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ORIGINAL RESEARCH PAPER

Technology

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ELECTROCARDIOGRAPHY DEFORMATIONS

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ABSTRACT

An electrocardiogram records the electrical signals in the heart. It's a common and painless test used to quickly detect heart problems and monitor the heart's health. An electrocardiogram — also called ECG or EKG — is often done in a health care provider's office, a clinic or a hospital room. ECG machines are standard equipment in operating rooms and ambulances. Some personal devices, such as smartwatches, offer ECG monitoring. Ask your health care provider if this is an option for you.

FREQUENCY DISTORTION

Not all electrocardiographs meet the frequency response specifications that must be met. When this happens, we have the case of frequency distortion as shown in the electrocardiogram of Figure 1 where it appears that the frequency distortion may alter the shape of the electrocardiogram.

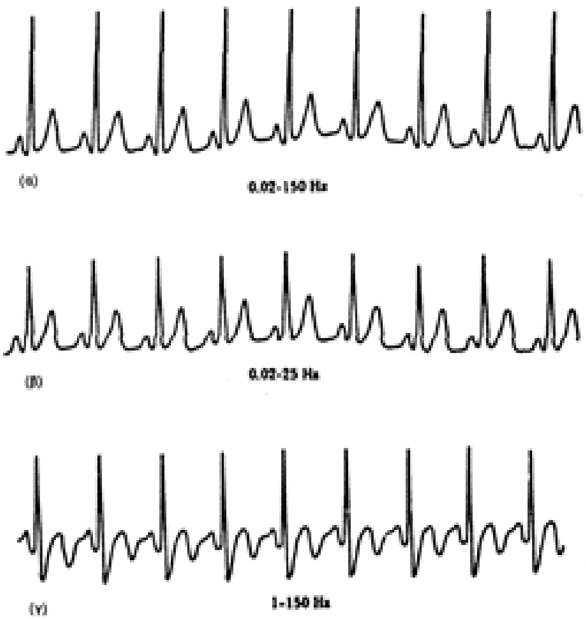


Fig 1.

Figure 1a shows a normal form of electrocardiogram, as seen in a device with a frequency response of 0.02 - 150 Hz. Figure 1b shows the same electrocardiogram as recorded by a device with a frequency response of 0.02 - 25 Hz. In this case we have the so-called high frequency distortion, which cuts and rounds the high ends of the waveform while reducing the amplitude of the QRS complex. Figure 1c shows the same electrocardiogram as recorded by a device with a frequency response of 1 - 150 Hz. It is worth noting the deformation at the base of the electrocardiogram level (baseline), where it no longer ceases to be horizontal after recording each complete heart function. It also appears that single-phase waves are depicted here as biphasic. All the above phenomena can be described by the general title: low frequency distortion of the electrocardiogram.

Amplifier saturation and clipping deformation

High compensation voltage values at the electrodes or poorly tuned amplifier stages can cause the signal to clutter, but also drive the electrocardiograph amplifier to the core, significantly altering the output of the electrocardiogram.

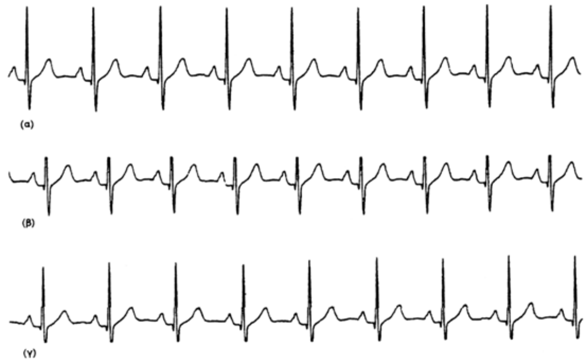


Fig 2.

Figure 2a shows a normal electrocardiogram.

Figure 2b shows the above waveform deformed due to the amplitude of the amplifier stage. In this case the combination of the input signal amplitude and the compensation voltages led the amplifier to the core during the QRS complex. The peaks of the QRS have been cut off because the amplifier output is at a standstill for these voltage values.

Figure 2c shows the case where the lower parts of the electrocardiogram have been cut. This is due to the negative saturation of the amplifier. We observe that in this case the level of the base of the electrocardiogram is completely flat. The peaks of the P and T waveforms can be recorded unless they are lower than the cut-off plane in which only R.

Ground loops

Many patients whose cardiac activity is constantly monitored in a clinic are connected to other electrical devices besides the electrocardiograph. Each electrical appliance has its own ground either along with the power supply or in a common ground channel of the room.

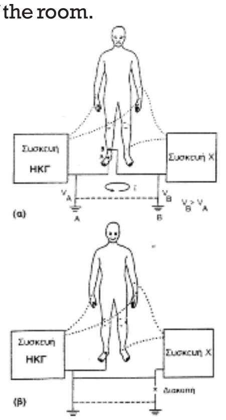


Fig 3.

The ground loop effect occurs when the case of Figure 3a occurs. Here we have a patient who is connected to two devices. Both the electrocardiograph and the X device have the signal ground electrodes in the patient. The electrocard iograph has an operating ground on the supply line with the standard plug, let A be this point. Device X also has an operating ground on the power line, but now the socket is in a different and remote location in the room, let B be at this point. Let us now assume that the potential of B for whatever reason acquires, even slightly, a higher value than that of position A. This will result in the circulation of a current from ground B through the electrodes of device X and leaking patient will enter to the electrocardiograph through its ground electrode with output to the supply ground.

In addition to the risk to his safety, which the patient runs, his total potential can be raised at a price slightly higher than that of the device reference (here in us the reference ground A). In the example of figure 3a the patient will be at a potential with an intermediate value from points A and B. This results in the generation of common signal voltages at the input, which if applied to a device with low common signal rejection, increase the noise in the final picture.

This exact path of the current between the two earths as shown in Figure 3a is referred to as the earth loop. This is an issue that should be avoided in biomedical signaling systems.

A more careful installation is shown in Figure 3b. Here the two devices are grounded at the same point (ground node) and no ground loops are created. The reference ground potential of both the electrocardiograph and the X device will be the same, unless one of the two devices due to malfunction gives current through the ground circuit to earth. Then the device will be at a higher potential than the ground point, but even in this case the patient because he has a ground point will not leak current. Therefore, because both devices have a common ground and only one common point with the patient, the latter will not be at risk of leakage currents in his body. This is a directive that must be followed faithfully.

Another problem that occurs in parallel with ground currents is shown in Figure 3a. Because the ground wire is next to the signal cables and due to the ground loop, the magnetic fields generated by the current flow in this loop induce small voltages in the signal cables, resulting in the appearance of an additional cause of noise.

Due to their nature, earthing loops represent closed current paths. At the same time, they define an area of any geometric shape. If there is now a time-varying magnetic field in this area (eg from the power transformers of the devices or transmission lines) an additional current can be induced in this loop. The result of this current will be the flow of currents to the patient or the creation of common signal voltages with all the problems that entail.

