1 Introduction

The human finger is a complex structure with a variety of functions. It is highly adaptive to environmental changes in temperature and posture as well as other physical and/or emotional stimuli. The functional and morphological aspects of digital circulation are still inadequately understood after more than 100 years of study.

The circulation of the fingers has some unique characteristics. In the fingers the total tissue volume is dominated by that of the skin. Only a small fraction of this tissue volume is muscle tissue. Thus, up to 95 per cent of the total blood flow may pass through the skin (Porter and Swain, 1986). It is well known that the hands play an important role in the heat exchange of the human body. Arteriovenous anastomoses (AV-shunts) through which blood is shunted from the arterial to the venous side occur in great numbers. The flow through these shunts is controlled by vasoconstrictor activity in the sympathetic nervous system. At high environmental temperatures most of the finger blood flow passes through the AV-shunts. Burton (1939) demonstrated the variability and sensitivity of finger blood flow adaptation in response to thermal changes.

The study of digital circulation is of considerable interest because it can help us to understand physiological and pathological changes in the peripheral circulatory system.

Recent advances in vascular surgery and pharmacological treatment of circulatory disorders have emphasised the need for improved methods of assessing the digital circulation. The following subjects in connection with finger blood supply are of particular importance in the recent literature:

- Raynaud's phenomenon
- Ischaemic conditions
- Effect of smoking
- Effect of cooling
- Surgery
- Vibration effects
- Sports medicine

The methods of measurement used in these studies are all comparatively simple and relatively easy to apply. Each method has its own advantages and disadvantages. The particular circulatory problem under study seems to have guided most authors in selecting an appropriate method. For a complete survey of existing methods the reader is referred to a review article by Porter and Swain (1986). Here only short summaries are given.

Venous occlusion plethysmography using mercury strain-gauge (Whitney, 1953) and air-filled volume plethysmography as volume indicators (Windsor, 1957) are the most commonly used methods so far. Heat flow transducers including calorimetric methods have been used to study basic circulatory phenomena in the finger (Jepson, 1954; Arab, 1965). These methods are less suitable for
clinical use because of their need for standardised conditions. The laser Doppler method measures the flux of blood in the skin down to a depth of approximately 1 mm (ÖBERG et al., 1983). The Doppler methods offer ways of continuously measuring finger and skin blood flow.

So far only a few studies (BASHOUR and ELLWOOD JONES, 1965; MONTGOMERY, 1976) have compared the established occlusion plethysmography method with the less well known impedance variant. Comparisons of the two methods under new experimental conditions are justified to evaluate possible sources of inaccuracy. It is also of interest to study digital circulation by using the laser Doppler method. The reason is that this method only measures skin blood flow down to approximately 1 mm of the skin. Because finger blood flow is predominantly skin blood flow, this method holds promise as a useful addition to the already existing finger blood flow methods. This is especially true because it estimates the flux of red blood cells not only in the capillaries but also in the rest of the tissue, including the arteriovenous anastomoses.

The position of the fingers relative to the heart level during blood flow studies seems to be a forgotten variable when standardising the measurements of circulatory disorders. Standardisation of temperature, humidity, food intake and smoking seems to have been well taken care of. However, variations in position can introduce substantial changes in blood flow, thereby unnecessarily increasing the scattering of data. Variation in position can also be used as a well reproducible stimulus for finger blood flow and blood volume studies.

The aim of this paper is twofold:

(a) To compare venous occlusion plethysmography with the less well established method of impedance plethysmography and laser Doppler flowmetry in studies of digital blood flow.

(b) To study the effect of position on finger blood flow and volume.

2 Materials and methods

Finger blood flow was measured in ten healthy subjects, six males and four females between the ages of 20 and 43 years (mean: 28.4 years, SD: 8.17). The subjects rested for 30 min before the measurements were taken. The room temperature was kept constant in the range 20-22°C. The subjects were asked to refrain from food intake and smoking 4 h before the measurements. Light clothing (T-shirt and jogging shorts) were worn by all subjects during the experiments. No tight parts could hinder motion of the arms or obstruct blood flow.

During the experiments the subjects were sitting in a comfortable chair with the left forearm in a horizontal position and supported by a shelf. The levels of the arm, hand and finger were arranged in relation to the heart level (level II). Level 1 was 30 cm below heart level and levels III and IV were 30 and 60 cm, respectively, above heart level. During the measurements at each level the arm, hand and finger were kept in a horizontal position, supported by a bookshelf-like arrangement having 30 cm between the levels. The experimental arrangement is shown in Fig. 1.

The skin blood flow was measured by a laser Doppler flowmeter (Periflux PF1D, Perimed KB, Stockholm, Sweden). The design of this instrument has been described in detail by NILSSON et al. (1980). The optical fibre probe was mounted in the hand support and was adjusted to touch the tip of the middle finger. A bandwidth 12 kHz, low-pass filter with a time constant of 3 s and a gain of 3 × were used throughout the study. The instrument was connected to a three-channel strip chart recorder. The output signal was sampled 4096 times during the 200 s the recording lasted. A Hewlett-Packard Fourier analyser 5451C was used for this purpose.

Electrical impedance was measured by four electrodes using a constant current (50 kHz, 500 μA) and a phase-sensitive detector. The electrodes were gold-plated metal bands of adjustable size, 3 mm in width. Two current electrodes were adjusted to form a full circle (2π) contact with the middle finger (I₁) and with the index finger (I₂). Two voltage electrodes (P₁, P₂) were adjusted to obtain half-circle contact (π) on the medial side of the middle finger, as shown in Fig. 1. Polyethylene glycol containing PEG400, NaCl and H₂O was used as a paste to obtain good contact between the electrodes and the skin. The distance between the centres of two voltage electrodes was 13 mm. The distance between the electrodes I₁ and P₁ was larger than 13 mm.

Seven mercury-in-rubber strain-gauges of different sizes were prepared for subjects with different finger diameters. The diameters of the gauges were selected in such a way

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Fig. 1 Experimental arrangement for simultaneous measurement of digital blood flow by laser Doppler flowmetry, impedance- and strain-gauge plethysmography: F = fibre-optic probe; I₁, I₂ = current electrodes; P₁, P₂ = voltage electrodes; S = mercury-in-rubber strain-gauge; cuff = cuff for venous occlusion