Eur. Radiol. 9 (Suppl. 3), S318–S322 (1999) © Springer-Verlag 1999

Technology

European Radiology

Section III: New imaging techniques

Power Doppler

J. M. Rubin

Department of Radiology, University of Michigan, 1500 E Medical Center DR, Ann Arbor, MI 48109, USA

Introduction

Color Doppler imaging has had a great impact on ultrasonography. Most color Doppler scanners represent local flow by encoding an estimate of the mean Doppler frequency shift at a particular position in color. Yet, the choice of the mean frequency shift as the parameter for representing flow in color Doppler is somewhat arbitrary. One rationale for this choice is the ease of implementation of the mean, since it represents a natural extension from the autocorrelation of the Doppler shifted signal [1, 2, 3].

Although this parameter seems to have merit, there is no a priori reason why any of a number of other parameters which encode flow could not serve as well. For example, the modal or median frequency shifts at a given location may be of greater interest, and many machines give the option of displaying the local variance of the signal, which is also derived from the autocorrelation [1].

Problems and limitations of mean frequency color Doppler

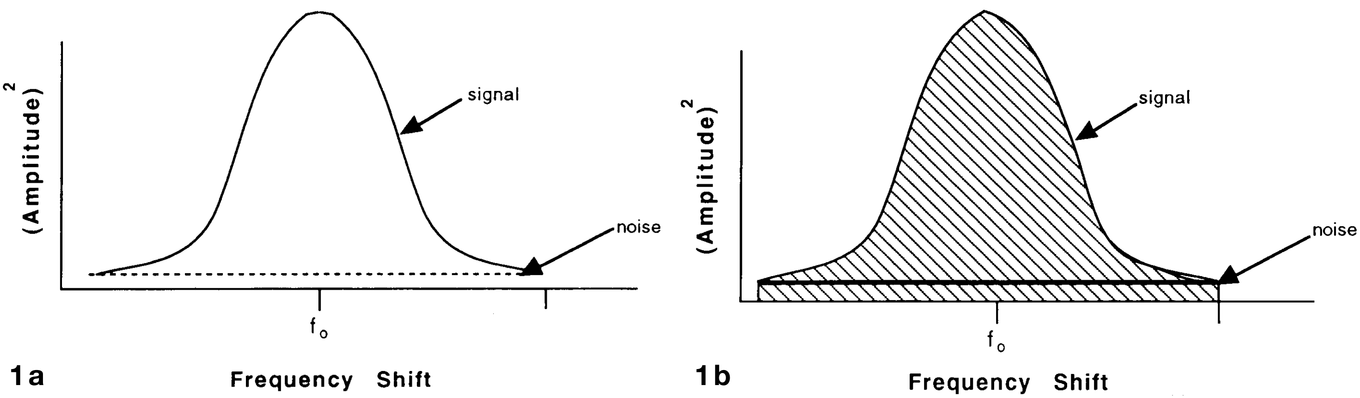
Albeit the most commonly used parameter, mean frequency color Doppler has its limitations. One obvious problem with employing the mean as the parameter of choice is that random noise in the ultrasound imaging system has a random frequency shift, making noise look like flow. This is because noise has a random phase distribution in time, and since frequency is defined as the rate of change of phase, noise has a random frequency shift. Therefore, in the mean frequency mode, noise can look like flow in any direction. As image noise increases, the more aberrant flow there appears to be, and the more the background appears to fill up with flow-related artifact. Eventually, this random noise totally dominates the image making the identification of true flow impossible.

Other problems that occur with standard color Doppler are less dramatic, but no less bothersome. By the mere fact that color Doppler is a frequency-detection technique, it necessarily aliases [2, 3]. Although we all live with aliasing, and at times aliasing in color can in fact be useful, in general aliasing is an annoyance. Aliasing can make vessels look discontinuous, and if the primary reason for a color Doppler scan is to identify vessels for sample volume placement, any apparent discontinuity can create problems in this task. Furthermore, aliasing distorts the directional and speed information in Doppler. This is especially a problem in slow-flow situations where low pulse repetition frequencies (PRFs) invariably produce aliasing. So the diagnostic detection of the presence or absence of flow would improve if aliasing could be avoided.

