Physics. — *Analyzing Physiological Tracings II* [1]. *Heart- and Pulse records.* By A. H. J. M. TOMEY and L. KAISER. (Communicated by Prof. J. G. VAN DER CORPUT.)

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Introduction.

The analyzing method for compound periodical phenomena with components of varying amplitudes indicated by TOMEY has been applied also on curves concerning the function of the heart and the phenomena in the blood vessels that depend on it.

On account of our experience with the vowels (Archives Néerlandaises de Phonétique Expérimentale, t. 19, 1943) and considering that vowel and pulse curves are similar to a certain extent, the application of the method described seemed desirable in the latter case too.

Indeed a remarkable resemblance appears between the qualities of the speech sounds and those of the compounds of waves being present in the circulatory system. In both cases we find impulses origining from muscular energy, forming sequences that show only an approximative regularity: starting from the glottis, that lets escape quantities of air, in the first case; starting from the heart, that lets escape quantities of blood, in the second case. In both cases these impulses are received in a system possessing special qualities as to resonance and extinguishing, which makes the pattern of a fundamental period characteristic for special qualities and conditions of this system. HERMANN, SCRIPTURE and GARTEN have interpreted in this way the phenomena observed in speech sounds. In none of the two cases the succeeding impulses induce the origin of a real fundamental tone, though the case of the function of the heart, not principally by a smaller frequency which falls below the territory of sound, but mainly by being more strictly found to physiological processes, shows a major deviation. But also in the case of the speech sounds we observe that each fundamental period is an event of its own, showing a pattern, only approximatively repeated by the adjacent periods. Nevertheless the ear perceives a fundamental tone, as SCHOUTEN has explained in his theory concerning the residual tone.

In the extensive literature concerning heart and pulse curves, we only once found an indication of the applying of analysis, namely a communication by BROEMSER, who applicated analysis after FOURIER on central and peripheral pulse tracings.

It is true that VON RECKLINGHAUSEN to a certain extent was analyzing

[1] I. Electro-encephalogrammen. Verh. Kon. Ned. Akad. v. Wetensch., Afd. Natuurk. Vol. LIII, 1944.

too, considering the pulse wave to be built up out of various elements as: a prime wave, a locally reflected wave and other reflected waves giving together the "Gewoge". The fluctuation of the blood would be caused by the latter, during the diastolic period of the heart. In the central vessels the "Gewoge" is dominating, whereas towards the periphery a coherent reflected wave gets more important as TULLIO had indicated already. The "Gewoge" would have an influence on the function of the heart, a backward coupling, which adds another accordance to those existing between the speech sounds and the vascular phenomena, HUSSON and WEISZ having pointed to this phenomenon in the case of speech sounds. VON RECKLINGHAUSEN differing from former investigators and from BROEMSER, did not consider the pulse to be a compound vibration, but, accepting only positive ordinates (which agrees with a remark of HOORWEG), called it a compound fluctuation.

Many investigators however interprete the form of the pulse curve as depending on vibration. HOORWEG, GRASHEY and others explained it by the interference of positively and negatively reflected waves. FRANCK and TIGERSTEDT supposed that the blood vessels might ahve their own vibrations, which might explain the rebound in the ascending part of the sphygmogram, recorded at a centrally situated artery. HOORWEG called the first part of the pulse curve, untill the incisura, a consequence of a borced vibration, whereas the second part would be the consequence of a free vibration of the vessel. A more active reaction of the arterial wall on the pulse wave was admitted by HÜRTHLE and LÉON FREDERICQ.

For the greater part these theories are combined in the theory which BROEMSER and his coworkers composed on the base of their experiments on models and animals.

BROEMSER considers the pulse curve as the result of a coupling of damped vibrations, the relation between the duration of the systole and the own frequency of the blood cistern determining the output of the heart. The latter appeared to show maxima and minima, depending on the value of 2 Sc/L being an odd or an even number ($S =$ the duration of the systole, $c =$ the velocity of the propagation of the pulse wave, $L =$ a certain average length of that part of the arterial system, that functions as a blood cistern). In AUB's article we find this simple representation. Checking the formula in experiments on animals, 1.4 was found as the value probably causing a maximum output (this value varying from 1.4—2.6 in various animals).

VAN DE POL conceived the pulse-curve, as well as many other biological tracings, as a representation of relaxation phenomena, which prettily well agrees with BROEMSER's views.

