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ULTRASONIC DOPPLER MTI SYSTEM FOR EVALUATION OF AORTOCORONARY BYPASS GRAFT PATENCY

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A new version of an analog multi-channel serial processing imaging gated pulse Doppler (IGPD) was developed. By combining double I/Q fixed echo cancellers with a phase detector and a double-loop recirculating delay line integrator (all made from C.C.D. delay lines), we obtained the degree of cancellation better than 60 dB. The penetration range of the device was 12 cm permitting the investigation of the intracardiac flow. The results of the preliminary application of IGPD to the detection of patency of coronary bypass grafts will be shown.

1. Introduction

Some existing ultrasonic instrumentation has shown great promise in being effective in examination of the coronary circulation [2, 7]. The left main coronary artery has been reliably detected and stenosis at this site has been diagnosed. The technique has not had a wide use, perhaps because of difficulty in use and restriction to only some vessels.

Our work seeks to improve ease of use and ability to detect the coronary vessels by imaging the flow in the vessels. This mapping requires the rejection of echoes from the strongly reflecting but slower moving structures of the heart tissues, while retaining the weak echoes scattered by the blood. Ideally the output A mode trace amplitude should be proportional to Doppler frequency.

The first successful efforts towards practical digital realisation of such system were made by GRANDCHAMP [3], BRANDESTINI [1], and recently by HOEKS [4]. An analog solution was sought for simplicity and to provide a large dynamic range, since the strong fixed echoes from the heart could surpass the range of available "flash" A-to-D converters.

We developed an economical and workable system which combines cancellation and phase detection to achieve a fixed-echo cancellation ratio of greater than 50 dB, thus allowing application of this technique in vivo. The first task was to build an improved pulse Doppler with a greater penetration depth than the original IGPD, developed at our Institutes [5]. The first prototype device developed in 1977 to 1978 had a penetration depth limited to about 4.5 cm, which was much too short for cardiac measurements in adults. Because of the quartz delay lines used in the stationary canceller, that system had to be operated with a frequency of 4.3 MHz. A new approach to the IGPD was developed using a stationary canceller, directonal phase detector and sweep integrator, all based on charge-coupled delay lines which have been manufactured by Reticon. The schematic diagram in Fig. 1 shows the double canceller which uses two of

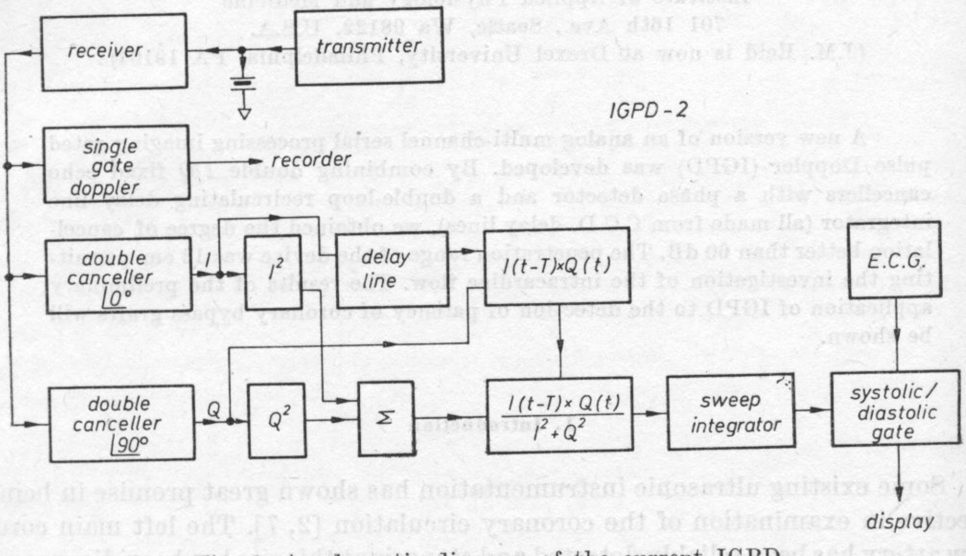

Fig. 1. A schematic diagram of the current IGPD

the CCD shift registers. The output of the double canceller consists of moving echoes only since the fixed echoes are suppressed by more than 60 dB. The only trade-off of this design, compared to the one based on quartz analog delay lines, is that the continuous delay available with quartz delay lines allowing an "infinite" number of gates has been replaced by CCD delay lines allowing 295 receiver gates of 0.5 μs duration overlapping due to 1 MHz bandwidth (along