Free pipes

Often a conductor that connects a biodynamic signal receiving terminal either disconnects or breaks due to some heavy handling, thus ceasing to be connected to the electrocardiograph. In this case it is possible to introduce relatively high potential values from the free end due to the presence of near electric fields from the power lines or from other electric fields in the surrounding area. This causes a constant amplitude deviation of the recorder pin across the spectral content of the interpolation and eventual loss of the useful signal. A similar case occurs when an electrode does not make good contact with the patient's body.

Alterations due to strong electrical transitions.

There are cases of patients who, while connected to the electrocardiograph, need cardiac defibrillation. In this case, a high voltage and intensity electric pulse is applied to the patient's chest, at which time strong transient dynamics are observed along the electrodes. The width of these dynamics can be several orders of magnitude higher than the usual widths that an electrocardiograph receives as input. There are of course other cases where we can have similar transitional phenomena. When this happens, a sharp deviation in the electrocardiogram is caused as shown in Figure 4. This is due to the saturation of the electrocardiograph amplifiers due to the large pulse width or excitation applied to their inputs. This pulse, in fact, is strong enough to show the concentration of charges in the coupling capacitors of the amplifier. Thus there is a stay in saturation for some time until the loads are removed and then the signal returns to the baseline level. The time constant of this phenomenon depends on the characteristic frequency of the amplifier as shown in Figure 4.

Similar changes can occur for reasons other than defibrillation. It is possible to cause signal distortion due to electrode friction (generation of static electricity) which ultimately results in the acquisition of an electrocardiogram with a width greater than normal. Also, the creation of static electricity on the patient and his gradual discharge, causes alterations. Older technology electrocardiographs showed similar phenomena when the operator selected the different electrodes externally with the switch, due to the different compensation potentials at each electrode. This phenomenon has been eliminated in the new technology electro cardiographs, because on the one hand the switching is done automatically and on the other hand the input capacitors are discharged during the switching process.

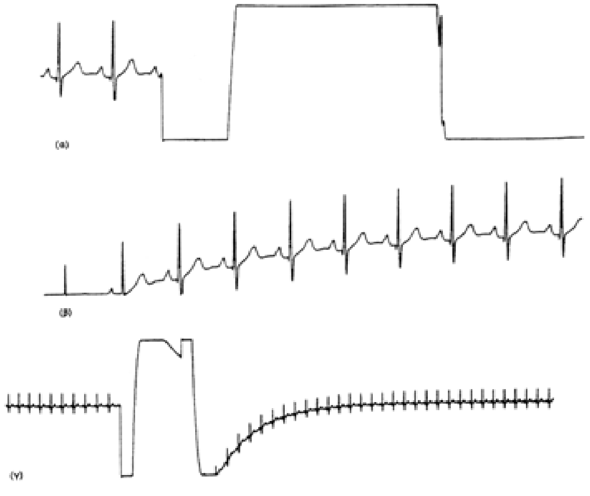


Fig 4.

In figure 4 a) Onset of a transitional phenomenon, b) Continuation of (a) where recovery begins to appear, c) Similar transition with reduced amplification to show the return to equilibrium conditions (first order system).

Because we do not have time to disconnect the electrocardiograph when a patient is receiving defibrillation, we can integrate a protection circuit into the device. In this way we succeed in reducing the high input voltage in the amplifier stage of the electrocardiograph by avoiding saturation as well as the phenomena of load accumulation due to precisely these high voltage values. This results in a faster return to baseline after such a strong transient phenomenon. Also the protection circuit also reduces the risk of damage to the device by these pulses.

The static electricity generated in the nursing staff who comes in contact with the patient, creates alterations in the image of the electrocardiogram. This can be reduced by allowing staff to wear conductive clothing and shoes, placing a conductive floor informing staff so that they can be grounded in a metal area before coming into direct contact with the patient.

Interference from electrical appliances (Electromagnetic Interference, EMI)

A serious source of interference for an electrocardiogram, which is either simply monitored or recorded, is the power supply network. In addition to the power supply to the electrocardiograph, the power lines are connected to other devices or equipment located nearby in a typical patient room or doctor's office. Power lines can be located on the wall, floor, ceiling of the room, run through it or even connect it to other parts of the building complex. So these lines radiate in close proximity and introduce interference, thus altering the recorded trace as shown in Figure 5. This interference that appears in the recordings is the result of two mechanisms that can operate independently or in some cases simultaneously.

Fig.5

The coupling of the electric field between the transmission lines, the electrocardiograph and / or the patient, is the result of the electric fields that exist in the main transmission lines and in the individual cables that connect various devices to the network. These fields still exist even if the device is not in operation, because electricity is not necessary to generate an electric field. So these fields are coupled with the patient, the signal conduction, and even the electrocardiograph itself. These couplings are implemented in circuits in the form of tiny capacitors (capacitive coupling) which connect the transmission lines to all the above elements, as shown in Figure 6.

The current through the capacitance C_3 that connects the phase or neutral of the transmission line with the electrocardiograph flows to the ground and does not cause any interference. Capacitor C_1 represents the capacitance between a transmission line and one of the electro cardiograph signal leads. The current id1 does not flow to the electrocardiograph, due to the high input resistance but goes to earth through Z_1 and Z_G (electrode-body contact resistors). Similarly id_2 flows through Z_2 and Z_G towards the earth. The resistance of the body, which is considered to be 500Ω, is not taken into account when compared to the other resistors shown. The voltage that is amplified is the one that appears between inputs A and B, ie V_A-V_B where $V_A - V_B = id_1\, Z_1 - id_2\, Z_2$.

Huhta and Webster (1973) suggested that if the two abductions are side by side then: $id_1 \approx id_2$

In this case: VA-VB = id1 • (Z1- Z2)

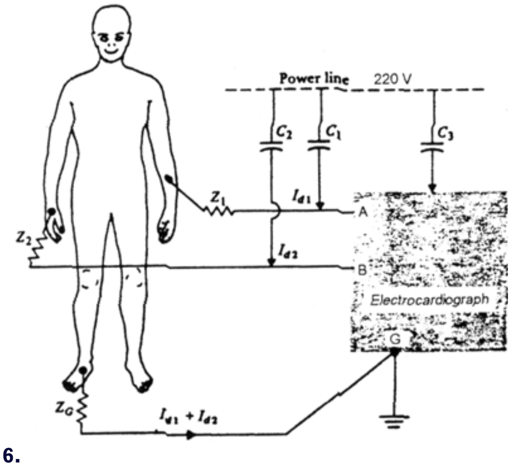


Fig 6.