Checking the analyzing method indicated by TOMEY by analyzing a relaxation curve, it appeared that a slight deviation of the sinusoidal form was to be found in the results of the analysis, whereas it is a wellknown fact that analysis after FOURIER gives no indication of a deviation whatsoever. Besides no overtones were found which were not present in reality, whereas analysis after FOURIER often gives irreal results.

On account of the indications given especially in recent publications, we may take it for granted that in the pulse curve extinguishing vibrations may be recognized, which means that analysis after TOMEY is at its place here.

To make it possible to judge the results of the analysis, it seemed important to know something about the frequencies of the vibrations, which were to be expected. We found only a few indications partly based on experiments, partly on theoretical considerations.

The rapidity of the propagation of the waves has been determined by various investigators to vary from 5 to 9 m per sec.

A great difficulty gives the evaluation of the distance between the semilunar valves and those places in the arterial system, where a positive reflection by narrowing, or a negative reflection by widening may be expected. As to the chances of the origining of standing waves, the opinions are divergent. If the maximum distance (between the heart and the foot) may be taken to be 150 cm and the minimum distance (between the heart and the bifurcation of the aorta) to be 75 cm, reckoning with positive and negative reflection, the rapidity of propagation being supposed to be 6 m, frequencies of 600/300, 600/150, 600/75, —that is of 2,4 and 8 per sec. may be expected. It goes without saying that this evaluation is a rough one.

LUCIANI parting from the duration of the outflow of the blood as determined in a tracing by EDGREN to 0.23", found a vibration frequency of $1/0.23 = 4.35$ and concluded the wave length to be 160 cm. pointing to the fact, that this indeed is nearly the distance from the heart to the foot. The influence of a resonancy of the blood cistern is not taken into account here.

As mentioned already BROEMSER concluded from his experiments on models checked in rabbits, that the optimal condition for the output existed if $Sc/L = 1.4$, as generally would be the case. In the rabbit BROEMSER and ROTH accept the value $\frac{0.1185 \times 457}{37.5} = 1.4$. For human proportions this might be about $\frac{0.23 \times 60}{100} = 1.4$, which would lead to the frequencies $600/200 = 3$, if negative, $600/100 = 6$, if positive reflection takes place.

Hence we may expect vibrations of a frequency from 2—8 per sec., which would mean the second till the eighth harmonic, if we put the frequency of the pulse to 1 per sec.

BROEMSER employing analysis after FOURIER as mentioned above, found a vibration of 2 per sec. which he called the fundamental tone, whereas nothing is said about the relation between this frequency and the periodicity of the heart. This certainly seems justified, the periodicity of the heart varying with the duration of the diastole. Nevertheless it seemed more attractive to us to consider the frequency of the heart as a sort of fundamental vibration.

Results of the Analysis.

1. A combination of synchronical periods of pressure curves of both ventricles, the aorta, the right atrium and the jugular vein (Handb. d. norm. u. pathol. Physiologie Bd. VII) 1).

Though it is a great disadvantage that only one single period of the tracings was given, which made it necessary to consider the curves as being strictly periodical, the analysis seemed useful for a general orientation.

In the ventricle curves a fundamental wave (of the frequency of the total phenomenon) appeared rather strong, whereas it was much less so in the aorta curve. It goes without saying that as to the amplitude only waves from one tracing may be compared (and perhaps these even not). As to phase both ventricle curves are similar, whereas the aorta tracing shows a distinct retardation as compared with the former ones. The value of this shifting of the phase depends on the physical value of the components found. A wave No 2 (having a frequency of about 2 per sec.) is present in the three curves, most so in the aorta tracing. Its phase again is similar in both ventricular tracings, whereas it is somewhat retardated in the aorta tracing. A wave with a frequency of about 3 appears especially in the aorta curve. The phase in the aorta tracing differs much from that in the ventricular curves. The vibration time of this element might equal the duration of the outflow of the blood. Not 2 but 3 in this case might be the frequency given by the heart, whereby it will be necessary to explain 2 by a proper vibration of the arterial system, which is communicated to the ventricles, probably to the contents of the ventricles.

The analysis of the tracings of the right atrium and of the jugular vein, showed that the fundamental vibration was unimportant in the first (and judging from its phase probably was transported from the ventricle), whereas in the second tracing it was more important, its phase being opposite here as compared to the four other curves. Indeed the usual explanation of the jugular pulse is based on something that only shows itself here, namely the traction by the moving basis of the heart during the systole.

