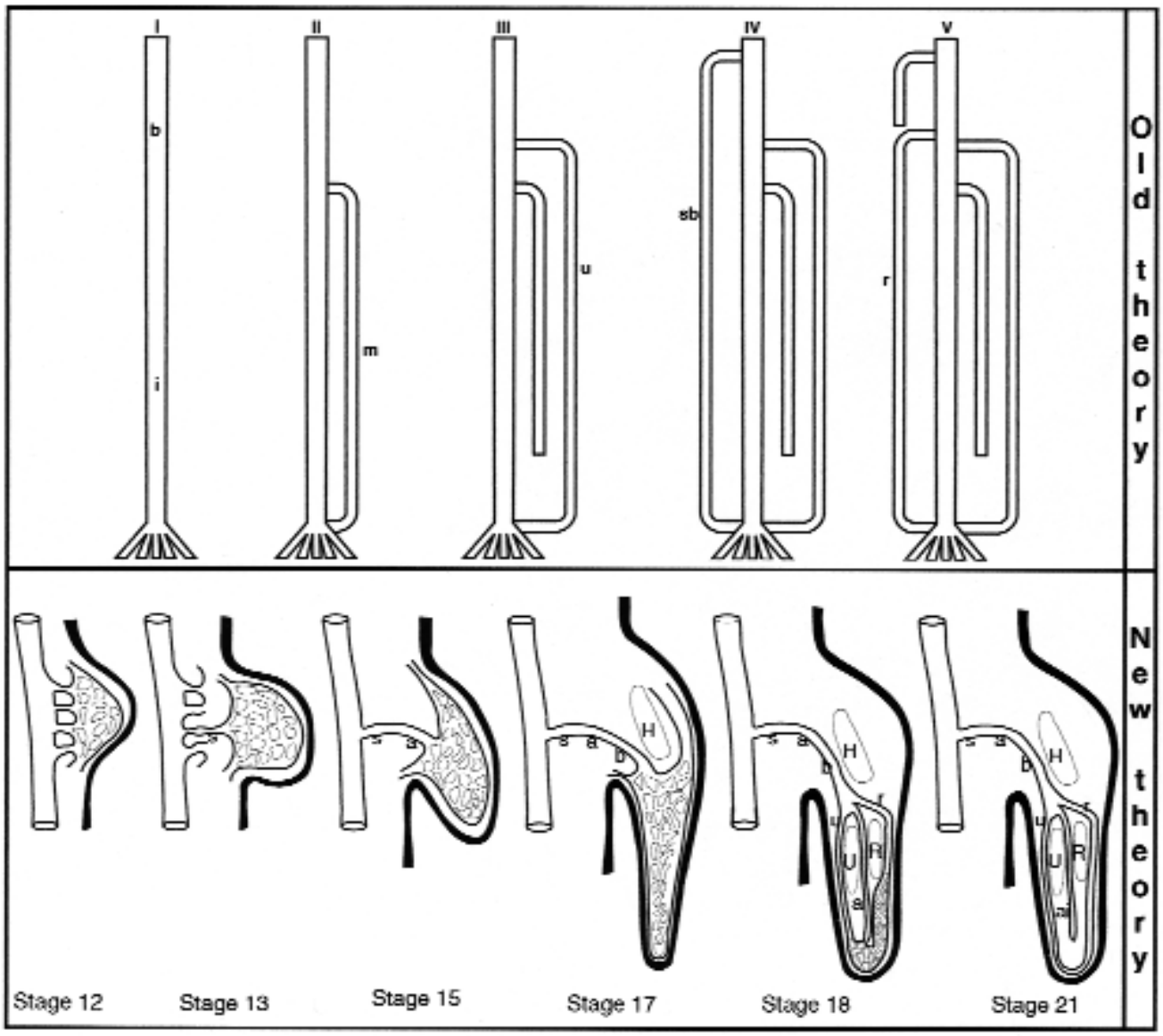


Figure 1. Comparison of the proposed theories about the development of the arterial patterns in the human upper limb. The old theory is redrawn after Singer (1933) and the new proposed theory is based on our study (Rodríguez-Niedenführ et al., 2001b).

Keen, 1961; Rodríguez-Niedenführ et al., 2001a,b).

2. Arterial variations located along the arm and forearm

The arteries addressed here originate in the arm and continue in the forearm as either the radial, ulnar, interosseous, median or radial and ulnar arteries, and are respectively named *brachioradial* (Fig. 2a), *brachioulnar, brachiointerosseous, brachiomedian* or *brachioulnoradial.*

The term superficial is added if the course is inside the superficial fascia; thus, the brachioradial will be a superficial brachioradial if it courses over the tendons delimiting the snuff box and the brachioulnar, brachioulnoradial and the brachiomedian will be named superficial brachioulnar (Fig. 2b), superficial brachioulnoradial (Fig. 2c) or superficial brachiomedian if they course over the forearm flexor muscles (Table 1).