The values measured for a 9m cable give an id current of 6nA. The electrode-body contact resistance can be of the order of 20 kΩ so:

$$V_A - V_B = (6\text{nA})\ \ (20\text{k}\Omega) = 120\mu\text{V}$$

This voltage value is a fairly strong interference, greatly distorting the signal. This effect can be reduced by shielding each conductor (eg using a coaxial cable) and grounding all the shields (outer coaxial grid) to ground the electro cardiograph. This is done from the beginning in all modern electrocardiographs. It also helps a lot to reduce the skin-abduction contact resistance, which is achieved by using self-adhesive terminals with high-conductivity materials and electrolyte cream.

Figure 7 shows that current also flows from the supply line into the patient's body. The Id_b displacement current flows through the ground resistance Z_G to ground. The result is the creation of a voltage drop that eventually becomes a common signal voltage and occurs throughout the body.

$$V_{cm} = id_b\ Z_G$$

By replacing standard prices we get:

$$V_{cm} = (0.2\mu\text{A})\ \ (50\text{k}\Omega) = 10\text{mV}$$

In an electrical environment with $id_b > 1\mu A$ the Vcm can be higher than 50mV. In an ideal amplifier this does not pose a problem because the differential input rejects common signal voltages. However real amplifiers have a finite Z_{in} input resistance, so we have a common signal rejection ratio (CMRR). Thus Vcm is reduced due to the attenuation introduced by both the skin-abduction contact resistance and Z_{in}.

So we have:

$$\text{bVA-VB=Vcm}\bullet\left(\frac{Z_{in}}{Z_{in}+Z_1}-\frac{Z_{in}}{Z_{in}+Z_2}\right)$$

Because Z_1 and Z_2 are much smaller than Zin we will have:

$$\text{bVA-VB=Vcm}\bullet\left(\frac{Z_2-Z_1}{Z_{in}}\right)$$

Substituting standard prices we have:

$$\text{VA-VB=(10mV)}\bullet\left(\frac{20\text{k}\Omega}{5\text{M}\Omega}\right)=40\mu\text{V}$$

The above value is simply observable for the electrocard iogram while for the electroencephalogram it is catastrophic and completely distorts the signal. This phenomenon can be addressed by improving as much as possible the skin-abduction contact resistance and by increasing as much as possible the input resistance of the amplifier. The above value is simply observable for the electrocardiogram while for the electroencephalogram it is catastrophic and completely distorts the signal. This phenomenon can be addressed by improving as much as possible the skin-abduction contact resistance and by increasing as much as possible the input resistance of the amplifier.

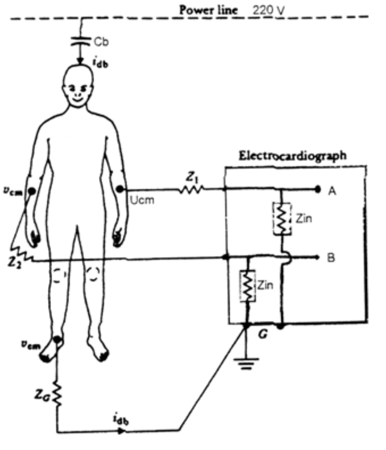


Fig 7.

Thus we see that the value difference between the skin-abduction contact resistors is something that should be taken seriously when designing biodynamic signal amplifiers. Some common signal voltage values are always present so the differences in Zin and input are critical factors that ultimately determine common signal rejection, regardless of the overall performance of the differential amplifier itself.

The other source of interference from the transmission line is magnetic induction. The electric current in the lines creates a magnetic field in their surrounding area. Even the magnetic fields are created by the transformers that are present in the power supplies of the devices and by the coils with iron core (ballast) that are necessary for the operation of the fluorescent lamps. If such a magnetic field passes through the simple loop, defined by the electrocardiograph device, the patient and the lead wires as shown in Figure 8, then a voltage is induced and a current is circulated in the loop. The value of the voltage is proportional to the strength of the magnetic field and the size of the surface enclosing the defined loop.

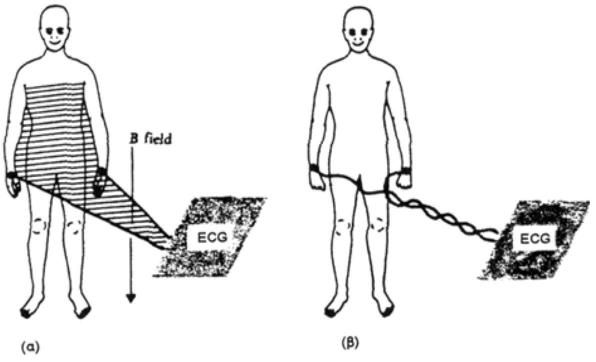


Fig 8.

This effect can be reduced:

- Using magnetic shielding of magnetic field sources.
- Keeping the electrocardiograph and electrode electrodes away from sources of strong electromagnetic fields (which in practice is quite difficult).
- Reducing the active cross-section of the defined loop. This can be achieved by twisting the cables together in pairs, as densely as possible, along their entire length, thus forming small loops. From the electromagnetic theory we know that they will give currents with opposite signs which in the whole cancel each other out, thus eliminating the total interference.

Other sources of electrical interference

The electrocardiogram can be affected by sources other than the power lines. Electromagnetic interference from radios, televisions or radar activities can be introduced into the electrocardiograph. This signal is amplified by the p-n junctions of the transistors or sometimes even by the electrolyte-electrode contact on the patient. In the case of these interferences both the cables and the patient behave like antennas. Once the signal is detected and inserted, its demodulated effect will immediately appear as interference on the electrocardiogram.

Electromagnetic interference can also be generated by high-frequency generators in the hospital itself. Diathermy and electrosurgery are sources of such frequencies. Grobstein and Gatzke (1977) demonstrated that the correct use of electrosurgery and at the same time the correct design of a heart rate signal amplifier are necessary conditions to eliminate interference.

Electromagnetic radiation can be emitted by X-ray machines, switches and power relays located in the hospital. Even the arc created in a flashing fluorescent lamp that needs to be replaced can cause serious interference.

Electromagnetic interference is usually eliminated by short-circuiting the input terminals with a small capacitor of approximately 200pF. The response of this capacitor is quite high in the electrocardiogram frequency range without significantly lowering the overall input resistance of the device. However with modern technology devices that have high input resistance it is important to be assured that it will continue to maintain a high value. At radio frequencies the response is low enough to effectively short-circuit the electromagnetic interference collected by the signal conduction cables and prevent them from reaching the transistors of the amplifier.

There is another source of electrical interference, which is located inside the body and can affect the electrocardiogram. Of course there are muscles in the area where the electrocardiogram receiving electrodes are located. Each time a muscle contracts, it generates its own electromy ographic signal, which is detected by the corresponding terminal of the device, causing interference, as shown in Figure 4. When we look only at the electrocardiograph and not at the patient, it is often difficult to understand what kind of interference we have, that is, whether it is the result of muscle activity or electromagnetic radiation. However, during the electrocardiogram procedure, we can easily separate the two sources, because the electromyographic interference is related to the patient's muscle contractions.