The component No 2 in both curves has the same phase, which is opposite to that in the arterial curves. It is not known whether a negative pressure is to be supposed here as in the fundamental wave.

The third component is only present in the tracing of the jugular vein and coincides with the wave which is ascribed to the influence of the arterial pulse. It is obscure however how a difference in phase may exist by which the wave in the jugular vein would precede that in the aorta.

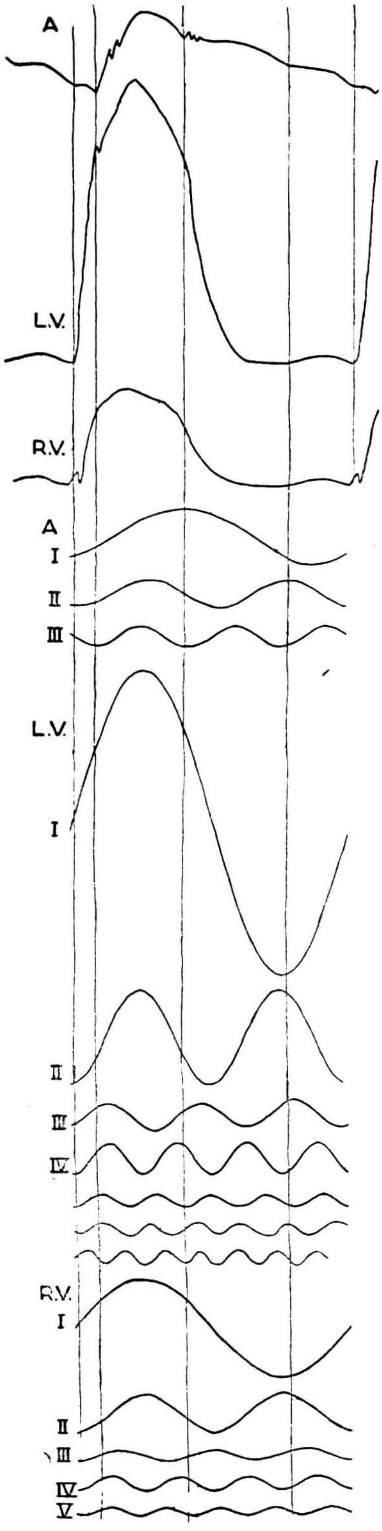


Fig. 1a.

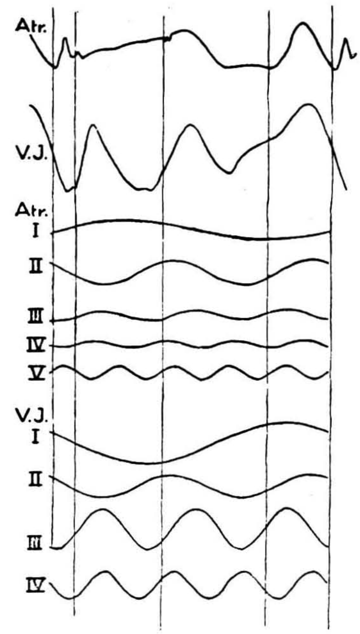


Fig. 1b.

Fig. 1a gives one period of the pressure curves in the aorta (A), the left ventricle (L.V.) and the right ventricle (R.V.), with the results of an analysis in which the phenomena were considered to be periodical.

Fig. 1b gives the tracings of the atrium and the jugular vein in the same way.

2. *Apex beat tracing.*

On a tracing of the apex beat recorded by WALLER the analysis might be applicated in its real way, though in this example as in most other, the number of the heart periods is very limited. The heart tones are indicated in the figure (Fig. 2). Though it must be admitted that the mechanical