11.5 cm penetration depth). The canceled I/Q signal after phase detection and sweep integration is applied to the diastolic gate producing the output only in diastolic gate producing the output only in diastole, when most of the coronary LAD flow occurs.

The $D.C.$ Fourier transform of the output signal is equal to

$$F(\Delta\omega_d)_{D.C.} = -\frac{1}{2}j\,\frac{\int\limits_{\infty}[\exp(j\Delta\omega_d T)-1]^2[\exp(-j\Delta\omega_d T)-1]^2\exp(j\Delta\omega_d T)}{\int\limits_{\infty}[\exp(j\Delta\omega_d T)-1]^2[\exp(-j\Delta\omega_d T)-1]^2}\times$$
$$\times\,\frac{S(\Delta\omega_d)\,d\Delta\omega_d}{S(\Delta\omega_d)\,d\Delta\omega_d}, \tag{1}$$

where $S(\Delta\omega_d)$ is the spectral density of the input signal $f(t)$, $\Delta\omega_d$ — Doppler frequencies, T — delay time.

The term $[\exp(\pm j\Delta\omega_d T)-1]^2$ stands for double cancelation function, $\exp(j\Delta\omega_d T)$ is due to the convolution in the phase detector.

For one scatterer or ensemble of particles moving with the same velocity the received signal is $A\ \sin\omega_d t$. The resulting output signal (real part of (1)) is given by $1/2\ \sin\omega_d T$.

The interpretation of the first formula is a little more troublesome. Taking the new function,

$$K(\omega) = [\exp(j\omega T)-1]^2[\exp(-j\omega T)-1]^2 S(\omega), \tag{2}$$

we can consider it as the spectral density superimposed on periodic function. Then we obtain a very similar expression to the one for the average frequency

$$F(\omega)_{D.C.} = -\frac{1}{2}j\,\frac{\int\limits_{\infty}\exp(j\omega T)K(\omega)\,d\omega}{\int\limits_{\infty}K(\omega)\,d\omega}. \tag{3}$$

According to the Taylor series, it is equal to the sum of the first, third and higher moments of the Doppler spectrum.

The signal-to-noise ratio of the IGPD was significantly increased by the addition of a sweep integrator. Due to the nature of the flow and variations in scattering intensity in the arteries, the resulting output from the canceller varies from pulse to pulse. For that reason a double-loop recirculating delay line integrator was added [6]. The effective number of integrated profilies corresponds to $(1-k)^{-1}$, where $1-k$ is the positive feedback loop gain. We achieved a $k = 0.97$ in our implementation. This integrator exibits no unwanted oscillation even for such a high value of k. Approximately 30 successive profiles are added, thereby increasing the signal-to-noise ratio by the square root 30. The principle of sweep integration is illustrated in Fig. 2. The lower trace represents a signal from the double canceller at the input to the sweep integrator.

The middle trace represents the train of succeeding pulses at the output of the sweep integrator when the delay time of the analog shift register is set purposely to be smaller than the repetition rate. The upper trace is the final output from the integrator when the delay time is equal to the repetition rate.