The brachioradial artery is the most frequent one with an incidence of 14%, followed by the other patterns stated in Table 2. Although we have presented some other possible variations in the terminology, no such cases have been yet reported (brachioulnoradial, brachiomedian).

This group of variations has been shown to be the most frequent variations in both the arm and forearm. No statistically significant differences were observed between male and female nor left and right sides, the unilateral appearance being more frequent than the bilateral.

The commonest morphological details of the artery in the arm were as follows. It originated most frequently from the upper third of the brachial artery (Fig. 2a); coursing superficial to the median nerve (Figs 2a, 2c) but deep to the brachial fascia. At the elbow level they most frequently passed behind the bicipital aponeurosis (Fig. 2c) and did not usually anastomose with

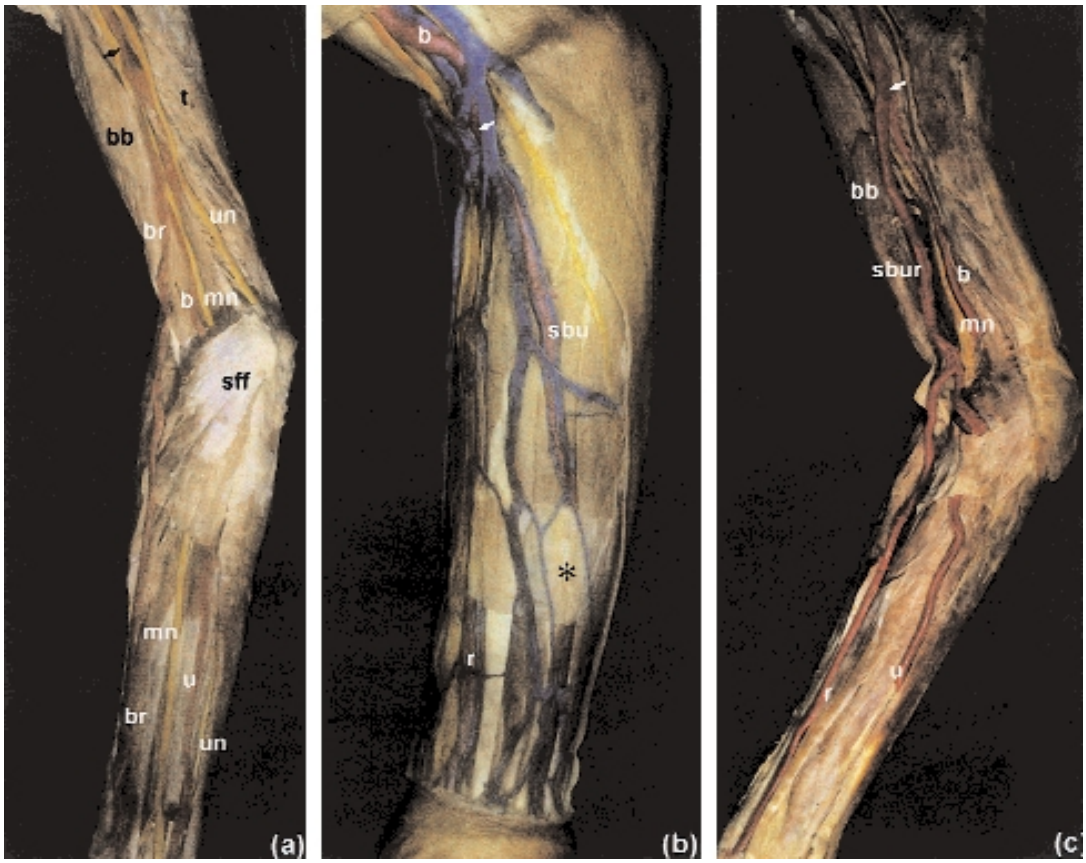


Figure 2. Arterial variations affecting both arm and forearm. (**a**) brachioradial (br); (**b**) superficial brachioulnar (sbu), (**c**) superficial brachioulnoradial (sbur). The arrows indicate the origin of the variation.
Bb: biceps brachii muscle; t: triceps brachii muscle; sff: superficial forearm flexor muscles; r: radial artery; u: ulnar artery; b: brachial artery; mn: median nerve; un: ulnar nerve.