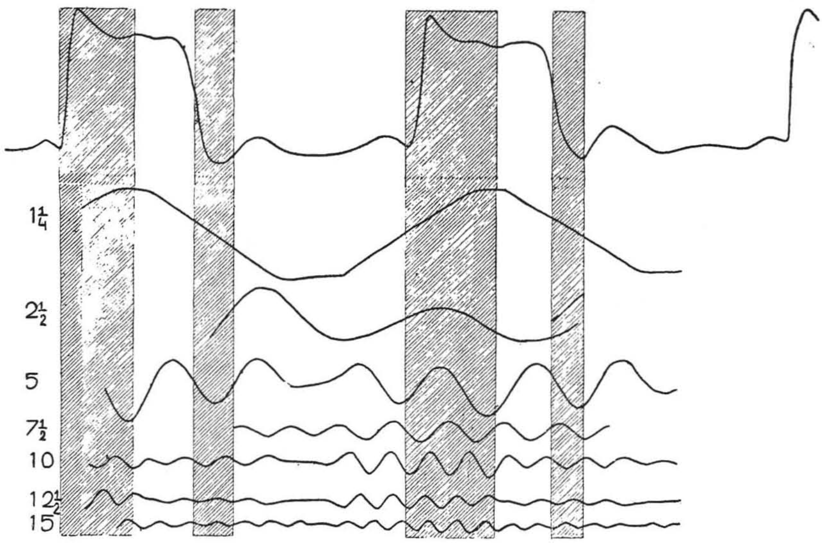


Fig. 2 shows a heart beat record published by WALLER, in which the duration of the heart sounds has been indicated. The results of the analysis are remarkable, most components showing distortion and extinguishing during the diastole, whereas the component of about 2½ per sec. behaves differently.

cardiogram shows important individual differences and depends to a large degree on the conditions under which it is recorded, we have to consider its origin as answering the demands for the development of extinguishing vibrations: the ballistic stroke of FREDERICQ, the pulling at the fibrous elements of the heart and its surroundings, the beat against the cartilagineous and fibrous elements of the thoracic wall. EDGREN and EDENS explained the apex beat tracing.

Generally spoken the results of the analysis showed the following facts. After the first heart-sound, but especially after the second, most of the components are distorted as to amplitude and phase. We feel the necessity to consider the occlusion of the semilunar valves to be responsible for this distortion: a system consisting in coupled cavities containing a liquid in which a compound vibration exists, by the occlusion of the valves is divided into two departments, the blood at the same time having been obliged to move backward to the heart. It seems comprehensible that hereby the existing vibrations appear distorted. The fundamental wave too, shows a distinct irregularity at the moment indicated, its form deviating from the sinusoidal form. Only No 2, a wave of about 2½ per sec., forms an exception, showing its greatest amplitude on the contrary immediately after the occlusion of the semilunar valves, whereas it shows a diminishing during the systole. One would feel inclined to think of a relation to the dicrotic wave of the pulse curve. As to the other components we only may remind of the general causes of vibration mentioned above. As was said already most of the components are distorted also after the first heart sound, which may be ascribed to the opening of the semilunar valves or to the closing of the atrioventricular valves.

It seemed worth while to check whether there was any component present having a frequency between the highest component found (15 per sec.) and the lowest element of the heart sounds (about 45 per sec.). To this purpose a tracing by EDENS was analyzed in which the mechanical conditions of the record did not prevent the presence of higher frequencies. It appeared that the region between 15 and 45 per sec. hardly was represented. Only a component of about 37½ per sec. was found, which probably will belong to the components of the heart sound. In a tracing of the left atrium, recorded synchronically and in the same way, Nos 8, 10, 12 and 16 showed a changing amplitude in such a manner that a coincidency of the lower frequencies with the heart sounds seemed to exist.

3. *Arterial pulse tracings.*

Two examples of the radial pulse, one recorded by FLINT and one by LEWIS, were analyzed. Both had a normal form.

The results of the analysis agree fully (Fig. 3a and Fig. 4a). Beside a fundamental wave, which in both cases is equally strong, a wave of about 2½ per sec. is present. This component by its phase forms the greater part of the systolic part of the pulse curve. In the diastolic part a distortion sets in: the amplitude diminishes and the phase is distorted. The higher components that are present: 6¼ and 7½ per sec. in both cases show irregularities at the same moment. This holds not true for the component 5 per sec., which being only present in FLINT's tracing, may be more or less occasional.

In the central curves and in the peripheral as well, the component 2½ per sec. is the most important (agreeing with the fundamental wave after BROEMSER). An opposition between the central and the peripheral pulse seems to exist in the fact, that in the first the impulse occurs at the beginning of the diastole, whereas in the second it occurs during the systole, the explanation being uncertain. TULLIO and VON RECKLINGHAUSEN already indicated that the principal wave of the pulse tracing gets more important towards the periphery, the importance of the "Gewoge" getting less. We may suppose a resonancy proper to the whole vascular system agrees with the frequency, but depending on the neighbourhood of the central or the peripheral end of the system, the impulse (in both cases origining from a positive reflection) occurs at the beginning of the diastole, or during the systolic part of the tracing.