The actual performance of this system is illustrated in Fig. 3. The upper trace represents the flow profiles in the common carotid artery during a 500

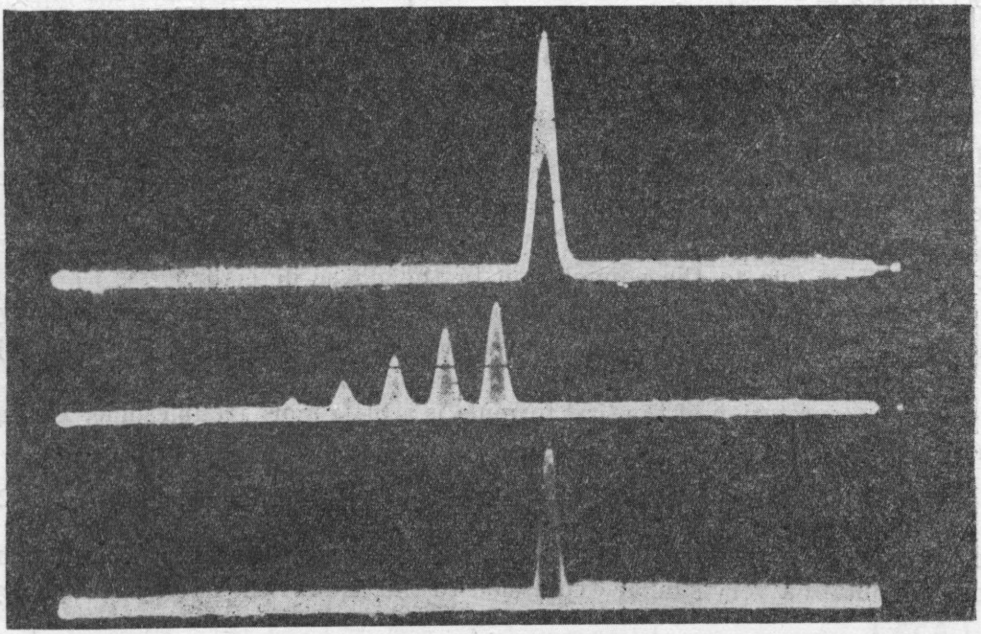

Fig. 2. The principle of sweep integration

millisecond period, this being a superposition over 100 signals from the integrator. The bottom trace represents the *RF* signal at the input to the canceller. In this case the degree of cancellation is better than 60 dB.

Improved penetration depth was achieved through a variety of improvements to the system. The addition of the sweep integrator, the lowering of the ultrasonic frequency to 4 MHz, and the use of low insertion loss, high sensitivity transducers obtained from Precision Acoustic Devices all contributed to this increased penetration depth. Flow signals were obtained from depth of 7-8 cm and large signals from valve motions were observed as deep as 11 cm. These improvements in the dynamic range and penetration depth of the IGPD have allowed us to progress to preliminary clinical evaluation of this system for detection of patency of coronary bypass grafts.

Future directions are the development of a wider range Doppler frequency determination, and the development of a true mapping display system to allow the full advantages of the instrument to be realised.