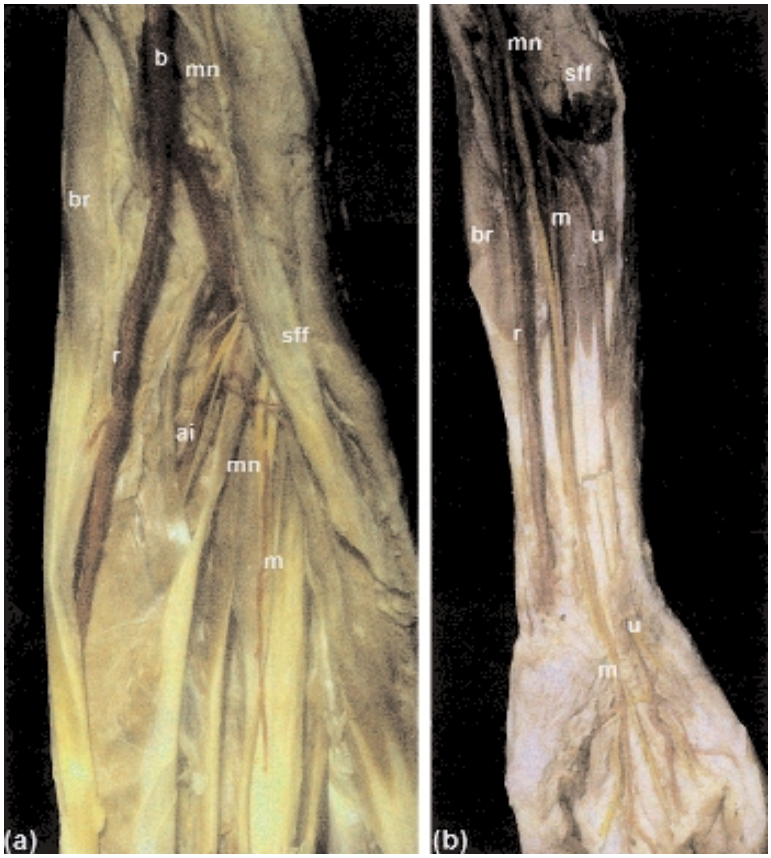


Figure 3. Arterial variations affecting only the forearm: median artery (m). (**a**) antebrachial pattern (note that it is not considered variations but it is included for comparison); (**b**) palmar pattern. r: radial artery; u: ulnar artery; b: brachial artery; ai: anterior interosseous artery; mn: median nerve; un: ulnar nerve; sff: superficial forearm flexor muscles; br: brachioradialis muscle.

the normal brachial artery. In the forearm they coursed deep to the fascia (Fig. 2b) and reached their usual positions –either radial, ulnar, interosseus or median– at different levels (Rodríguez-Niedenführ et al., 2001a).

The anastomosis at elbow level showed different features related to its morphology (sling-like loop or rectilinear form), calibre (large or slender), length (long or short), relationships with the bicipital tendon (in front of or behind it) and origin of the recurrent radial artery (originating or not from the anastomosis). These features were analyzed in detail in a recent study (Rodríguez-Niedenführ et al., 2000) and since they are not the most frequent ones, their discussion is omitted here.

Finally, there are two noteworthy cases in which the superficial brachioradial or the superficial brachioulnar artery coexists in the forearm respectively with the normal radial or ulnar artery and which have been described as a duplication of either the radial (Kadanoff and Balkansky, 1966) or ulnar arteries (Gruber, 1867; Rodriguez-Niedenführ et al., 2001b).

3. Arterial variations located exclusively in the forearm

The *median artery* has been shown to present two different patterns (Figs. 3a,b): the antebrachial pattern (Fig. 3a) ending in the forearm and the palmar one (Fig. 3b) reaching the palm to supply the fingers (Rodríguez-Niedenführ et al., 1999). The antebrachial pattern, due to its high incidence in adult forearms (76%), may be considered as a normal feature rather than as a variation and was therefore not analysed in the embryonic sample, although observed (Rodríguez-Niedenführ et al., 2001b). In contrast, the palmar pattern, appeared with a lower incidence in 12% of adult forearms (Rodríguez-Niedenführ et al., 1999) or in 18.7% of the embryonic forearms (Rodríguez-Niedenführ et al., 2001b) and is considered a variation.

The *superficial median artery* has been reported with an incidence of 1% (Lippert and Pabst, 1985; Nakatani et al., 1999) but was not found in our studies nor in previous others based on large samples (McCormack et al., 1953) or human embryos (Rodríguez-Niedenführ et al., 2001b).

The *superficial radial artery* is a radial artery coursing over the tendons defining the snuff box. This is a rare finding with an incidence around 0.4% of the adult upper limbs (Table 2) and not described in human embryos (Rodríguez-Niedenführ et al., 2001b). It may adopt its superficial course at different levels of the forearm (Schwalbe, 1898; Breme, 1899; Adachi 1928; McCormack et al., 1953; Keen, 1961; Loetzke and Kleinau, 1968; Sachs, 1987; Wood et al., 1997), the distal superficial course being considered the most frequent (Adachi, 1928; McCormack et al., 1953).