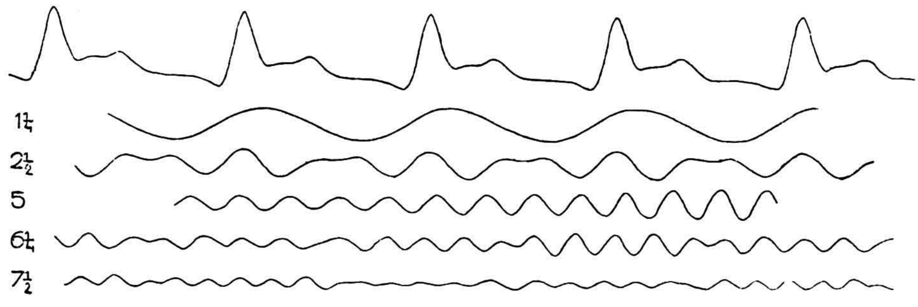


Fig. 3*a*.

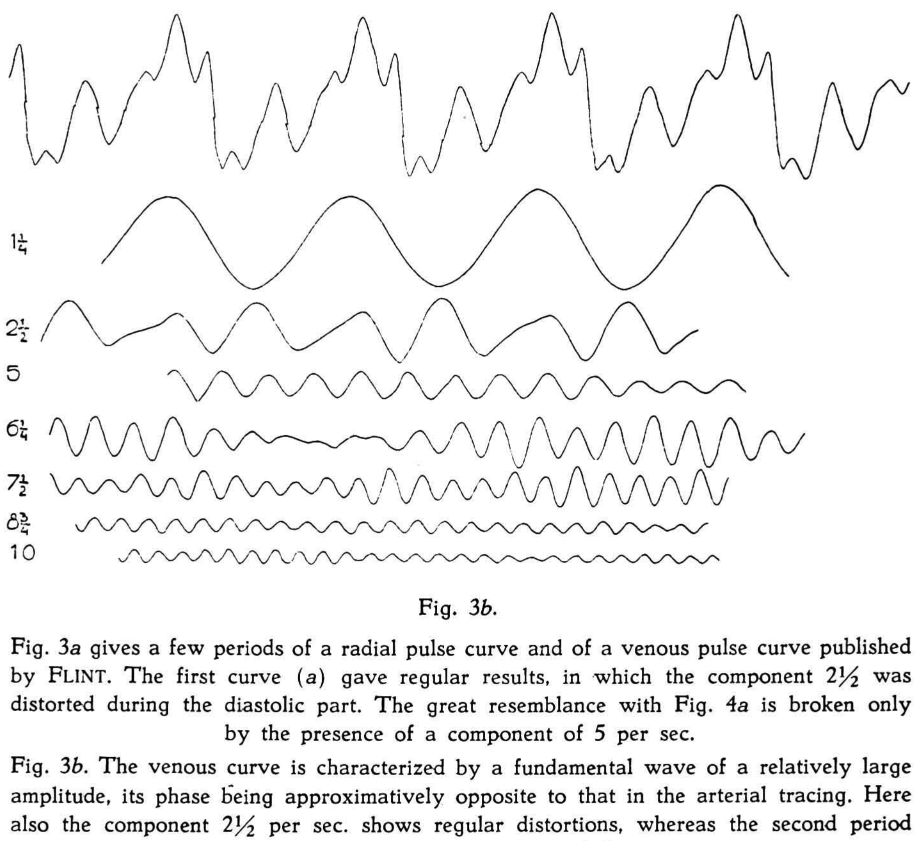


Fig. 3*b*.

Fig. 3*a* gives a few periods of a radial pulse curve and of a venous pulse curve published by FLINT. The first curve (*a*) gave regular results, in which the component 2½ was distorted during the diastolic part. The great resemblance with Fig. 4*a* is broken only by the presence of a component of 5 per sec.

Fig. 3*b*. The venous curve is characterized by a fundamental wave of a relatively large amplitude, its phase being approximatively opposite to that in the arterial tracing. Here also the component 2½ per sec. shows regular distortions, whereas the second period shows an almost general extinguishing of the components.

