Doppler ultrasound (US) is still considered the gold standard for in vivo blood flow measurements [1]. However, within past years several new magnetic resonance (MR) imaging methods for flow quantification evolved. All MR modalities essentially rely on the strong influence of the movement of spins on the amplitude and phase of the MR imaging signal. The phase-modulation method [3] has gained the greatest importance for flow quantification. The linear relationship between the phase of the MR imaging signal and the velocity of the moving spins permits a straightforward quantification of instantaneous flow velocity and direction in every pixel over the entire cross section of the vessel. The flow sensitivity of the phase mapping sequences can be adjusted widely to suit physiological velocities ranging from slow cerebrospinal fluid flow to accelerated flow in a stenosed artery.

Fast gradient-echo (GRE) sequences enable short repetition times (TRs) on the order of 20 ms and less by means of a time-saving reversal of the readout gradient instead of the 180° radio-frequency (RF) echopulse applied in spin-echo sequences. This and electrocardiographic triggering allows for a temporal sufficiently resolved quantitative analysis of repetitive pulsatile flow over the entire cardiac cycle. In comparison to other established methods such as thermodilution, electromagnetic flowmetry and Doppler US, the new MR imaging modality is neither invasive nor limited in its application by access windows. These are some of the reasons why MR velocity mapping is becoming an important method for flow quantification in clinical diagnosis [4]. The clinical relevance of quantitative flow measurements should further increase once the normal reference values for various vessels are established.

Previously, in vivo flow measurements by means of MR imaging were compared with other methods. Lipton et al. [5] measured the blood flow in the ascending and descending aorta with MR and standard thermodilution. Matsuda et al. [6] compared the MR flow measurements in the abdominal aorta with those achieved by a single-gated Doppler US. However, these authors utilized time of flight MR methods which are not sensitive to flow direction and provide no spatial resolution, thus preventing comparisons between the cross-sectional velocity profiles. These drawbacks can be overcome when phase-based MR methods are employed, allowing the measurement of the
instantaneous two-dimensional velocity distribution within vessels. The results have been confirmed using multigated Doppler US methods [7, 8]. This allows the acquisition of one-dimensional velocity profiles and under the assumption of an axially symmetric velocity distribution [9] flow rates can be calculated and compared with MR volumetric flow.

Initially, the quantification of the flow rate with phase-based MR velocity mapping was validated with continuous and pulsatile flow on phantoms [10, 11]. Based on the results of these initial studies it became obvious that particularly for in vivo examinations the accuracy of the MR flow determination strongly depends upon a precise phase correction, which is applied to the data after the examination. The phase correction includes the subtraction of motion independent phase errors due to different causes and the exact determination of the zero-velocity baseline.

**Established Methods for Noninvasive Flow Quantification**

Plethysmography and Doppler US are well-known noninvasive flow quantification methods. Only the latter can be considered sufficiently accurate providing a semiquantitative estimation of blood flow. The analysis at the spectrum of the reflected Doppler waves typically allows only the determination of mean velocity and direction, hence velocity mapping or accurate flow rate determination is not feasible except under invasive conditions [12]. To acquire one- or two-dimensional velocity profiles it is necessary to use a pulsed multigated Doppler US instrument [13]. The velocity information is sampled at multiple sites along a focused US beam. The repeated acquisition of the same volume elements at a rate equal to the pulse rate gives an accurate estimation of the motion-induced Doppler frequency shifts. The scan rate should be at least twice as high as the maximal Doppler frequency shifts to avoid aliasing. With current designs utilizing a pulse rates of several kHz it is possible to measure physiological blood flow velocities up to a voxel size of 1 mm$^3$ at a temporal resolution of 20 ms. Employing the semiannular integration technique [9] and assuming an axially symmetric velocity distribution, volume flow rate can be estimated with a high accuracy. The multigated US is however, very sensitive to misalignments of the Doppler beam and to the measurements vessel diameter.

**Flow Quantification by Phase-Based MR Imaging**

**Physical Principles**

For the precession frequency $\omega$ of a spin system excited by a RF pulse at the time $t_0$ the following general relation applies

$$\omega(\vec{r}, t) = \gamma B(\vec{r}, t) = \gamma B_0 + \gamma \vec{G}(t) \vec{r}(t),$$

(1)