Finally, color Doppler is angle dependent. This impacts imaging in several ways. Doppler devices lose sensitivity to flows that are perpendicular to the sound field, thus requiring that the beam be directed to detect these flows. Because the beam cannot be continuously steered in all directions, lost segments not containing flow invariably occur. This raises the issue of vessel continuity. This is also confounded when vessels turn across the sound field, changing colors in the process [2]. Color Doppler can easily underestimate the presence of vessels, or at least it is hard to be certain that a completely thorough search has been performed because some vessels may not be seen when they course perpendicular to the sound field. This final problem added to the multiple colors within each vessel caused by varying insonifying angles along a vessel's path, can make vessel tracking and identification difficult.

Power Doppler imaging

An alternative to standard mean-frequency color Doppler is a color Doppler technique that encodes the power in the Doppler signal in color [4, 5]. Although calculated from the autocorrelation function, this parameter is fundamentally different from the mean frequency shift. The primary advantage of using power is that the



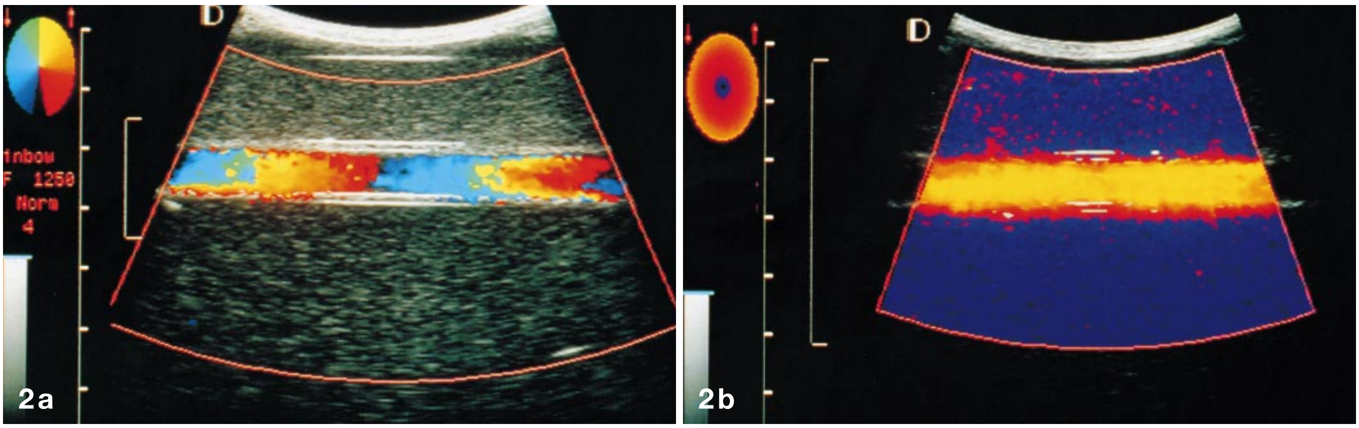


Fig. 1. a Spectral plot for mean frequency flow estimation. The graph is spectral power, (amplitude)^2, as a function of frequency shift. The mean frequency shift, f_o, is noted along with the signal, solid gaussian curve and noise floor *(dotted line)*. When the signal is weak, it begins to fall into the noise floor which is white in character, i.e., contains all frequencies. **b** Same plot except *cross-hatching* represents the integral under the curve. Both the signal and the noise are integrated. The noise integral is always low, making it possible to separate the signal from the noise when the signal is weak