4. *Venous pulse curves.*

Two examples of venous pulse curves were analyzed, belonging together with the radial pulse curves described above. (Fig. 3b and fig. 4b). Especially in the case of the venous pulse it seems appropriate to employ analysis. Not only the height of the tops varies very much, EDENS declaring that he could not attach any value to this, but besides there is an uncertainty concerning the presence of the two, resp. three waves. If two elevations are to be recognized these are called *a* and *c*, while they are considered to origin from the contraction of the atrium and from that of the

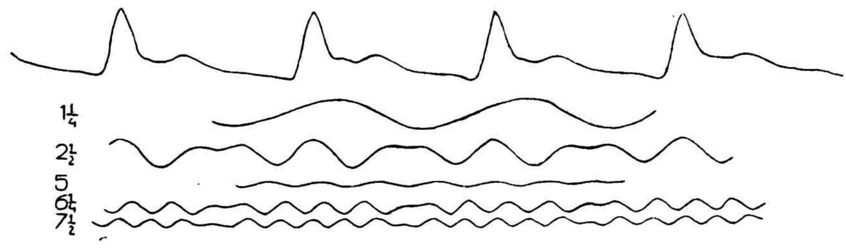


Fig. 4*a*.

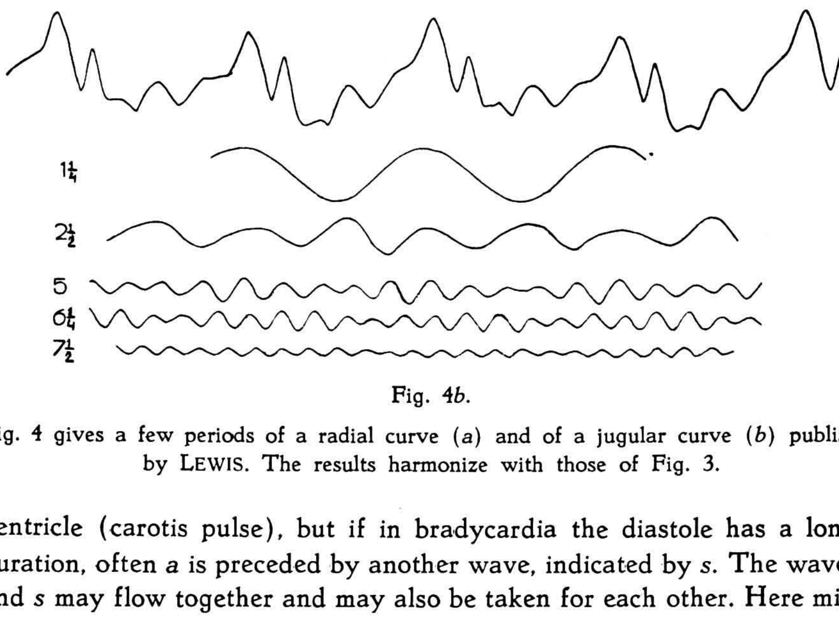


Fig. 4*b*.

Fig. 4 gives a few periods of a radial curve (*a*) and of a jugular curve (*b*) published by LEWIS. The results harmonize with those of Fig. 3.

ventricle (carotis pulse), but if in bradycardia the diastole has a longer duration, often *a* is preceded by another wave, indicated by *s*. The waves *a* and *s* may flow together and may also be taken for each other. Here might be the indication of a resonancy, the number of visible waves being larger the more a long diastole gives them the opportunity to appear.

The analysis in the first place showed a relatively strong fundamental wave, having its negative phase during the systole. It seems of some importance that in three cases (see also Fig. 1) this wave shows itself so constantly. Then a wave of 2½ per sec. is present, its impulse origining during the diastole (*vd* of the venous pulse curve), whereas an element follows, differing from the sinusoidal form, which fills up the further part of the period. As in the heart beat tracing the closing of the semilunar valves seems to cause the beginning of this wave.

FLINT's curve shows besides the frequencies 5, 6¼, 7½, 8¾ and 10, one of 6¼ having the greatest amplitude. LEWIS' curve shows 5, 6¼ and

$7\frac{1}{2}$, 5 surpassing $6\frac{1}{4}$ in amplitude. In the latter curve a distortion is visible in these elements at the beginning of the diastole the explanation as given above being applicable also here. The most interesting point of the first tracing is an extinction during the whole second pulse wave.