Fig 9.

Summary and graphic illustration of electromagnetic interference.

Figure 10 shows, the use of the differential amplifier in an electrocardiographic recording system. The desired input of our system is the Vecg voltage, which appears between the two electrodes that are attached to the surface of the body. Exogenous electromagnetic interference is clearly visible. The 50Hz noise is induced in the network, in the form of current of the same frequency of course, due to the existence of the shaded loop and the magnetic fields of the surrounding space. Even the displacement currents that due to capacitive connections are introduced in the electrodes, cause parasitic voltages. These appear on the Zbody resistor and on the resistors Z_1 and Z_2 of the conductors. The orientation of the conductors in relation to the magnetic field of the surrounding space also plays a role. That is, if the field and conductors are parallel, I do not have induced interference, but if it is vertical the interference is maximum.

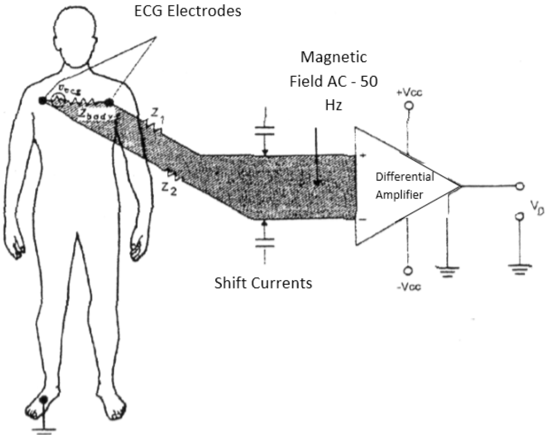


Fig 10.

METHODS OF PROTECTION FROM INTERFERENCE

Clipping circuits

As we mentioned, there are cases when a strong voltage is applied to the input of the electrocardiograph (eg due to defibrillation to the patient) when we have a strong transient phenomenon at the input of our device. This results in the amplification steps being saturated with the known results. So our problem is to protect the device from such surges. The solution is given to us by the scissor circuits, which owe their behavior to the existence of a diode or diodes.

They are used to select to transmit that part of a random waveform that moves up, down or even symmetrically around a reference level. Clipping circuits are even referred to as voltage (or current) limiters, amplifier selectors, or shredders. A simple clipping circuit is shown in Figure 11, where input voltages below Vγ are not transmitted to the output, as shown by the waveforms.

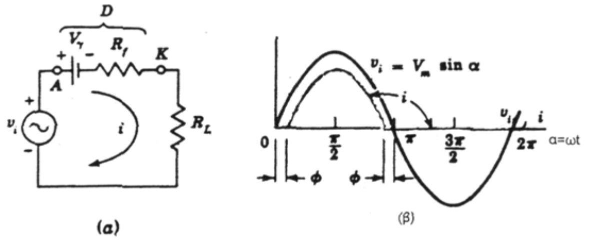


Fig 11.

Figure 11 a) the equivalent of a diode (ON state) in series with a load resistor RL and a sinusoidal voltage ui b) The input waveform ui and the rectified current I.

In our case, the family of two-way shears is useful, because they limit the signal to a useful area, which we make sure in advance is exactly that of the linear operation of the amplifier so as not to lead to saturation. So this category uses diodes in pairs, in order to achieve clipping at both ends in independent levels. The diodes can be connected in series, in parallel or in series and in parallel. A parallel wiring device is that of Figure 12a. Figure 12b shows the continuous curve of linear input-output sections for Figure 12a.

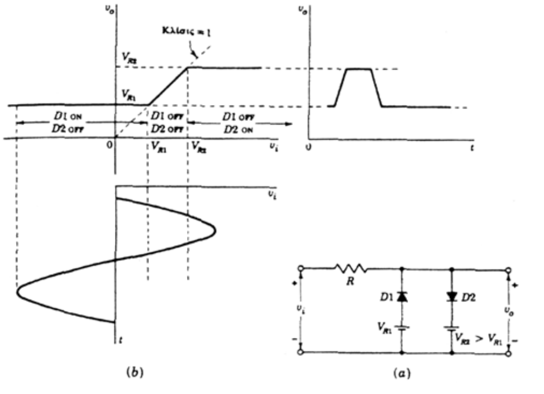


Fig 12.

Figure 12 a) A two-pass shear, which restricts to two independent levels, b) The linear transfer curve for circuit (a). The double-clipped output signal corresponding to the input halftone.

The transfer curve has two refraction points, one at uo = ui = VR1 and the second at uo = ui = VR2 and has the following characteristics (if $V_{R2} > VR >> V_\gamma$ and $R_f << R$):

Είσοδος u_i	Εξοδος u_o	Καταστάσεις διόδου
$u_i \leq V_{R1}$	$u_o = V_{R1}$	D_1 ON, D_2 OFF
$V_{R1} < u_i < V_{R2}$	$u_o = u_i$	D_1 OFF, D_2 OFF
$u_i \geq V_{R2}$	$u_o = V_{R2}$	D_1 OFF, D_2 ON

The circuit in Figure 12a is also referred to as a shredder, because the output contains a portion of the output signal located between the two reference stations VR_1 and Vr_2.

Two avalanche diodes in series and opposite as shown in Figure 12a constitute another form of double shear. If the diodes have identical characteristics, then we get a symmetrical shear. If the breakdown voltage is VZ and the conduction voltage is Vγ, then we get a transfer characteristic as shown in Figure 13b.

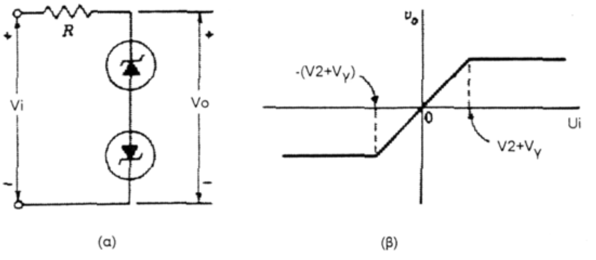


Fig 13.

Figure 13 a) Double-ended shear, in which avalanche diodes are used, b) The transfer characteristic.

Other circuits used to eliminate interference.

As we have already observed, common signal trends are responsible for a wide range of interferences in biodynamic signal amplifiers. Although an amplifier with a high common signal rejection ratio reduces the phenomena associated with these voltages, an additional effort is made to find suitable solutions that will further reduce the phenomenon.