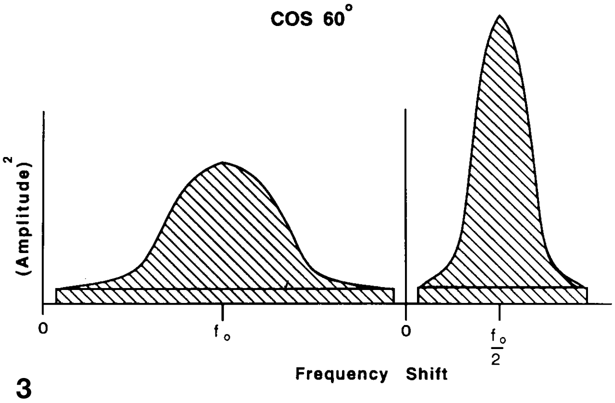
Fig. 2. Flow tube showing aliasing in **a** mean frequency mode and **b** no aliasing in power mode. Unfortunately, the pulse repetition frequency (PRF) is not recorded on the power image in **b**. However, **b** does accurately represent what would be seen if flow in this tube were imaged in power mode at the same PRF as was used in mean frequency mode

representation of random noise in the power mode is much different from that in a mean frequency mode. This is because the noise always has uniformly low power due to the standard signal to noise requirements of a color Doppler scanner. This is fundamentally different from the random phase noise introduces when calculating the mean frequency shift. If noise had power approaching the signal in any given device, color Doppler scanning would be impossible by any technique. Because noise has uniformly low power, when we encode power in color and raise the sensitivity of the color Doppler unit to image the noise floor, instead of seeing a random distribution of colors that represents any possible flow, only a uniformly colored background is imaged representing low power. Any true flow will have more power in the Doppler signal than does the noise, and hence will literally pop out of the noise background (Fig. 1). The improvement in flow sensitivity using this technique is somewhat equipment and situation dependent, but we have been able to improve flow sensitivities by a factor of three to five in some cases; however, it is safe to say that one will almost never do worse in sensitivity using power mode compared with mean frequency.

Advantages of power Doppler imaging

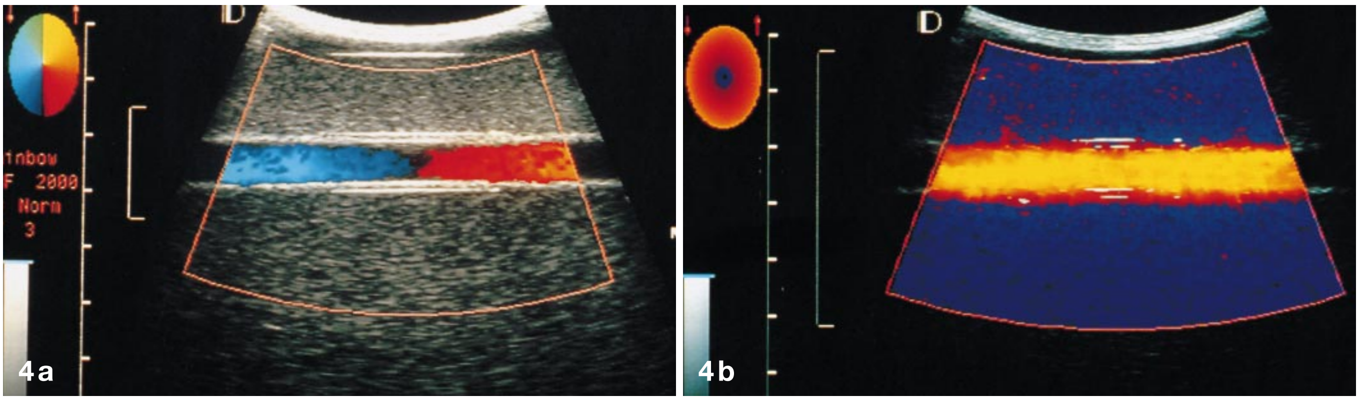
A significant advantage of power Doppler imaging is that it does not alias. This is because the total power in the signal is represented by the integral under Doppler power curve also called the power spectrum [6]. It is clear that the mean frequency can alias when it exceeds PRF/2, but the integral of the power spectrum does not change (Fig. 2).