Conclusions.

With the aid of the analyzing method of TOMEY some tracings recorded at various places of the heart and the vascular system showed definite components. In opposition to what had been found in the vowels, in all these cases a wave with the frequency of the phenomenon itself, i.e. the heart period, was present. During the analysis of the vowels, but also in trials to analyse the electrocardiogram, it appeared that not every periodical or quasi periodical tracing shows to contain a wave of the fundamental period of the frequency. Supposing that the components found here have a physical value indeed, we have to look for the explanation of this wave. It seems natural that in recording the pressure within the ventricles the activity of the muscular wall shows itself in this way. In the heart beat tracing too, as in the curves of the atrium and the vena jugularis it is comprehensible that the effect of the same force shows itself in a similar way. The negative phase at the beginning of the venous tracing makes this still more probable, as the extension of the venous part of the heart by the lowering of the basis of the heart during the systole is a well-known fact. It is more difficult to explain the fundamental wave that is found in the central and peripheral arterial tracings. Local activities of the muscular tissue situated in the arterial wall might be of importance here.

The simpleness of the fundamental form of the heart curve, only due to the activity of the heart muscle goes forth from the examples given by MAREY and VON FREY, whereas the presence of the blood gives the tracing a normal shape. (Fig. 5).

A component of about the double frequency was found in all the cases analyzed. This frequency of about $2\frac{1}{2}$ per sec. agrees well with the essential component of the pulse found by others. Though it may be expected in the first place to be present in the arterial part of the vascular system, it shows itself also in the records from the heart and the jugular vein. The central and the peripheral arterial pulse curves show a difference in so far as in the first the largest amplitude is found during the diastole, whereas in the second this occurs during the systole. As this element generally is supposed to be derived by the vein from the arterial pulse, this explains the presence of the same element in the venous curves. That the heart beat tracing in some way or another shows a phenomenon present in the arterial system does wonder neither. Its presence within the heart might be explained by the back coupling of the "Gewoge", which VON RECKLINGHAUSEN showed.

A component of about the triple frequency of the fundamental periodicity was found only in a few cases. A component of about the fourfold frequency, i.e. of about 5 per sec. was found regularly.

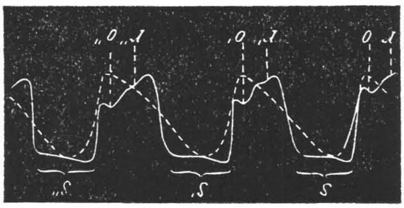
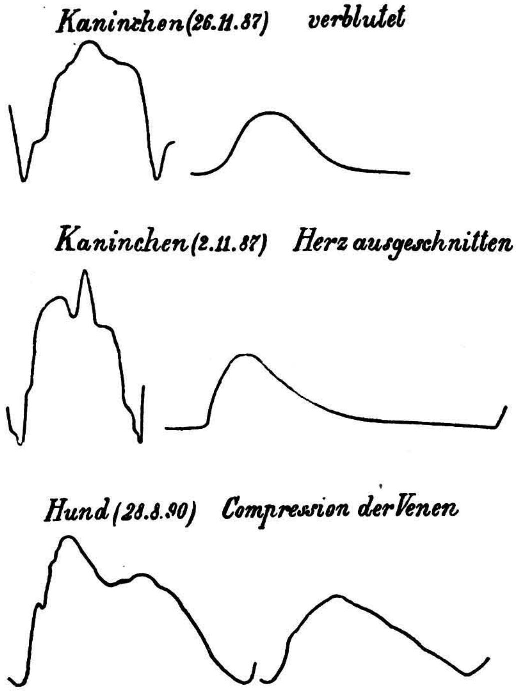


Fig. 5 shows by means of the records of MAREY and VON FREY that the contraction curve of the empty heart has a simple shape, which by a filling of the heart with blood changes into the normal aspect, which in so far as it deviates from the first must be caused by components for which the presence of the blood is essential.



With the exception of the special tracings recorded by EDENS the tracings showed no higher frequency than 15 per sec., and usually the limit was found as low as 7 or 8 per sec. This answers fully what might be expected.

The absence of some frequencies and the distortion of the phase occurring now and then seem to indicate that the components found are of a physical reality.