Shielding by electric and magnetic fields

In the previous chapter we saw that electrical interference is introduced into biodynamic signal reception systems via capacitive coupling and magnetic induction. These interferences are reduced when the sources that cause them are neutralized, this is achieved by the use of shielding techniques. Figure 14 shows an electrostatic shield, which is achieved by installing a conductive and at the same time grounded surface between the electric field source and the biodynamic signal receiving device. In particular, measurements of very weak biodynamic signals, such as the electroencephalogram, are usually taken exclusively in a shielded area of the previous type to completely isolate interference. Many hospitals have armored areas for electroencephalography laboratories, where all surfaces use solid metal sheets or at least ground copper grids for the chest.

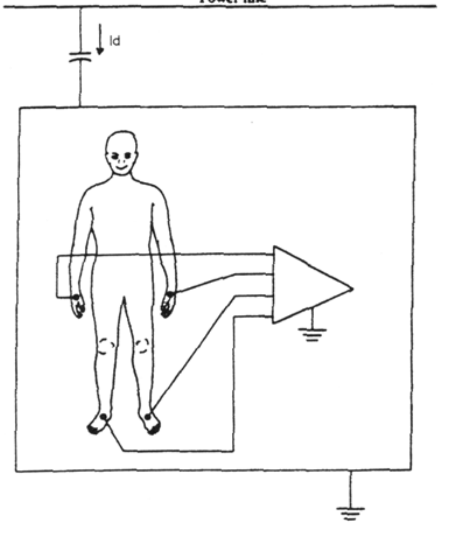


Fig 14.

This type of shield is not suitable for protection against magnetic fields unless the selected metal is characterized by a high value of magnetic permeability (eg steel sheets). In other words, metal sheets should be characterized as both good conductors of electricity and magnetism. Such spaces do provide magnetic shielding, but a more economical way to reduce magnetically induced signals is to reduce the active cross-section of the loops defined by the various conductors of the differential inputs of the biodynamic amplifier when referring to differential signals. When it comes to common signal voltages we reduce the active cross section of the loops defined between the inputs and the ground. Something that is quite simple and improves the situation is the use of a twisted pair duct as we saw in the previous chapter.

Elimination of ground loops

Ground loops are responsible for generating common signal voltages due to currents flowing in the ground network. This can be caused by magnetic induction or by the existence of even small differences in values in the dynamics from different devices that are connected to the same patient. In any case, eliminating common signal voltages is simple: Neutralize all ground loops. All measuring devices as well as all devices related to a patient should be grounded in a common place. Figure 13b illustrates how the ground loop of Figure 13a can be modified and ultimately avoided. The engineer when installing biodynamic signal receiving devices should make sure that there is a single ground path that connects the devices to the ground. Also, all the individual conductors that connect the devices must end at a single point (ground node). So we can compare the topology of the ground network with that of a star by placing the ground node in the center of light, while the conductors leading to each device are the rays.

Lower right extremity drive system.

In several modern electrocardiographs the patient is not grounded. Instead the lower right end electrode is connected - figure 15 - to the output of an auxiliary operating amplifier. Common signal voltages in the patient's body are detected by two resistors Ra, reversed, amplified and fed back to the lower right extremity. This negative feedback leads the common signal voltage to a very low value. Shift currents in the patient's body now flow to the output stage of the operating amplifier rather than to ground. This circuit significantly improves the situation since the amplifier itself now takes into account the attempted change. The circuit outputs the common signal voltage through a pair of resistors connected to V_3 and V_4. The lower right end is no longer grounded, but connected to the output of the auxiliary operating amplifier.

This circuit also provides a form of electrical protection. If an unusually high voltage occurs between the patient and the ground as a result of an electrical leak or other cause, then the auxiliary operational amplifier is driven to the crotch and thus the patient is disconnected from the ground because the amplifier can no longer drive the lower right end. . Now the parallel resistors R_f and Ro are located between the patient and the ground. These can have a value of enough MegaOhms to limit the current value. These resistances protect the patient. But a 220V leak to the patient would damage the transistors of the operating amplifier and the current would go back to earth.

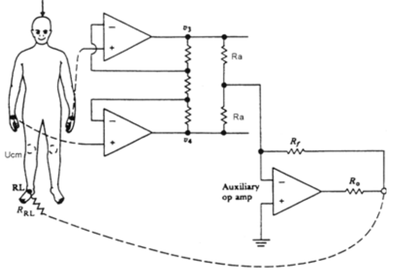
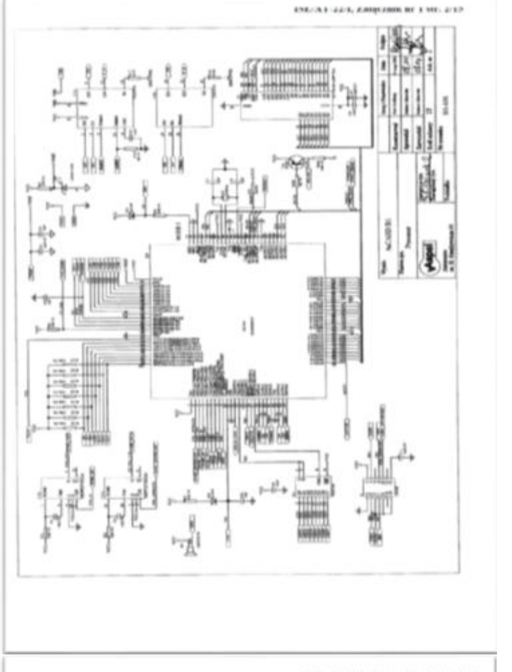
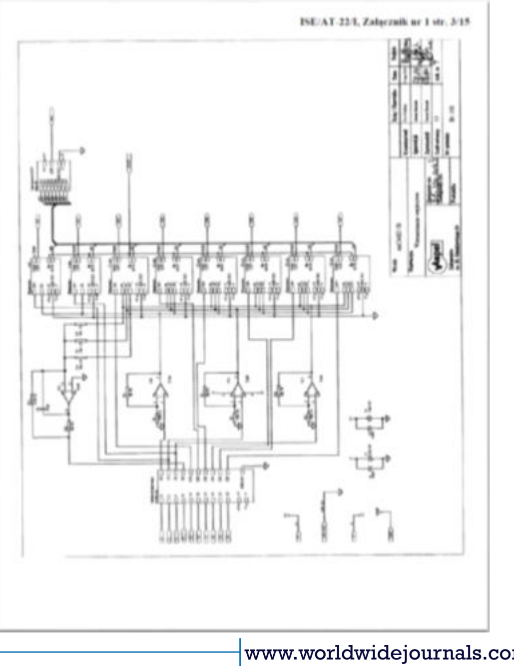