Thirdly, power Doppler imaging is relatively angle independent, certainly compared with mean frequency color Doppler. This is again because power is based on the integral of the Doppler power spectrum. It is well known that the power in the Doppler signal is related to the number of moving scatterers, red blood cells in the absence of contrast agents, producing the recorded Doppler shifts [7]. If one changes the angle of insonification relative to these red blood cells, their mean Doppler shift will change, but the power will not change. One can think of it as changing the shape of the frequency distribution, but not the integral. Thus, a power image will change very little with changing angle (Figs. 3,



3

Fig. 3. Two side-by-side plots of spectral power distribution functions similar to Fig. 1. Note that there are two zeros representing two origins. The *left-hand plot* represents the distribution at zero degrees, and the *right-hand plot* represents the distribution when sampling at 60°. Each frequency shift in the *left-hand distribution* is multiplied by half, so the mean value on the left, f_o, is exactly twice the mean value on the right, $f_o/2$; however, the areas are unchanged. Hence, the plot on the left is broad and short, whereas the one on the right is tall and thin. Thus, the mean frequencies appear different depending on the angle of insonation, but the power remains essentially unchanged. The only difference is the amount of signal that falls into the wall filter



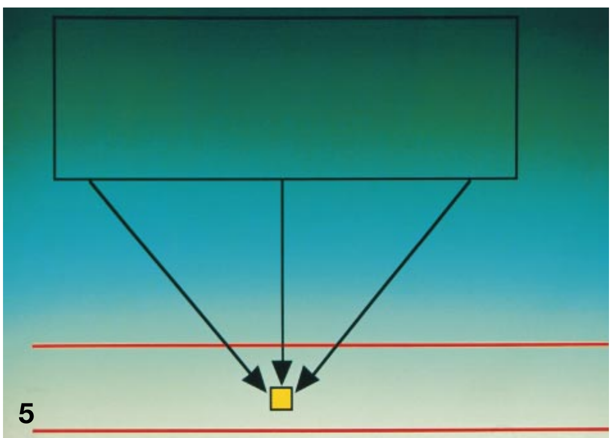


Fig. 4. **a** Flow tube in mean frequency showing color change as flowing medium moves across the aperture of the scanhead. **b** Same flow tube in power mode showing essentially no change across the tube

Fig. 5. A linear-array scanhead (*rectangle* at top of image) sampling a site *(yellow box)* in a "blood vessel" represented by *two parallel red lines*. The entire aperture is sampling the box for optimal focusing. The central *black arrow* projecting down from the center of the aperture is perpendicular to the vessel and would detect no Doppler shift. The *arrows* projecting from the *right-hand side* and *left-hand side* of the scanhead would detect exactly the same Doppler shifts, but of opposite signs. They would cancel out in mean frequency mode; however, their powers would be the same, and they would not cancel out in power mode; hence, flow can be detected at 90°. Note, however, that the power is less than what would have been obtained with a better Doppler angle

4). This can, in fact, extend to normal incidence because a mean frequency shift of zero does not imply that the power is zero. As shown by Newhouse and Reid, it is possible to see flow at normal Doppler incidences due to spectral broadening caused by aperture effects (Figs. 4, 5) [8]. This spectral broadening has power and can be seen using power imaging, even if the mean frequency shift is zero. This is still a Doppler technique, so there will be less power at perpendicular incidence, but it may not be zero. Hence, vessels look continuous, and in many cases, there is no need to steer the beam at all.

Other advantages of power mode are now being recognized. These include better boundary detection, improved quantification of vascularity, better 3D depiction of blood vessel anatomy, and advantageous properties of blooming in power mode with contrast agents. The first two advantages are both based on the fact that power mode is a continuous estimator of the amount of blood in a pixel compared with standard mean frequency color Doppler, which is a bistable estimator of pixel blood content. Bistable means that an arbitrary threshold, the color-write echo priority, is defined for color Doppler below which no flow is written and above which a pixel is written as entirely containing flow. For example, if a threshold of 50 % blood is chosen, a pixel containing 49 % blood would appear completely devoid of flow, whereas one with 51 % blood would appear completely blood filled.