The *absence of the radial artery* has been rarely reported (Charles, 1894; Schwalbe, 1898; Kadanoff and Balkansky, 1966; Poteat, 1986) with an estimated incidence lower than 0.2% (Table 2). In those cases, the radial blood supply territory was provided by the anterior interosseous (Gruber, 1864; Poteat, 1986; Kadanoff and Balkansky, 1966) or the median artery (Schwalbe, 1898).

The *absence of the ulnar artery* is even rarer than that of the radial artery. Not even studies based on very large samples did found it (Gruber 1867; McCormack et al., 1953; Wankoff, 1962). In the available literature there are only three reported cases in which the ulnar artery ended as the ulnar recurrent and interosseous branches, a large median artery (Calori, 1868; Bankart et al., 1869) or the radial and interosseous arteries compensating this absence (Nunoo-Mensah, 1998).

Normal development

It was observed that formation of the arterial system in the upper limb takes place as a dual process. An initial capillary plexus originating from the dorsal aorta enters the limb bud during stage 12 when the limb bud begins its outgrowth (Fig. 1). This plexus develops at the same rate as the limb. At stage 13, the capillary plexus begins a maturation process involving the enlargement and differentiation of selected canals. This remodelling process starts in the aorta and continues in a proximal to distal sequence. By stage 15 the differentiation has reached the subclavian and axillary arteries, by stage 17 the brachial artery as far as the elbow, by stage 18 the forearm arteries except for the distal part of the radial, and finally by stage 21 the whole arterial pattern is present in its definitive morphology (Rodríguez-Niedenführ et al., 2001b).

Embryological justification of the existence of arterial variations in the adult upper limb

Based on our results (Rodríguez-Niedenführ et al., 2001b), injection studies on animal embryos (Wollard, 1922; Feinberg and Noden, 1991; Aizawa et al., 1999) and experimental data which showed that when an endothelial tube gets a muscular coating it looses its remodelling ability (Benjamin et al., 1998), we proposed that the sprouting theory described in many of the embryological and anatomical textbooks and reproduced in Figure 1 was obsolete (Lippert and Pabst, 1985; O'Rahilly and Müller, 1992; Schmidt

and Lanz, 1992; Williams, 1995; Larsen, 1993; Carlson, 1999). The new findings suggest that the arterial pattern of the upper limb develops from an initial capillary plexus by a proximal to distal differentiation (in the forearm with a posterior-anterior polaritiy) due to the maintenance, enlargement and differentiation of certain capillary vessels, and the regression of others (Fig. 1). It is suggested that the persistence, enlargement and differentiation of capillaries forming the initial capillary plexus, which would normally remain in a capillary state or even regress, gives rise to arterial variations of the definitive arterial pattern, rather than the sprouting of aberrant vessels (Singer, 1933; Lippert and Pabst, 1985; O'Rahilly and Müller, 1992; Schmidt and Lanz, 1992; Larsen, 1993; Williams, 1995; Carlson, 1999).

The establishment of the superficial brachial, accessory brachial and the brachial part of those variations affecting the arm and forearm must be determined before stage 17 as then, the arteries until the elbow would have already got a definitive morphology of its wall and no further remodelling would be possible. The variations affecting the forearm arteries as well as the antebrachial part of those variations affecting the arm and forearm, have to be established before stage 18 as then the forearm arteries have got their definitive wall morphology except the distal part of the radial. The superficial radial and the distal part of the superficial brachioradial arteries would be determined before stage 21 when they get their definitive morphology (Fig. 1).

Clinical importance

The arterial variations of the upper limb have been implicated in different clinical situations. The brachioradial and superficial brachioulnar arteries have been encountered during elevation of the radial forearm flap (Fatah et al., 1985; Thoma and Young, 1992; Heden and Gylbert, 1990; Funk et al., 1995; Yuksel et al., 1999). Furthermore, the superficial brachioulnar artery has also been suggested as a basis for a skin flap (Devansh, 1996). Possible intra-arterial injection of drugs due to the proximity of normal vein puncture sites has also been reported (Cohen, 1948; Hazlett, 1949; Deligonul et al., 1988) as well as possible arteriographic misinterpretations when the contrast dye is injected distal to the origin of these variant arteries (Keller et al., 1980; Karlsson and Niechajev, 1982; Uglietta and Kadir, 1989). The existence of a superficial radial artery implies the absence of the normal radial pulse at wrist level (Sachs, 1987; Diz et al., 1998). It has also been reported to produce problems in cannulation for operation monitoring (Diz et al., 1998) and as a symptomatic presence that required surgical treatment (Brown et al., 1999). Finally, in a recently reported clinical case, the absence of the ulnar artery was responsible for hand ischaemia after radial artery grafting for coronary bypass (Nunoo-Mensah, 1998).

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