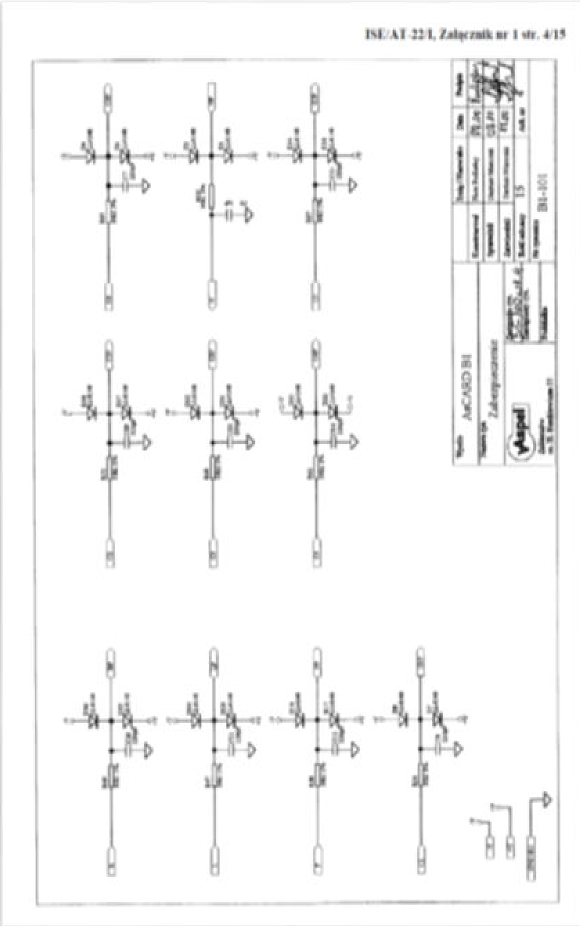
Fig 15.

Fig 16.

Digital Cardiographs with ECG lead electrodes. (Six procardia & two upper and two lower extremities).



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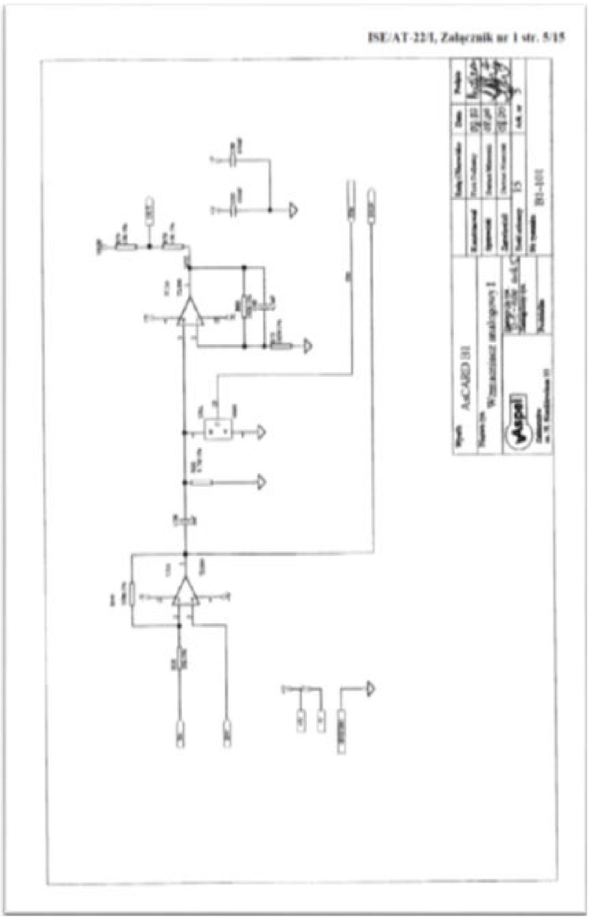
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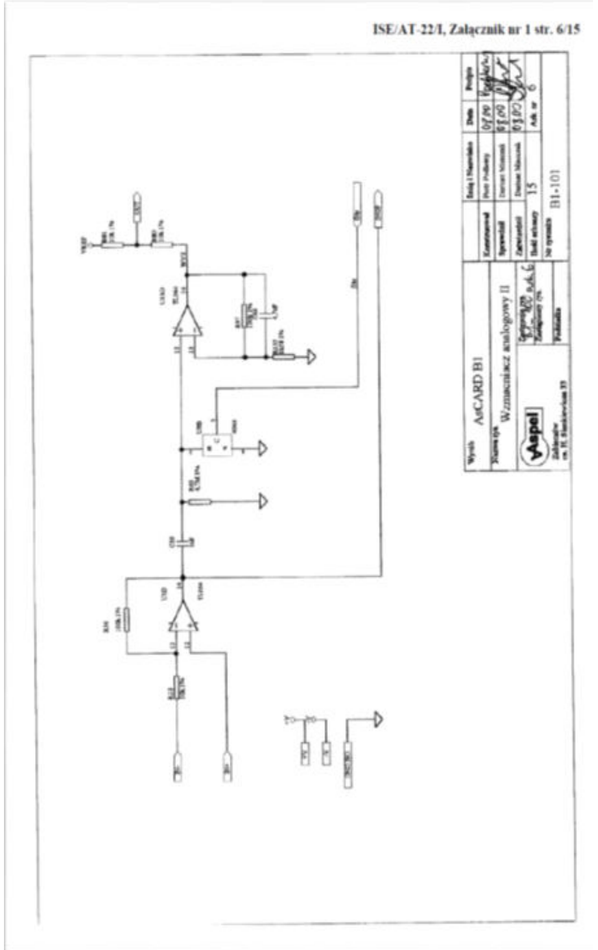
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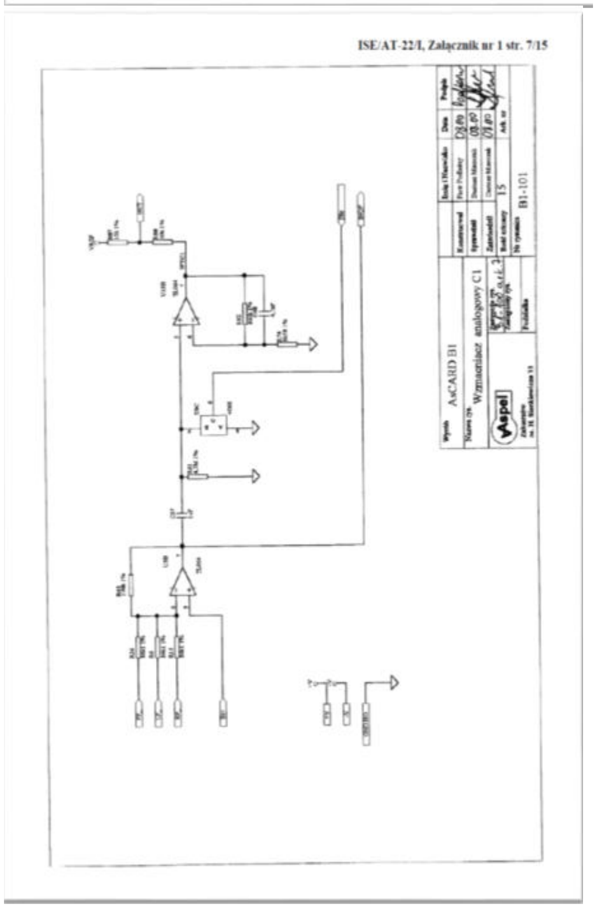
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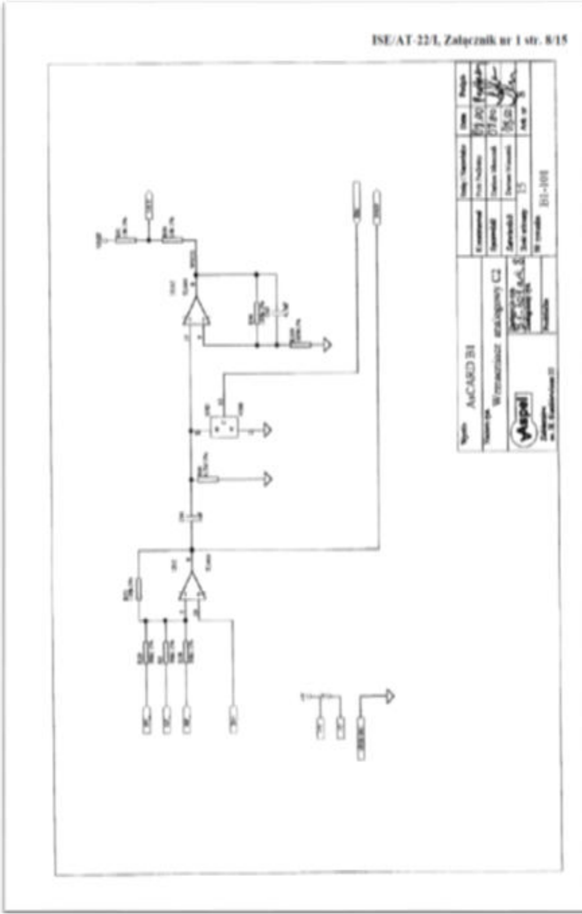
B1-101