Power mode represents blood content differently. Although the functional relationship is complex, the amount of Doppler power in a pixel corresponds to the amount of moving blood that is present. Hence, different amounts of blood in a pixel will appear with different powers. Thus, one obtains a continuous map of vas-

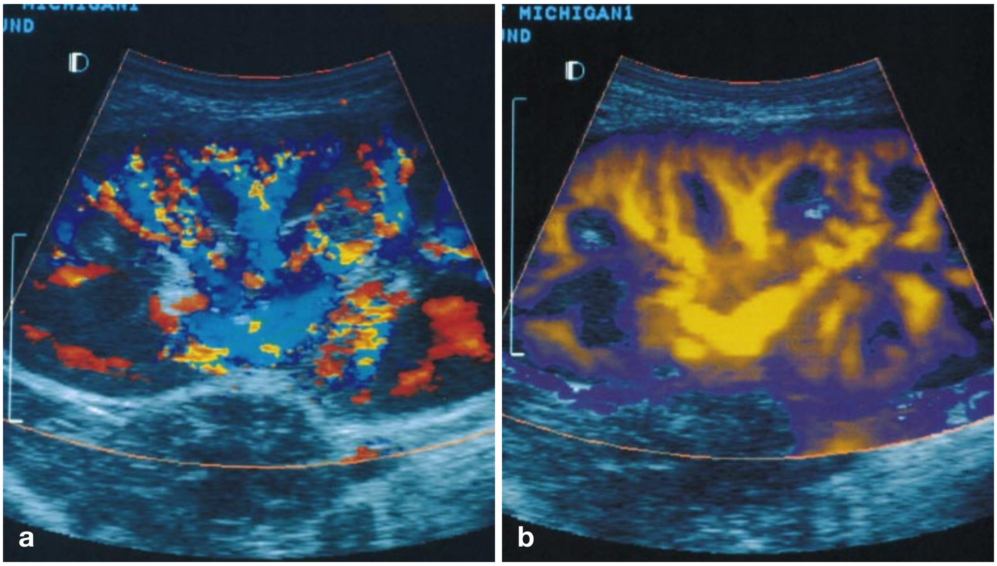


Fig. 6 a,b. Image of renal transplant in power mode and mean frequency. **a** Mean frequency image shows less flow in the cortex and poorer detail of the vessel margins. This is because color Doppler is a bistable indicator of flow, i.e., all or nothing. **b** Power Doppler image of the same kidney at same PRF. The gain is set higher in power mode. There is more flow depicted in the renal cortex, and the vessels are better visualized. This is because the continuous depiction of flow allows the vessels to "pop" out of the background

cularity. In addition, it is possible to compensate the Doppler power for depth and transducer affects. This can be done by normalizing pixel values at a given depth by a known backscattered power value at the same depth and location, i.e., 100% blood in blood vessels. By comparing the power in a given pixel to the power in a neighboring blood vessel, one can normalize the tissue signal for depth and transducer affects [9]. Preliminary attempts at using this technique to estimate vascularity in normal kidneys in a small volunteer population has lead to results that fall well within the expected vascularity of the kidney [10]. The estimates may have a variability of up to ±10% for any given kidney; however, it is hard to know at this stage whether the variability is in the estimate itself or what is actually in the kidney. It appears that the variability is similar to what is seen in other less well-defined parameters such as RIs or PIs.

Power mode's natural ability to represent pixel blood content continuously leads directly to improved representations of boundaries compared with mean frequency color Doppler. This is again because mean frequency represents boundaries as all-or-nothing phenomena. Power mode depicts continuous smooth representation of boundaries, making boundaries very easy to see (Fig. 6).

In 3D the lack of aliasing and directional information is an advantage for power mode. In power mode, vessels look continuous and are easy to track visually no matter what the perspective. The continual change in color with direction and velocity, either true or aliased, makes mean frequency representations of 3D representation of vascular structure very hard to sort out [11].