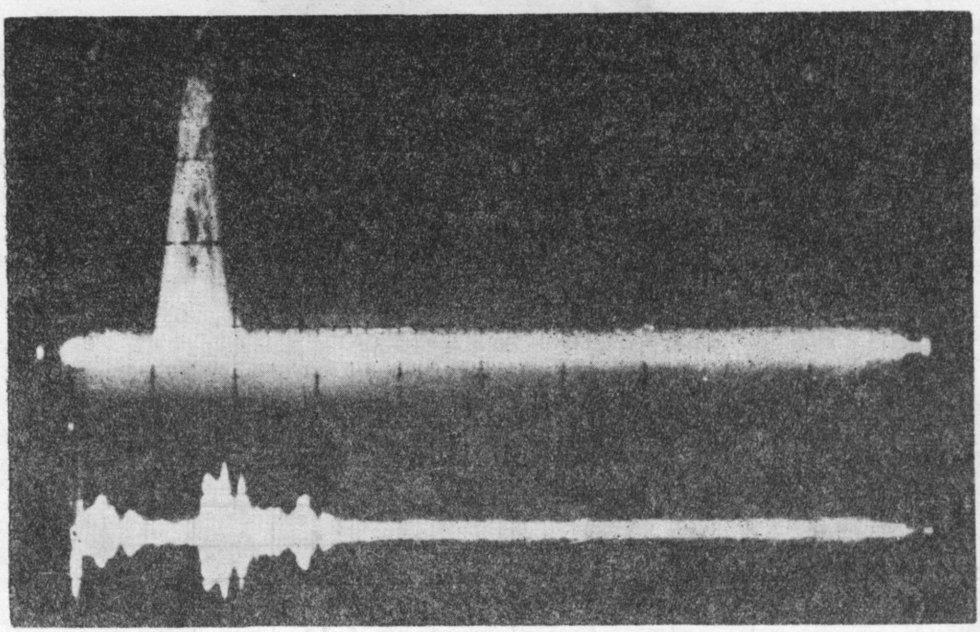

Fig. 3. The performance of the IGPD

2. Clinical results

At present we are completing the first stage of the validation of the application of the IPGD to detection of the patency of coronary bypass grafts. We concentrated mainly on grafts to the left anterior descending coronary artery LAD, because this graft is the most easily attainable via pulse Doppler. Patients were examined in the left lateral position with the probe located in the second or third intercostal space. The signal from the patent graft is expected to be found in the vicinity of the right ventricular outflow tract. The criteria of diastolic flow in close approximation to the right ventricular outflow tract was chosen to determine the patency of LAD bypass grafts. To avoid possible errors the Valsalva maneuver was often performed to eliminate signals coming from the mammary vein which may be located close to the graft. Once the graft had been located by displaying the whole penetrated range covered by the 295 gates from the IGPD, the single gate was located to provide a ZCC output for the signal corresponding to the bypass graft. An example recording of this zero-crossing output is shown in Fig. 4. Both ECG and zero-crossing output are shown in this figure. Diastolic flow is clearly evident. Separation of bypass graft signal from mammary vein signal by Valsalva maneuver is illustrated by Fig. 5. As can be seen, two diastolic signals were present before the Valsalva maneuver was performed.