ISE/AT-22/I, Załącznik nr 1 str. 8/15
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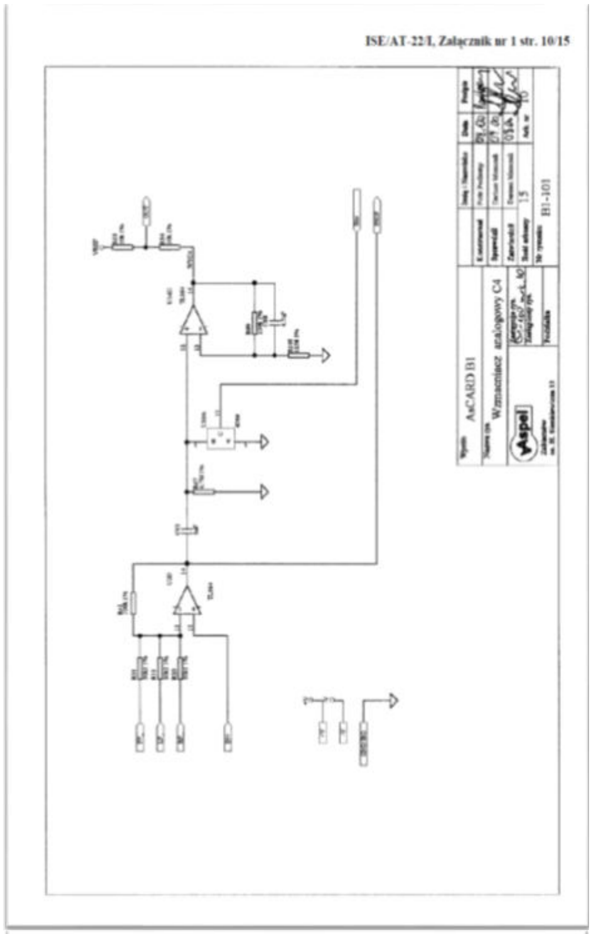
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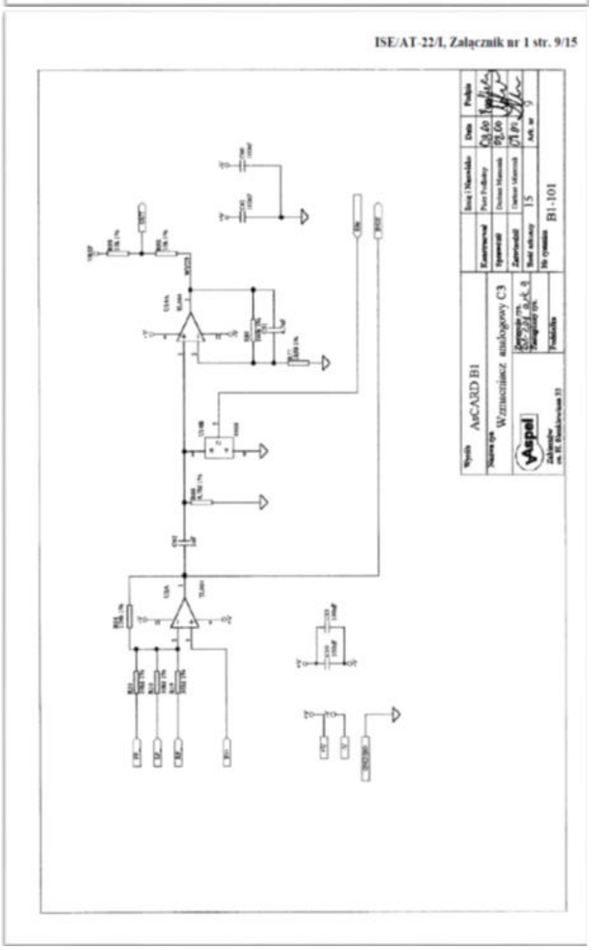
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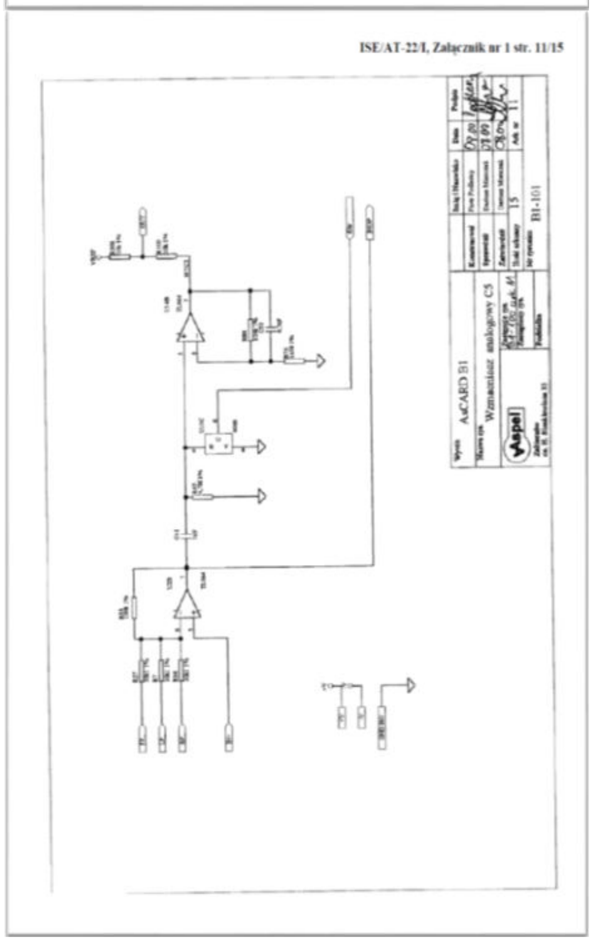
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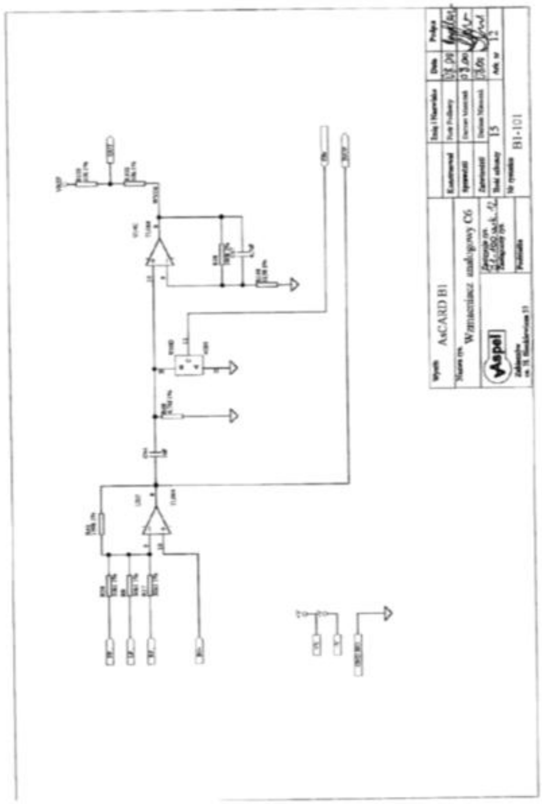
ISE/AT-22/I, Załącznik nr 1 str. 12/1