Problems and limitations of power Doppler imaging

A disadvantage of power imaging is that it provides no information about speed of flow or direction of flow. If these parameters are of interest, the technique should not be used. Yet, as mentioned previously, color Doppler is often used only to localize vessels for placement of sample volumes or to determine the presence or absence of flow. In these cases this limitation of power Doppler presents no problem. The biggest limitation is that the method is extremely motion sensitive. Minimal soft tissue motion can seriously degrade the image. This is due to the fact that power Doppler is a high-sensitivity technique in which any motion is detected. Soft tissue motion can be difficult to distinguish from blood flow. Very strong soft tissue scatterers can still give a structured noise that can look like flow-containing objects under certain conditions. This makes it mandatory that additional sophisticated soft tissue motion suppression schemes be used with this technique. It is encouraging at how well motion-suppression schemes have already worked, and there seems to have been progressive improvement in flash suppression over time.

Contrast-enhanced power Doppler imaging

Power mode has a big advantage over mean frequency color with contrast agents. The problem with contrast agents is that they provide too much signal. The large amount of signal raises the backscattered power of the Doppler signal in tissue itself above the noise floor or any other threshold one might likely chose. In mean frequency just like in the circumstances described above, any signal above threshold is written as 100% blood. The tissue appears full of blood. Furthermore, the signal in the vessels themselves becomes so great that it appears to bloom outside of its boundaries. Together, the signals merge completely obscuring vascular and anatomical detail. In order to compensate for this, it is necessary to do the paradoxical thing of turning down the receiver gain to compensate for the increased signal.

In power mode, the power in the signal is what is being represented in color; hence, the more the power the brighter the signal. Therefore, large vessels just increase in brightness over the background. The background gets brighter, but any vessels in the background will shine out of the background due to the larger amount of contrast agent in them. Thus, large vessels look brighter than small vessels, previously invisible without contrast, which now appear brighter than the background. This all occurs without compromising receive gain. Thus, one gets a huge sensitivity benefit from contrast agents and power mode without any compromises [12].

The major limitation of the contrast effect in power mode is saturation of the receiver due to the huge signals with contrast agents. To whatever degree blood vessels and background are saturated, blooming will make the vessels and background indistinguishable. This problem will hopefully be solved when manufacturers increase the color dynamic range of their scanners to accommodate the increased signal provided by contrast agents.

References

1. Kasai C, Namekawa K, Koyano A, Omoto R (1985) Real-time two-dimensional blood flow imaging using an autocorrelation technique. IEEE Trans Sonics Ultrasonics SU-32: 458–464
2. Omoto R, Kasai C (1987) Physics and instrumentation of Doppler color flow mapping. Echocardiography 4: 467–483
3. Kremkau FW (1992) Principles and instrumentation. In: Merritt CRB (ed) Doppler color imaging. Churchill Liviingstone, New York, pp 7–61
4. Rubin JM, Adler RS (1993) Power Doppler expands standard color capability. Diagn Imaging 12: 66–69
5. Rubin JM, Bude RO, Carson PL, Bree RL, Adler RS (1994) Power Doppler: a potentially useful alternative to mean-frequency based color Doppler sonography. Radiology 190: 853–856
6. Bracewell RE (1978) The Fourier transform and its applications. McGraw-Hill, New York
7. Shung KK, Sigelmann RA, Reid JM (1976) Scattering of ultrasound by blood. IEEE Trans Biomed Eng 23: 460–467
8. Newhouse V, Reid J (1991) Invariance of the Doppler bandwidth with flow displacement in the illuminating field. J Acoust Soc Am 90: 2595–2601
9. Rubin JM, Adler RS, Fowlkes JB, Spratt S, Pallister JE, Chen JF, Carson PL (1995) Fractional moving blood volume estimation with power Doppler imaging. Radiology197: 183–190
10. Rubin JM, Bude RO, Fowlkes JB, Spratt RS, Carson PL, Adler RS (1997) Normalized moving blood volume estimates with power Doppler US: defining a stable intravascular point with cumulative power distribution function. Radiology 205: 757–765
11. Downey DB, Fenster A (1995) Vascular imaging with a three-dimensional power Doppler system. AJR 165: 665–668
12. Murphy KJ, Bude RO, Dickensen L, Rubin JM (1997) Use of intravenous contrast in transcranial sonography: preliminary observations. Acad Radiol 4: 577–582