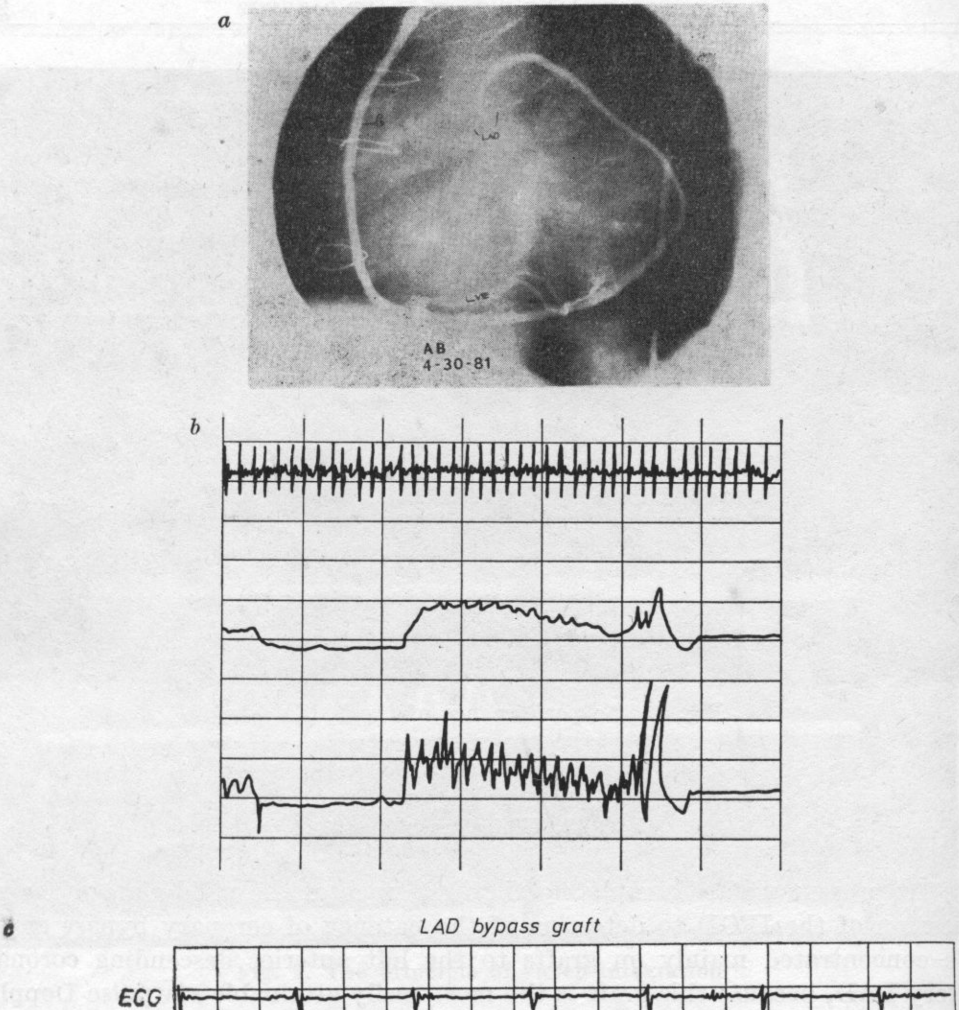

Fig. 4. A sample zero-crossing output of an LAD bypass graft signal measured transcutaneously with the IGPD. (*a*) is a left later oblique angiogram of the bypass graft done post-operatively; (*b*) is the electromagnetic flowmeter tracing of the bypass graft done inter-operatively, the middle trace being the average output for calibration and the lower trace illustrates the pulsatile waveform exhibiting the diastolic waveform when compared with the ECG; (*c*) is the zero-crossing output of the IGPD when the signale-gate is located in depth in the LAD bypass graft

After, or during the Valsalva maneuver, the diastolic flow component from the mammary vein is removed and only a diastolic flow component from the LAD bypass graft is present in the zero-crossing output.

To date this study has included examination of 15 patients with saphenous vein bypass grafts. These 15 patients were studied blind after the state of patency of their LAD bypass graft was determined by angiography. Of the 15 patients studied, 10 had patent LAD bypass grafts, and 5 had occluded LAD bypass grafts. No appropriate diastolic signal was found in the five patients

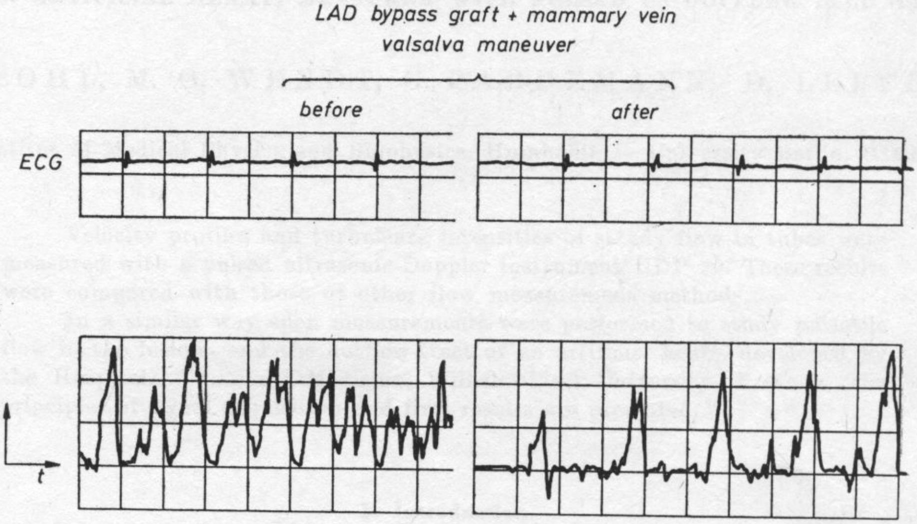

Fig. 5. Superposition of LAD bypass graft and mammary vein signals separated by the Valsalva maneuver

with occluded LAD grafts, which could be interpreted as a flow signal in such a graft. Of the ten patients determined to have a patent graft by angiography, six were found to have patent grafts via examination using the IGPD. Of those four patients with patent grafts that were not detected through our examination, three were patients examined very early in the study. This indicates a significant learning curve may be present with the use of the IGPD in its current signale A-mode output state.

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