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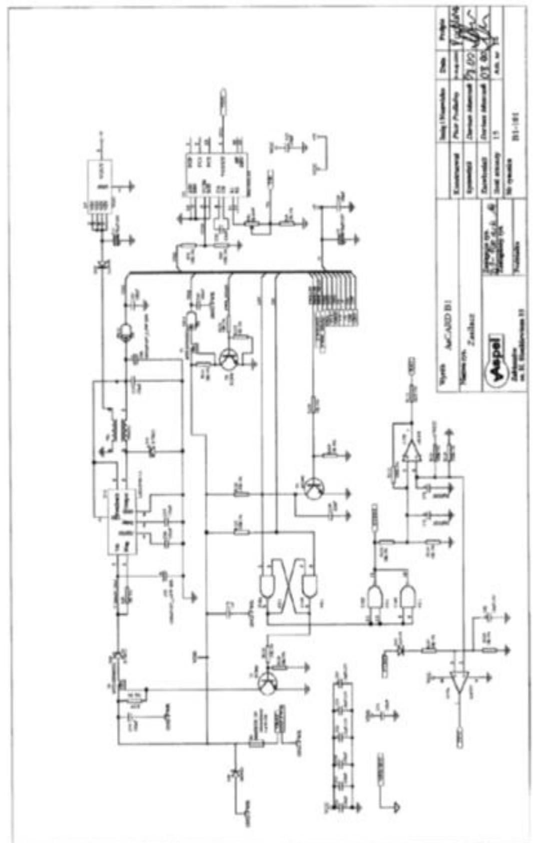

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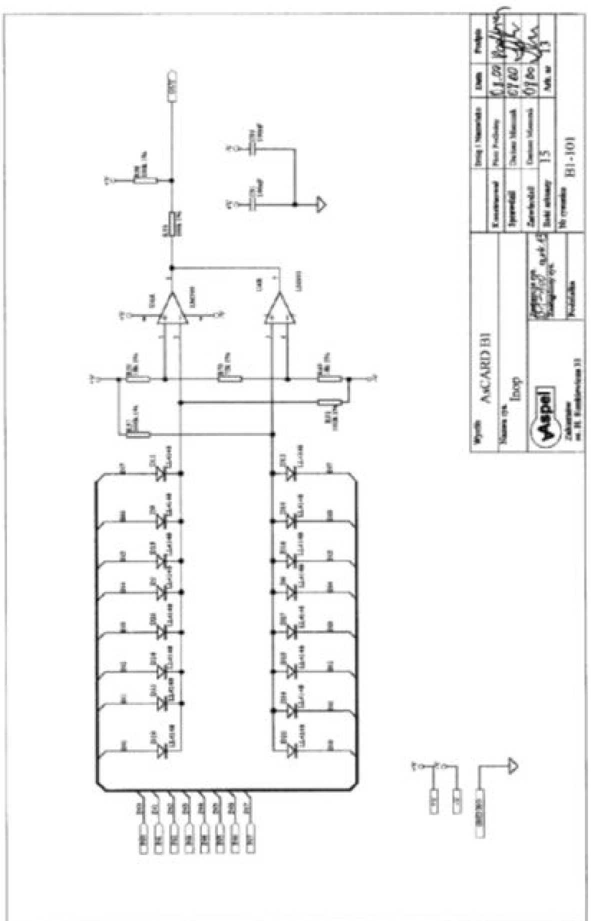

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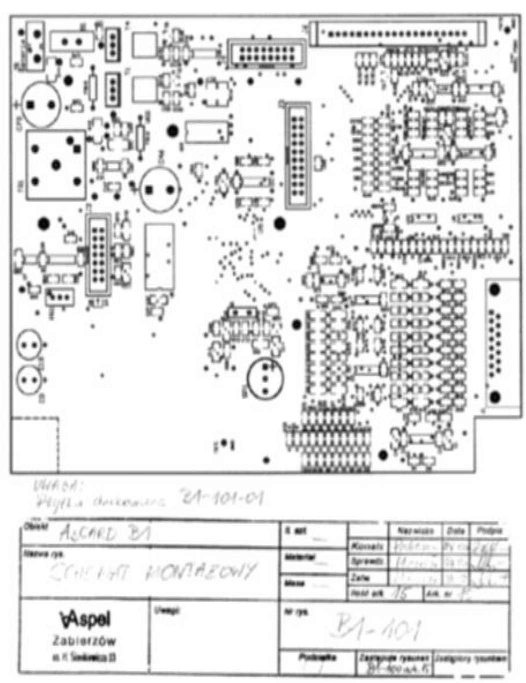

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